UN environment programme

A future we choose

Why investing in Earth now can lead to a trillion-dollar benefit for all

Global Environment Outlook Seventh edition-2025

© 2025 United Nations Environment Programme

ISBN: 978-92-807-4246-6
Job number: DEW/2728/NA
DOI: https://doi.org//10.59117/20.500.11822/49014

Acknowledgements

Reproduction

This publication may be reproduced in whole or in part and in any form for educational or non-profit services without special permission from the copyright holder, provided acknowledgement of the source is made. The United Nations Environment Programme would appreciate receiving a copy of any publication that uses this publication as a source.

No use of this publication may be made for resale or any other commercial purpose whatsoever without prior permission in writing from the United Nations Environment Programme. Applications for such permission, with a statement of the purpose and extent of the reproduction, should be addressed to unep-communication-director@un.org

Disclaimers

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area of its authorities, or concerning the delimitation of its frontiers or boundaries.

Mention of firm names and commercial products in this document does not imply endorsement by the United Nations Environment Programme or the authors. The use of information from this document for publicity or advertising is not permitted. Trademark names and symbols are used in an editorial fashion with no intention of infringement of trademark or copyright laws.

The views expressed in this publication are those of the authors and do not necessarily reflect the views of the United Nations Environment Programme. We regret any errors or omissions that may have been unwittingly made.

© Maps, photos and illustrations as specified

Suggested citation
United Nations Environment Programme (2025). *Global Environment Outlook 7: A future we choose – Why investing in Earth now can lead to a trillion-dollar benefit for all*. Nairobi. https://wedocs.unep.org/handle/20.500.11822/49014.

Production: Nairobi
URL: https://www.unep.org/resources/global-environment-outlook-7
Cover image: AI-generated visual created by Beverley McDonald / UNEP

A future we choose

Why investing in Earth now can lead
to a trillion-dollar benefit for all

Acknowledgements

The seventh edition of the Global Environment Outlook (GEO-7) assessment report is a product of the generous dedication and extraordinary investment of numerous individuals, whose knowledge, expertise and insight helped shape this important body of work. The United Nations Environment Programme acknowledges the contributions made by many governments, individuals, and institutions to the preparation and publication of this report. A more complete list of names of individuals and institutions involved in the assessment process is included following the annexes of this publication. Special thanks are extended to:

Assessment Co-chairs

Edgar E. Gutiérrez-Espeleta, Nyovani Madise, Ying Wang, Robert Watson

Intergovernmental and Multi-stakeholder Advisory Group (IMAG)

Arthur Eijs (Co-chair), Anna Mampye (Co-chair), Rolenas Baereleo (Vice-chair), Miroslav Havránek (Vice-chair), Ana Julieta Calvo - Obando (Rapporteur), Mohamed Abdelraouf, Zahra Abu Taha, Thuraya Said Al Sariri, Silvio Albuquerque e Silva, Djatougbe Aziaka, Leila Bendifallah, Thomas Chali, Merylene Chitharai, Ingrid Coetzee, Lisa Eriksson (Alternate), Toghrul Feyziyev, Marek Haliniak, Meri Harutyunyan, Neyra Herrera, Keri Holland (Alternate), Yi Huang, Claudia Kabel, Christina Komorski, Maha Maayta, Takashi Otsuka, Toral Patel - Weynand, Dušica Pešević, Salla Rantala, Kenset Amaury Rosales Riveiro, Modibo Sacko, Jerome Lugumira Sebadduka, Ruth Viola Spencer, Gillian Stanislaus, Jan - Gustav Strandenaes, Prem Singh Tharu, Alexandra Gurgel Valente da Costa (Alternate), Carlos Cordero Vega (Alternate), Fabian Wagner, Dominic Kailash Nath Waughray

Multidisciplinary Expert Scientific Advisory Group (MESAG)

Nicholas King (Co - chair), Maria del Mar Viana Rodriguez (Co-chair), Ervin Balázs (Vice-chair), Rosemarie Casimiro (Vice-chair), Gian Carlo Delgado-Ramos (Rapporteur), Ousséni Arouna, Dolors Armenteras Pascual, Alberto Santos Capra, Lorenzo Ciccarese, Sandra Bibiana Correa, Eric Davidson, Nagwa El Karawy, Tambe Honourine Enow, James D. Ford, Catherine Ganzleben, Razieh Ghayoumi, Joyeeta Gupta, Tatiana Kuznetsova, Yonglong Lu, Mónica Moraes R., Amal Moufarreh, Janez Potocnik, Nijavalli Ravindranath, Majid Shafie pour Motlagh, Belay Simane, Asha Singh, Inna Stecenko, Shau Hwai Aileen Tan, Alban Thomas

Coordinating Lead Authors (CLAs)

Tamiru A. Abiye, Ana Paula Aguiar, Peter Alexander, Barbara Amon, Apoorva Arya, Ghassem Asrar, Lindsay Beevers, Medani Bhandari, Meena Bohara, Gillian Bowser, David Broadstock, Monday Businge, Donovan Campbell, Kateřina Černý Pixová, Lynette Cheah, Leila Dagher, Vassilis Daioglou, Jonathan Davies, Mark Elder, Parfait M. Eloundou-Enyegue, Pierre Failler, Pedro Fidelman, Shinichiro Fujimori, Erica Brown Gaddis, Keisha Garcia, Sarah Green, Andres Guhl, Gladys Cecilia Hernandez-Pedraza, Susie Ho, Min Hu, Madhav Bahadur Karki, Monica Kerretts-Makau, Mizanur Khan, Andrei Kirilenko, Kyung Ah Koo, Joanna Kulczycka, Debora Ley, Jianguo Liu, Paul Lucas, Clever Mafuta, Sarah-Lan Mathez-Stiefel, Karina Miglioranza, Ruben Mnatsakanian, Rachid Mrabet, Kevin Nnanye Nwaigwe, Alice Odingo, S. Nadia Ouedraogo, Jacob Park, Jan Plesnik, Riya Rahiman, Adina Manuela Relicovschi, Henri Rueff, Aibek Samakov, Tek Sapkota, Heinz Schandl, Patrick Schröder, Jeff Seadon, Binaya Raj Shivakoti, George Florin Staicu, Paul Sutton, Gail Taylor, Catalina Turcu, Bruno Turnheim, Detlef van Vuuren, Sotiris Vardoulakis, Karen Helen Wiltshire, Xiyan Xu, Fang Yu, Pandi Zdruli, Eric Zusman

Lead Authors

Fagr Abdel-Gawad, Adolf Acquaye, Susana Beatriz Adamo, Kofi Akamani, Adenike Akinsemolu, Alaa Al Khourdajie, Aliyu Aliyu, Maryam Alkharusi, Farshad Amiraslani, Steve Arquitt, Quosay Awad Ahmed, Janelle Baker, Aistė Balžekienė, Aliyu Salisu Barau, Ricardo O. Barra, Claudio Belis, Lorenzo Benini, Hester Biemans, Fiffy Hanisdah Binti Saikim, Elliot Boateng, Souhila Bouilouta,

Edward Byers, Shaneel Chandra, Kalpana Chaudhari, Joanne Clarke, Salud Deudero Company, Jan Cools, Hancheng Dai, Loïc De Weerdt, Danielle Mendes Thame Denny, Sybil Derrible, Leila Devia, Jagath Premakumara Dickella Gamaralalage, Jonathan Doelman, Peter Edwards, Sibel Eker, Isa Olalekan Elegbede, Eduardo Erazo Acosta, Jessica Fanzo, Vinicius F. Farjalla, Dulce Flores-Renteria, Michele Fontefrancesco, Panagiotis Fragkos, Bonmwa Fwangkwal, Elisabeth Gilmore, Alex Godoy-Faundez, Mariana Guttieres-Paz, Taylor Hanna, Stephan Harrison, Maryna Henrysson, Rozana Himaz, Beata Houšková, Saleemul Huq, Ekhtekharul Islam, Efitre Jackson, Nandakumar Janardhanan, Kejun Jiang, Modupe O. Jimoh, Mulako Kabisa, Miho Kamei, Joanna Kámiche Zegarra, Govind Kelkar, Peter King, Mahdi Kolahi, Vojtech Kotecky, Lydie-Stella Koutika, Jyotsna Krishnakumar, Pankaj Kumar, Sigrid Kusch-Brandt, Juliana Subtil Lacerda, Annamaria Lammel, Tao Lin, Jinlong Liu, Melisa Ljusa, David Lopez-Carr, Yolanda López-Maldonado, Christian Löwe, , Simone Lucatello, Patricia Maccagno, Nomanesi Madikizela-Madiya, William Armand Mala, Aynur Mammadova, Olena Maslyukivska, , Alma Mendoza-Ponce, Juliana Merçon, Jonathan D. Moyer, Indu K Murthy, Veronica Mwangi, Ravendra Naidu, Didacus Namanya, Valerie Nelson, Thang Nguyen Trung, Jaee Nikam, Karachepone Ninan, Judit Oláh, Simon Høiberg Olsen, Jean Pierre Ometto, Evans Osabuohien, Nkechi Owoo, Leonidas Paroussos, Leisa Perch, Laura Pereira, Ramon Pichs-Madruga, József Popp, Joana Portugal Pereira, Svetlana Radionova, Graciela Raga, Kamal Kumar Rai, Stefan Reis, Chao Ren, Kamaljit K Sangha, Sanchit Saran Agarwal, Pallavi Saxena, Ronaldo Seroa Da Motta, Kalim Shah, Fangxia Shen, Fred Steward, Roopesh Kevin Sungkur, Elias Symeonakis, Natalia Tarasova, Audrone Telesiene, Thomas Thornton, Maria Cristina Tirado-von der Pahlen, Sandra Torrusio, Stella Tsani, Chiara Varazzani, Maria Virginia Vilariño, Samanta Villegas, Ken Webster, Jianhua Xu, Le Yu, Carol Zavaleta-Cortijo, Xianlai Zeng

Contributing Authors

Adedoyin Adeleke, Rob Alkemade, Michel Bakkenes, Sofia Belardinelli, Arthur Beusen, Suruchi Bhadwal, Bhabananda Biswas, Tanya Brodie Rudolph, Tatenda Dalu, Kenel Delusca, Catia Motta Domingues, Alan Feest, Steven Fletcher, Rose Foster, Dimitris Fragiadakis, Dimistris Fragkiadakis, Jessica Fuller, Sabine Fuss, Sandya Gunasekara, Henry Häkkinen, Julia Hammann, Britta Denise Hardesty, Tomoko Hasegawa, Chenmin He, Olga Illarionova, Mengxing Li, Yingying Lu, Stephen Maycock, Troy McGee, Estee Miltz, Amy Molotoks, Jiayi Ng, Yuki Ochi, Ken Oshiro, Paul Overduin, Daniel Alejandro Pacheco Rojas, Ruben Prutz, Hareenanden Ramasawmy, Lucia Reisch, Savio Rousseau Rozario, Arthur Silva, Helen Spence-Jones, Kazuaki Tsuchiya, Kaj-Ivar van der Wijst, Laszlo Vreedenburgh, Michaela Werning, Leila Zamani, Shaneica Lester

Fellows

Aseel Ibrahim Mohammed Abo-Taleb, Ayodeji Stephen Adekanbi, Tarik Alkharusi, Raphael Villela Almeida, Nadege Amizero, Alison Amoussou, Francis Boafo Asamoah, Zoe Barr, Marianna Baslandze, Sofia Belardinelli, Acasia Broomes, Ruijun Chen, Victoria Del Pilar Chicmana Zapata, Maryam Eqan, Tegan Evans, Laura Fanciulli, Rose Foster, Emmanuelle Freitas, Slobodan Gnjato, Zhuang Han, Qian Jia, Christina Karakizi, Gabriela Kreutzberger, Shaneica Lester, Astride Messaga Maffo, Jan Matuštík, Claude Mbarga Ella, Estee Miltz, Fanni Moilanen, Amy Molotoks, Botho Bahumi Motlhanka, Katie Noble, Iryna Ponedelnik, Jimena Reyeros Sanchez, Martina Rotolo, Michael Ruggeri, Arthur Silva, Eleni Sofik, Helen Spence-Jones, Sénankpon Stephane Marcel Tcheton, Ekaterina Terenteva, Pushp Raj Tiwari, Kelo Uchendu, Soham Vaidya

Review Editors

Ahmed Abdelrehim (Lead Review Editor), Bettina Hedden-Dunkhorst (Lead Review Editor), Kofi Akamani, Ramia Al Bakain, Chandani Appadoo, Amanullah Bahriuloom, William Balée, Suruchi Bhadwal, Miranda Boettcher, Ashok Das, Naa Dodua Dodoo, Oswaldo dos Santos Lucon, Timothy Dube, Paul Dumble, Samia Elfitouri Grimida, Miguel Equihua, Gabriela Fernandez, Elsa Galarza, Nadezhda Gaponenko, Konstantin Gongalsky, Wame Lucretia Hambira, Shan Hu, Arnulf Jaeger-Waldau, Rumiana Jeleva, Injy Johnstone, Joni Jupesta, Lian Pin Koh, Anil Markandya, David McCollum, Nibedita Mukherjee, Adetoun Mustapha, Alick Bulala Muvundika, Leonard Nurse, Eni Oko, Robert Onyeneke, Jiesper Pedersen, Dimitris Poursanidis, Kálmán László Rajkai, Kilaparti Ramakrishna, Abdulkarim Rashed, Ariana Rossen, Mayar Sabet, Georg Schiller, Faizi Shahul Hameed, Diogo Silva, Tannecia Stephenson, Saritha Sudharmma Vishwanathan, Miguel Angel Taboada, Ram Devi Tachamo Shah, Goran Trbic, Oksana Volosko-Demkiv, Fei Wang, Sarah Whitmee, Lucia Helena Xavier, Xinzhu Zheng, Malgorzata Zimniewska

Donors and partners

Producing an assessment of this scale requires many generous contributions. The following Member States and organizations provided funding directly or indirectly to the seventh edition of Global Environment Outlook: The European Union, Governments of Austria, Canada, China, Germany, Italy, Jordan, Norway, Republic of Korea, Netherlands (Kingdom of the), Sweden, and United Kingdom of Great Britain and Northern Ireland, and Asia Indigenous Peoples Pact, Korea Environment Institute, Society of Entrepreneurs and Ecology Foundation, Tongji University. Together with UNEP's Environment Fund and Regular Budget, these contributions allowed the production of GEO-7 and its accompanying Executive Summary, as well as subsequent outreach activities.

Technical Partners

GEO-7 also benefited from the generous contributions of several technical partners, including: Brazilian National Institute for Space Research, Center for Environment and Development for the Arab Region and Europe (CEDARE), Chenjiang Laboratory, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Energy and Resources Institute, the Environmental Pulse Institute, European Commission Joint Research Centre, E3 Modelling, Frederick S. Pardee Institute for International Futures, GRID-Arendal, Institute for Global Environmental Strategies (IGES), International Institute for Applied Systems Analysis (IIASA), International Research Center of Big Data for Sustainable Development Goals, Kyoto University, Laboratory of Energy & Environmental Economics and Policy (LEEEP), Millennium Institute, National Autonomous University of Mexico, PBL Netherlands Environmental Assessment Agency, SENDAS Association Civil, Tyndall Centre for Climate Change Research, and Wageningen University & Research.

GEO-7 Secretariat

Ignacio Sánchez Díaz (Acting Head GEO Unit), Maarten Kappelle (Acting Head GEO Secretariat), Pierre Boileau (Former GEO Head), Hilary Allison, Atina Aliyeva, Sunny Beyene, Matthew Billot, Yunting Duan, Muthoni Kangethe, Caroline Kaimuru, Paula Kawka, Rachel Kosse, Allan Lelei, Ruoxi Li, Caroline Mureithi, Birgita Ohanga, Franklin Odhiambo, Grace Odhiambo, Adele Roccato, Pinya Sarasas, Martha Stokes, Ying Wang, Edoardo Zandri

UNEP Chapter Coordinators

Hilary Allison, Atina Aliyeva, Sunny Beyene, Pierre Boileau, Kilian Christ, Yunting Duan, Melchior Elsler, Valentin Foltescu, Francesco Gaetani, Sophia Groll, Muthoni Kangethe, Caroline Kaimuru, Rachel Kosse, Allan Lelei, James Lomax, Ruoxi Li, Cheikh Tidjane N'dongo, Nada Matta, Llorenç Milà i Canals, Grace Odhiambo, Adele Roccato, Julia Rugo, Ignacio Sánchez Díaz, Romanas Savickas, Sudhir Sharma, Martha Stokes, Feng Wang, Ying Wang, Jinhua Zhang

Peer-review System

Mina Elnagar (CEDARE), Mayar Sabet (CEDARE), Samir Sayed (CEDARE)

GEO-7 Workspace

Stian Grønning (Egde), Andy Harrison (Egde), Christian Knarvik (Crayon), Oddmar Lid (Egde), Miles Macmillan-Lawler (GRID-Arendal), Clever Mafuta (GRID-Arendal), Marco Vinaccia (GRID-Arendal), Pål Andre Ropstad (Crayon), Håvard Setra Sørvik (Crayon), Martin Størkson (Egde)

Editorial Team

Alexandra Horton (Editor), Catherine P. McMullen (Science Editor), Nora Mžavanadze (Glossary Editor), Ekaterina Bessonova (Editor), Lene Søjberg (Project management, Phoenix Aid Design), GRID-Arendal

Maps and Graphics

blossom.it, Fang Chen (CBAS/Chenjiang Laboratory), Jane Muriithi (UNEP), Carlos Reyes (Reyes Work Studio), Audrey Ringler (UNEP), Lei Wang (CBAS), Liang Xiao (Chenjiang Laboratory), Bo Yu (CBAS), Haiying Zhang (CBAS)

Design and Layout

blossom.it**, Virginia Njoroge (UNEP), Reagan Sirengo (UNEP)**

Media and Launch Support

Daniel Cooney, Nicolien Delange, Carlota Estalella Alba, Iman Fasla, Florian Fussstetter, Miranda Grant, Nancy Groves, Anastasia Isyuk, Gabrielle Lipton, Michael Logan, Beverly McDonald, Gregory Mwara, Virginia Njoroge, Michael Onyiego, Moses Osani, Andrew Raven, Keishamaza Rukikaire, Amina Said, Mila Shopova, Reagan Sirengo, Nandita Surendan, Yahan You, Ahmed Yusuf

Special thanks are also extended to

Jordan Harold (Tyndall Centre for Climate Change Research), Andrea Hinwood (UNEP), Florence Kahiro (UNEP), Gladys Karanja (UNEP), Raees Khan (UNEP), Tito Kimathi (UNEP), Jian Liu (UNEP), Irene Lorenzoni (Tyndall Centre for Climate Change Research), Peter Muriithi (UNEP), Kelly West (UNEP).

Table of contents

Acknowledgements ..... **iv**
Foreword ..... **xxix**
Preface by GEO-7 Co-Chairs ..... **xxx**

Part A: Overview and Context **2**
Indigenous Knowledge and Local Knowledge Chapeau A **4**

1 Introduction **9**
1.1 Acting now for a healthy planet: initiating transformative change 10
1.2 A solution-focused approach for sustainability transformations 12
1.3 Realizing transformative change: solution pathways and driving the transformation 15
1.4 Structure of GEO-7 17
Appendix 1.1 Key findings from previous global environmental assessments since 2019 21
Reference 25

2 Historical, current, and projected drivers and pressures of environmental change **29**
Chapter Summary 30
2.1 Introduction 34
2.2 Drivers of Change 34
2.3 Pressures that Affect the Global Environment 56
2.4 Drivers, Pressures, and the Global Environmental Crises: Connecting the Dots 69
References 73

Part B: State and Trends of the Environment **84**
Global Environment Crises Chapeau **86**
Indigenous Knowledge and Local Knowledge Chapeau B **108**

3 Air **113**
Chapter summary 114
3.1 Introduction 117
3.2 State and trends of atmospheric composition 119
3.3 Connections between the atmosphere and biodiversity loss and land degradation 126
3.4 Impacts on human systems 131
3.5 Progress towards the goals of global agreements 141
References 146

4 Land and Soils **159**
Chapter summary 160
4.1 Introduction 163
4.2 Pressures on land and soils 164
4.3 State and trends of the land 167
4.4 Impacts of natural ecosystems on human well-being and human systems 190
4.5 Progress towards internationally agreed environmental goals 192
4.6 Indigenous as well as Local Knowledge in land and soil management 196
References 199

5 Oceans and Coasts 213
Chapter summary 214
5.1 Introduction 217
5.2 State and trends 218
5.3 Human systems 238
5.4 Progress towards internationally agreed goals 242
References 250

6 Freshwater 261
Chapter Summary 262
6.1 Introduction 265
6.2 Pressures on freshwater systems 265
6.3 Water resources 271
6.4 Water quality 275
6.5 Freshwater biodiversity 278
6.6 Impacts of freshwater system changes on human well-being and human systems 283
6.7 Progress towards meeting internationally agreed-upon freshwater goals 291
References 293

7 Implication of Environmental Crises on the Socioeconomic Dimensions of the Sustainable Development Goals 305
Chapter Summary 306
7.1 Introduction 309
7.2 Implications of the global environmental crises on the socioeconomic dimensions of individual SDGs 310
7.3 Common Themes 332
7.4 Conclusion 334
References 337

8 Interlinkages Across Environmental Changes, Scales and Geographic Regions and Subregions 349
Chapter Summary 350
8.1 Introduction 354
8.2 Africa and subregions 356
8.3 Asia and the Pacific and subregions 369
8.4 Eastern Europe and subregions 378
8.5 Latin America and the Caribbean and subregions 391
8.6 Western Europe and Others Group and subregions 407
8.7 Telecoupling 424
References 430

Part C: System Transformations and Outlooks 458
Indigenous Knowledge and Local Knowledge Chapeau C 460

9 Scenario Methodology: Current Trends and Transformation Pathways 465
Chapter Summary 466
9.1 Introduction 468
9.2 Explorative and target-seeking scenarios 468
9.3 Internationally agreed goals used in the scenario analysis 471
9.4 Process of building the narratives for the target-seeking scenarios 473
9.5 Models used to quantify the scenarios 475
9.6 Challenges and limitations of the scenario approach 477
9.7 Presentation of results 478

Appendix 9.1: Models used in global analysis (Chapters 10 and 11) ... 479
References ... 498

10 Continuation of current trends – global implications ... 501
Chapter Summary ... 502
10.1 Introduction ... 505
10.2 Drivers of environmental change under current trends ... 505
10.3 Systems development under current trends ... 507
10.4 Environmental implications under current trends ... 511
10.5 Tipping points and non-linearities ... 521
10.6 Socioeconomic implications under current trends ... 525
10.7 The need to break with current trends ... 533
References ... 534

11 Transformation pathways towards achieving global goals – global implications ... 543
Chapter Summary ... 544
11.1 Introduction ... 547
11.2 Two narratives of transformation ... 548
11.3 Systems transformations ... 552
11.4 Environmental implications ... 561
11.5 Socioeconomic implications ... 570
11.6 Synergies in the transformation ... 579
11.7 Challenges and opportunities ... 584
Appendix 11.1 Narratives quantification and mapping to solution pathways ... 587
References ... 591

Part D: Solution Pathways towards Transformation ... 596
Solution Pathways Chapeau ... 598
Indigenous Knowledge and Local Knowledge Chapeau D ... 604

12 Transforming systems – principles and levers in action ... 611
Chapter Summary ... 612
12.1 Introduction ... 615
12.2 Science-policy rationales for system transformation ... 616
12.3 Scientific perspectives for system transformations ... 618
12.4 Six fundamental principles for system transformations ... 628
12.5 From principles to requirements for intentional action within and beyond existing governance structures ... 636
12.6 Lessons from experiences of intentional transformative action principles acting on levers ... 641
12.7 New policy design for our times ... 650
Appendix 12.1 Definitions of system transformation and transformative change in global environmental assessment reports ... 654
References ... 655

13 Methodology for developing solution pathways towards system transformations ... 663
Chapter Summary ... 664
13.1 Introduction ... 667
13.2 Background ... 668
13.3 Evaluation of theories of development and environmental change and embracing complexity ... 670
13.4 Incorporation of Indigenous Knowledge and Local Knowledge ... 670
13.5 Policy effectiveness, coherence and decision-making ... 672
13.6 Presenting the 7-step methodology ... 673

13.7 Presenting the X-curve 675
13.8 Step-by-step description of the 7 steps 677
13.9 Monitoring and evaluation 684
13.10 Concluding thoughts 685
Appendix 13.1 Guidelines for the evaluation process in the GSL Framework 687
References 689

14 Solution pathways for the transformation of economic and financial systems 695
Chapter Summary 696
14.1 Introduction 700
14.2 Solution Pathways to achieve transformative change 707
14.3 Solution Pathway 1: Internalizing the externalities – correcting pricing 711
14.4 Solution Pathway 2: Making sustainability core in economic governance 717
14.5 Solution Pathway 3: Enhancing financial sector resilience and contribution to sustainability 722
14.6 Solution Pathway 4: Fostering non-pricing approaches towards greening behaviours 732
14.7 Combining solutions to achieve the goals 736
14.8 Synergies 737
Appendix 14.1 Additional detail on examples of payment for ecosystem services implementation in selected countries 739
References 744

15 Solution pathways for transformation towards circularity 751
Chapter Summary 752
15.1 Introduction 756
15.2 Potential solutions to achieve transformative change – immediate policy actions and strategic long-term planning 767
15.3 Solutions case studies 793
15.4 Synergies and trade-off interactions with other systems 795
References 797

16 Energy System Transformation Pathways 809
Chapter Summary 810
16.1 Introduction 813
16.2 Solution pathways for energy system transformation 814
16.3 Combination of solutions to achieve the desired goals 836
16.4 Case studies 840
16.5 Implication of the solution pathways on the other systems 842
16.6 Conclusions 845
References 847

17 Food Systems Transformation Pathways 855
Chapter Summary 856
17.1 Introduction 860
17.2 Solution pathways for food system transformation 868
17.3 Combination of solutions to achieve the desired goals 888
17.4 Implications of the solution pathways on the other systems 894
References 896

18 Solution pathways enabling a sustainable and resilient environment for systems transformation 909
Chapter Summary 910
18.1 Introduction 915

18.2 Solution pathways for a resilient and sustainable environment system 919
18.3 Implication of the solution pathways for a resilient sustainable environment on other systems 947
References 949

19 Implications for Different Economic Development Contexts 963
Chapter Summary 964
19.1 Introduction 967
19.2 Country groupings 967
19.3 Transformation of economic Systems 969
19.4 Transformation towards circularity and sustainable materials management 972
19.5 Transformation of energy systems 975
19.6 Transformation of food systems 981
19.7 Transformation of environmental Systems 988
19.8 Implications for the three economic groups 995
19.9 Summary and conclusions 995
Appendix 19.1 Country Data 997
Appendix 19.2 Renewable energy use by region 1007
Appendix 19.3 Disaggregation of model data by country grouping 1008
References 1009

20 Regional Dimensions of the Transformative Solutions for the Global Environmental Crises 1015
Chapter Summary 1016
20.1 Introduction 1024
20.2 Approach 1024
20.3 The GEO-7 Current Trends Scenario is not a Future Option 1025
20.4 Africa Region 1026
20.5 Asia and the Pacific Region 1041
20.6 Eastern European Region 1055
20.7 Latin America and the Caribbean Region 1069
20.8 Western Europe and Other Groups 1088
20.9 Changing Interrelationships Across Regions 1103
20.10 Conclusion 1107
Appendix 20.1 Eastern Europe Key Trends Across the 2030-2040-2050 Milestones 1108
References 1111

21 Driving the transformations 1123
Chapter Summary 1124
21.1 Introduction 1128
21.2 Co-producing transformations across systems and regions 1128
21.3 Overcoming barriers and breaking lock-ins 1131
21.4 Leveraging motivation 1136
21.5 Accelerating a sustainable transformation 1149
21.6 Concluding thoughts 1153
References 1154

Annex 1 1160
Annex 2 1163
Annex 3 1166
Contributors 1168
Abbreviations and Acronyms 1185
Glossary 1192

List of Figures

2 Historical, current, and projected drivers and pressures of environmental change

Figure 2.1 Transforming key human systems is essential to address the global environmental crises 35
Figure 2.2 Past and future trends in global and regional population size, 1950-2050. 36
Figure 2.3 Stages of the demographic transition and the interplay of birth, deaths and total population. 36
Figure 2.4 Trends in selected key demographic indicators in 2020 (estimated) and 2050 (projected) by region ... 38
Figure 2.5 Projected changes in population density between 2015 and 2030 40
Figure 2.6 Trends of per capita GDP (constant 2015 thousand US$) in the world and UN regions from 1960 to 2023 41
Figure 2.7 Trends of Trade Openness across UNEP Regions (1960-2023) 43
Figure 2.8 Human Development Index (HDI) 44
Figure 2.9 Percentage of population residing in urban areas by income group, 1950-2050 47
Figure 2.10 Percentage of population residing in urban areas by geographic region, 1950-2050 48
Figure 2.11 Urban population size in 2018 and increase in the projected urban population between 2018 and 2050 by countries 49
Figure 2.12 Population and number of cities of the world, by size class of urban settlement 50
Figure 2.13 Population per region living in slums and informal settlements 50
Figure 2.14 Trends in numbers of natural and human-caused shocks. 55
Figure 2.15 Proportions of land-use change gross loss and gross gain from 1992 to 2020 57
Figure 2.16 Global land-use change map (a) at 0.5° scale with change hotspot, and (b) dominant change types at ecoregion scale 58
Figure 2.17 Global cropland changes during 2000-2020 59
Figure 2.18 Forest land and planted forest area (1990-2020) 60
Figure 2.19 Global Forest changes during 2000-2020 at 300m 61
Figure 2.20 Global Forest changes during 2000-2020 at 30m 61
Figure 2.21 Average annual growth rate (AAGR) in the use of key natural resources over two decades (2000 to 2023) 62
Figure 2.22 Sectoral GHG emissions and emissions per capita from 1970 to 2023 64
Figure 2.23 Global CO_2 emissions by sector from 2019 to 2022 65
Figure 2.24 Change in CO_2 emissions by region 66
Figure 2.25 Pesticide use by region 67
Figure 2.26 Number of established alien species (terrestrial and freshwater) in the 18 IPBES subregions and marine ecoregions (marine) 68
Figure 2.27 Pressures leading to climate change. 70
Figure 2.28 Pressures leading to pollution and waste. 70
Figure 2.29 Pressures leading to nature biodiversity loss. 71
Figure 2.30 Pressures leading to land degradation. 72

Global Environmental Crises Chapeau

Figure C.1 Interconnectedness of the global environmental crises of climate change, biodiversity loss, land degradation and desertification, and pollution and waste. 92
Figure C.2 Geographical variation in intensity of overlapping pressures associated with the global environmental crises. 99

Figure C.3 Interconnected worldview of the global environmental crises recognizing that the crises can be considered together as a single crisis – the crisis in human–nature relationships 100

3 Air

Figure 3.1 Sources of air pollutants and greenhouse gases..... 118
Figure 3.2 Total global greenhouse gas emissions and global radiative forcing from anthropogenic and natural sources..... 120
Figure 3.3 Evolution of temperature anomaly with respect to 1850-1900 baseline..... 121
Figure 3.4 Change in population-weighted $PM_{2.5}$ concentrations between 2000 and 2019 123
Figure 3.5 Changes in $PM_{2.5}$ concentrations over China for February 2019 and 2020 (pre- and post-COVID-19 lockdowns) derived from satellite observations 124
Figure 3.6 Potential reinforcing feedback loop of climate change on wildfires 133
Figure 3.7 Montreal Protocol protection of ozone and climate 143

4 Land and Soils

Figure 4.1 Historical trends in global agricultural land use including croplands and pasture forlivestock 163
Figure 4.2 Global land use for food production in 2019..... 165
Figure 4.3 Organic pollutants' source and transport linking to mining operations 169
Figure 4.4 The effect of chemical pollutants on food security and food safety 171
Figure 4.5 Soil erosion estimates predicted through the GloSEM platform (Global Soil Erosion Modelling) 173
Figure 4.6 Global distribution of sand and dust storms..... 177
Figure 4.7 Conceptual framework showing the interdependence of biodiversity, a healthy environment and human health regulated by ecosystem services (protection, maintenance, and restoration)..... 178
Figure 4.8 Permafrost warming trends 180
Figure 4.9 Food insecurity in Sub-Saharan Africa..... 182
Figure 4.10 Mean annual burned area and burned biomass by forest and savanna fires 183
Figure 4.11 A conceptual model showing the drivers affecting wildfire occurrence and severity 184
Figure 4.12 Extreme fire weather trend from 1979-2020 184
Figure 4.13 Burned area and biomass of forests, grasslands, shrublands, and savannas globally 185
Figure 4.14 Expert estimates of global biodiversity loss 186
Figure 4.15 Biodiversity loss: drivers and examples of loss in nature 187
Figure 4.16 The complex nature of soil biodiversity 189
Figure 4.17 Predicted environmental migration worldwide measured in standard deviation changes in migration ... 190
Figure 4.18 Implications of human health affected by agricultural management practices..... 191
Figure 4.19 Status of SDG 15 and the main issues of concern 193
Figure 4.20 A 30-meter resolution global land productivity dynamics dataset from 2013 to 2022 194
Figure 4.21 Mean categorization of each nature-based solution pathway and its scale of estimated potential impact 195
Figure 4.22 Global distribution of publications on Indigenous Knowledge and Local Knowledge in climate change adaptation practices. Each yellow dot is a case study..... 197

5 Oceans and coasts

Figure 5.1 Daily sea surface temperatures averaged over 60˚N to 60˚S from 1980 to 2023 219
Figure 5.2 Projected global mean sea level rise under different warming scenarios 224
Figure 5.3 Direct risks and impacts of marine litter and plastics..... 226
Figure 5.4 Global distribution of particulate organic carbon in seawater, implying marine eutrophication 227
Figure 5.5 Global fishery and aquaculture production from 1960 to 2023 228

Figure 5.6 Examples of biodiversity changes within global marine regions demonstrating the variety of impacts and changes seen in marine ecosystems 230
Figure 5.7 International treaties on marine law and management 243
Figure 5.8 Industrial use of coasts and oceans 244
Figure 5.9 Timeline of regulatory action to cut shipping emissions 245
Figure 5.10 Growth in marine protected area coverage 246

6 Fresh Water

Figure 6.1 Primary sources of global water pollution 265
Figure 6.2 The decreasing trend of global agricultural land and increased use of pesticides from 2000 to 2022 266
Figure 6.3 Percentage of domestic wastewater flows that are safely treated 267
Figure 6.4 Global distribution of mine areas 268
Figure 6.5 Summary of global freshwater withdrawals between 1980 and 2020 calculated as the sum of all country data reporting sectoral water withdrawals 270
Figure 6.6 Global distribution of dams and river barriers 271
Figure 6.7 Estimated change in water storage for the period 1971–2020 272
Figure 6.8 Extinction risk of tetrapods and freshwater species 279
Figure 6.9 Level of water stress by country 284
Figure 6.10 Number of countries with 90% or more of their transboundary basin covered by operational arrangements 285
Figure 6.11 Cholera cases reported by WHO regions from 2000 to 2024 286
Figure 6.12 The trend in the areas equipped for irrigated agriculture from 2000 to 2022 287
Figure 6.13 Decadal trend in the capture fisheries and aquaculture production in inland waters 288
Figure 6.14 Changes in contribution of different products to global virtual water trade (VWT) 289

7 Implication of Environmental Crises on the Socioeconomic Dimensions of the Sustainable Development Goals

Figure 7.1 Gender differential impact of climate change 315
Figure 7.2 Climate effects on the infrastructure sector 321
Figure 7.3 Examples of climate change effects on infrastructure 322
Figure 7.4 Impact of global environmental crises on vulnerable populations (SDG 10). 325
Figure 7.5 Overview of environmental crises' impact on SDG 11 targets. 326
Figure 7.6 Overview of impacts of environmental crises on economic and social dimensions of the SDGs 335

8 Interlinkages across environmental changes, scales and geographic regions and subregions

Figure 8.1 Proportion of degraded land in 2015 and 2019 354
Figure 8.2 Criteria for selecting regional environmental priorities 356
Figure 8.3 The interplay of the global environmental crises as they affect Africa's resource use, ecosystem degradation and climate extremes 357
Figure 8.4 Selected effects of climate change on Africa 359
Figure 8.5 Africa's resources map 361
Figure 8.6 Sea level trends from 1999 to 2024 367
Figure 8.7 Climate-related hazards and number of affected people per sub-region of Africa 367
Figure 8.8 Estimated increase to road maintenance costs due to climate change. 368
Figure 8.9 The inter-play of the global environmental crises as they affect Eurasia's resource use, ecosystem degradation and climate extremes 370
Figure 8.10 Selected interlinkages assessed within the Asia and Pacific region 371
Figure 8.11 Exposure to air pollution 377
Figure 8.12 GDP per capita of the Eastern European countries 379

Figure 8.13 The interplay of the global environmental crises and regional priority issues: effects on Eastern Europe's ecosystem services, health and energy, and biodiversity 380
Figure 8.14 Share of total agricultural area used for organic farming in the Eastern Europe countries in 2023 ... 382
Figure 8.15 Pesticide risk scores for EE countries 384
Figure 8.16 Proportion of protected area, including terrestrial and inland waters areas, with and without Protected Area Management Effectiveness (PAME) assessment in Eastern Europe 389
Figure 8.17 Latin America and the Caribbean Climate Risk Index (CRI) 2022 393
Figure 8.18 Red List Index 2023 for countries in Latin America and the Caribbean 394
Figure 8.19 The interplay of the global environmental crises and regional priority issues: effects on Latin America and the Caribbean's land cover dynamics, freshwater quality and availability, and coastal and marine resources 395
Figure 8.20 Latin America and the Caribbean forests risk assessment 398
Figure 8.21 Share of electricity production from hydropower in Latin America and the Caribbean 401
Figure 8.22 Baseline water stress in LAC 402
Figure 8.23 Average number of yearly tropical storms, hurricanes, and major hurricanes in the Atlantic 403
Figure 8.24 Eutrophication and hypoxic zones in Latin America and the Caribbean and parts of the United States of America 404
Figure 8.25 Ocean Health Index trends (biodiversity component) for Latin America and the Caribbean from 2012 to 2023 405
Figure 8.26 Subregional trends in mangrove forests in Latin America and the Caribbean from 1990 to 2020 406
Figure 8.27 The interplay of the global environmental crises and regional priority issues: effects on Western Europe and Others Group's biodiversity and ecosystems, climate extreme events, and pollution and waste 408
Figure 8.28 Selected indicators of biodiversity status and trends across WEOG, from recent government assessments or government-supported reports 412
Figure 8.29 Pollinator shifts in response to changing climate conditions 413
Figure 8.30 Selected case studies of diseases, disease vectors and significant changes in range or prevalence in response to climate change 415
Figure 8.31 Drivers and impacts of wildfires, which are accentuated by climate change, based on an example from Southern California in 2012–2018 416
Figure 8.32 Global distribution of climatic hazards documented by UNESCO to have climate change impacts on World Heritage Sites by country 417
Figure 8.33 Climate impacts on infrastructure sector in Europe 419
Figure 8.34 Nitrogen cycle and impacts of excess nitrogen on human and natural systems, as well as European Union directives and international agreements aiming to reducethese impacts 420
Figure 8.35 Trends in emissions of major air pollutants from 2005 to 2022 for the European Union 422
Figure 8.36 Mean population-weighted exposure to $PM_{2.5}$ from 2000 to 2020 423
Figure 8.37 Conceptual diagram illustrating four types of telecoupling among the five UN regions 425

Indigenous Knowledge and Local Knowledge Chapeau C

Figure C.1 Diverse knowledge sources for co-creating target seeking scenarios that sustain people and Mother Nature 462

9 Scenario methodology: Current Trends and Transformation Pathways

Figure 9.1 Feedback and complementary aspects between qualitative and quantitative aspects of the GEO-7 scenarios 469
Figure 9.2 Scenarios used in the Outlook Chapters 470
Figure 9.3 Models used, their role in framework and connections to the other models 476

10 Continuation of current trends – global implications

Figure 10.1 Global GDP per capita in PPP terms and total and urban populations 506
Figure 10.2 Primary energy use and power generation including heat 507
Figure 10.3 Final energy use by end user and by technology 508
Figure 10.4 Food demand, total crop production, and mean cereal yield 509
Figure 10.5 Total and per capita global material extraction 510
Figure 10.6 Total GHG emissions and global mean temperature increase 511
Figure 10.7 People exposed to temperature- and precipitation-related climate impacts in 2050 512
Figure 10.8 Global emission trends of air pollutants 513
Figure 10.9 Total population and share of population exposed to $PM_{2.5}$ levels above 25 µg/m^3 514
Figure 10.10 Global land use and land-use changes relative to 2020 516
Figure 10.11 Average soil organic carbon in 2020 and changes in average soil organic carbon 517
Figure 10.12 Loss of Mean Species Abundance (MSA) 517
Figure 10.13 Delivery of nitrogen and phosphorus to surface water 519
Figure 10.14 Area with nitrogen and phosphorus concentrations above threshold levels in surface water and groundwater 519
Figure 10.15 Global water withdrawal and population at risk of water stress 520
Figure 10.16 The risk of climate tipping points is rising rapidly as the world heats up 522
Figure 10.17 Trend in selected socioeconomic SDG targets 526
Figure 10.18 Global mortality by overall category of cause and sex 528
Figure 10.19 Relative shares of GDP per capita compared to high-income economies 530
Figure 10.20 Global aggregate GDP losses from climate impacts 531

11 Transformation pathways towards achieving global goals – global implications

Figure 11.1 Primary energy disaggregated across energy resources for the Behaviour-focused and Technology-focused transformation pathways 552
Figure 11.2 Electricity generation disaggregated across primary energy sources for the Behaviourfocused and Technology-focused transformation pathways 553
Figure 11.3 Consumption of crop-based products and animal-based products per capita per day 555
Figure 11.4 Projections of food crop and livestock production 555
Figure 11.5 Projections of aggregate cereal crop yields. 556
Figure 11.6 Changes, compared to 2020, in land areaby land-use classification in 2030 and 2050 557
Figure 11.7 Material extraction and resource productivity 558
Figure 11.8 Protected areas in the Technology-focused transformation pathway 559
Figure 11.9 Revenues from carbon pricing, used to accelerate R&D and support low-income households 561
Figure 11.10 Global emissions of greenhouse gases, CO_2, CH_4 and N_2O 562
Figure 11.11 Sectoral GHG emissions in the year 2050 under the current trends, and at the respective year of net zero CO_2 for the two transformation pathways, compared to 2020 emissions 563
Figure 11.12 Additional population exposed to climate impacts in 2050 564
Figure 11.13 Global trends of $PM_{2.5}$ and ozone from 2020 to 2050 in the Behaviour-focused and Technology-focused transformation pathways compared to the current trends 565
Figure 11.14 Difference in exposure to ambient air pollution in the Transformation Pathways compared to the Current Trends in 2050 566
Figure 11.15 Prevented premature deaths from air pollution in transformation pathways compared to current trends 566
Figure 11.16 Natural land conversion in the Current Trends, Technology-focused and Behaviour-focused Transformation Pathways from 2020 to 2050 567
Figure 11.17 Carbon stocks in soils and vegetation in 2020, and changes in total soil and vegetation carbon

stocks from 2020 to 2050 568
Figure 11.18 Projections of Mean Species Abundance (MSA), and factors contributing the MSA difference in the transformation pathways with respect to the current trends in 2050 569
Figure 11.19 Delivery of nitrogen and phosphorus to surface water from the different sources for 2020 and 2050 571
Figure 11.20 Area in Mkm^2 in 2050 which has a concentration above the threshold of nitrogen in groundwater, nitrogen in surface water, and phosphorus in surface water 571
Figure 11.21 Change in total blue water withdrawal (2020 to 2050) for irrigation, energy generation (including cooling water), and industrial and municipal use 572
Figure 11.22 Changes in total rainfed cropland extent, and the rainfed cropland that is experiencing a water yield gap of over 30 per cent and 50 per cent 573
Figure 11.23 Trend in selected SDG targets 574
Figure 11.24 Annual avoided deaths of the transformation pathways relative to the current trends 576
Figure 11.25 The number of women in excess of men living in extreme poverty (less than US$ 2.15 per day at PPP in 2017 US$) for the ages 24-55, by UN regions and pathway across time 577

Solution Pathways Chapeau

Figure C.1 Transforming systems: examples of solutions proposed in GEO-7Materials 600

12 Transforming systems – principles and levers in action

Figure 12.1 Three phases of socio-ecological transformations 619
Figure 12.2 A dynamic multi-level perspective on system innovations 622
Figure 12.3 Concept of decoupling 626
Figure 12.4 Transformation principle 1: Target policies at whole systems 628
Figure 12.5 Transformation principle 2: Combine innovation with phase-out 630
Figure 12.6: Transformation principle 3: Align present prospects with future perspectives 631
Figure 12.7: Transformation principle 4: Handle uncertainty – don't avoid it 632
Figure 12.8: Transformation principle 5: Mobilise diverse actors 633
Figure 12.9: Transformation principle 6: Don't ignore the political nature of transformations 634
Figure 12.10: Levers and intersections 636

13 Methodology for developing solution pathways towards system transformations

Figure 13.1 Bridging principles and action: aligning steps for effective system transformation 674
Figure 13.2 Summarized 7 steps fit to the GSL, 6 principles and evaluation 675
Figure 13.3 Curve in relation to Goals-Solutions-Levers Framework 676
Figure 13.4 Categories and levels of actions for changes 680

14 Solution pathways for the transformation of economic and financial systems

Figure 14.1 An outline of the Indigenous Economy. 702
Figure 14.2 Finance and the economy - an extended circular flow diagram of an economy 703
Figure 14.3 Goals, solutions, barriers and levers diagram to show combination of solutions and levers to achieve goals for the economic and financial systems 706
Figure 14.4 Solution Pathways for Transforming Economic and Financial Systems 709
Figure 14.5 Environmentally related tax revenues in OECD countries 713
Figure 14.6 Examples of payment for ecosystem services implementation in selected countries 715
Figure 14.7 Total cost elements 719
Figure 14.8 Global energy investment in clean energy and in fossil fuels 724
Figure 14.9 Financial commitments – 5 Pillars, 1 Vision 725

15 Solution pathways for transformation towards circularity

Figure 15.1 Global material extraction of four main material categories from 1970 to 2024 757
Figure 15.2 Global material flows, waste and emissions 758
Figure 15.3 Connecting natural and man-made assets through regenerative and circular flows 761
Figure 15.4 Resource extraction globally by major categories and per capita by income group 764
Figure 15.5 Summary of the proposed five solution pathways and actions for transformative change towards a circular economy from now until 2050 768
Figure 15.6 Closing the loop: Transforming systems through circularity 769
Figure 15.7 Simplified overview of interactions between levers, solutions and goals of the circular economy solution pathways and actions 792

16 Energy System Transformation Pathways

Figure 16.1 Representative Goals-Solutions-Levers (GSL) Diagram of the Solution Pathways for transformation of Energy Systems 815
Figure 16.3 Illustrative Goals-Solutions- Levers (GSL) diagram to show combination of solutions and levers to achieve goal 1 819
Figure 16.4 Illustrative GSL diagram to describe which combination of solutions and levers will achieve goal 2 ... 820
Figure 16.5 Energy use by sector in IEA countries in 2021 821
Figure 16.2 Solution Pathways for Energy Transformation 822
Figure 16.6 Solutions by sector and their energy demand reduction potential 825
Figure 16.7 Illustrative GSL diagram to describe which combination of solutions and levers will achieve Goal 3 ... 828
Figure 16.8 Illustrative GSL diagram to show combination of solutions and levers to achieve Goal 4 831
Figure 16.9 Core Principles of a responsible CETM value chain 833

17 Food Systems Transformation Pathways

Figure 17.1 Food System Map showing interactions between food consumption and supply, governed by the interactions of the social, political, economic and financial, and environmental systems 860
Figure 17.2 Current (2010) and projected (2050) environmental pressures on five environmental domains by food group 861
Figure 17.3 Interactions between overall goals, solutions and levers in the food system, showing both synergies and trade-offs 867
Figure 17.4 Food System Transformation 865
Figure 17.5 Current sugar-sweetened beverage (SSB) taxes implemented around the world 868

18 Solution pathways enabling a sustainable and resilient environment for systems transformation

Figure 18.1 Current status of control variables for all nine planetary boundaries 916
Figure 18.2 The Goals and Solution Pathways, with key levers identified to enable a sustainable and resilient environment system for nature, finance, waste/circularity, energy and food 920
Figure 18.3 Examples of nature based solutions for climate change adaptation 926
Figure 18.4 Four pillars of Early-Warning-for-All initiative for effective multi-hazard early warning 932
Figure 18.5 Biomass flows are critical to the bioeconomy 937

19 Implications for Different Economic Development Contexts

Figure 19.1 World map with adapted country groupings defined according to the World Bank's economic classification 968
Figure 19.2 GDP per capita (2010 US$) across the three country groups 969

Figure 19.3 Reduction in Domestic Material Consumption (DMC) by 2050 in the behaviour-focused and technology-focused transformation pathways compared to the baseline, absolute values and per capita 973
Figure 19.4 Projected power generation (including heat) across income groups 977
Figure 19.5 Projected final energy demand per capita across income groups under behaviour-focused and technology-focused transformation pathways 978
Figure 19.6 Changes in land cover for intensive land use (cropland and pasture) vs extensive land use (forest and other natural lands) comparing the current trends to the behaviour-focused and technology-focused transformation pathways from 2020 to 2050 986
Figure 19.7 Land availability of cropland, pasture, and forest and other natural lands for the current trends, technology-focused and behavioural-focused scenarios from 2020 to 2050 987
Figure 19.8 Simulated per capita GHG emissions and terrestrial biodiversity in percentage Mean Species Abundance (MSA) in high-income countries under current trends and behavioural-focused and technology-focused transformation pathways 991
Figure 19.9 Simulated per capita GHG emissions and terrestrial biodiversity in percentage Mean Species Abundance (MSA) in middle-income countries under current trends and behavioural-focused and technology-focused transformations 993
Figure 19.10 Simulated per capita GHG emissions and terrestrial biodiversity in percentage Mean Species Abundance (MSA) in low-income countries under current trends and behavioural-focused and technology-focused transformations 994

20 Regional Dimensions of the Transformative Solutions for the Global Environmental Crises

Figure 20.1 Regional groups of UN Member States 1024
Figure 20.2 Increased uptake of renewable energies 1028
Figure 20.3 Simulated SDG attainment at year 2050 with and without investment 1030
Figure 20.4 Shift towards a plant-based diet from 2020 to 2050 1034
Figure 20.5 Total materials demand as a function of transformation pathways 1035
Figure 20.6 Percentage share of primary energy mix in Asia and the Pacific region 1042
Figure 20.7 Population at risk of hunger 1043
Figure 20.8 Population at risk of hunger and projected GDP in Asia and the Pacific under the technology-focused transformation pathway 1044
Figure 20.9 Future of E-waste 1045
Figure 20.10 Nature-based solutions for coastal flood protection and ecosystem services provision 1048
Figure 20.11 Carbon neutrality transformation pathways for China and its implications for energy, environmental and food systems 1053
Figure 20.12 Total material demand scenarios in Eastern Europe 1057
Figure 20.13 Forestry production scenarios in Eastern Europe 1057
Figure 20.14 Renewable energy supply scenarios in Eastern Europe 1058
Figure 20.15 Agricultural demand scenarios in Eastern Europe 1059
Figure 20.16 Agricultural production scenarios in Eastern Europe 1059
Figure 20.17 Net-emission of Kyoto greenhouse gases for scenarios in Eastern Europe 1060
Figure 20.18 Climate damage corrected by loss relative to GDP in Eastern Europe 1061
Figure 20.19 Effects of alternative pathways and reference scenarios 1064
Figure 20.20 Current Trends, Technology-focused and Behaviour-focused Scenario pathway projections for key energy systems indicators 1071
Figure 20.21 Current Trends, Technology-focused and Behaviour-focused Scenario pathway projections for key food systems indicators 1073

Figure 20.22 Projected changes to carbon stocks and biodiversity from 2020 to 2050 1074
Figure 20.23 Projected changes in key socio-economic indicators for LAC and the World from 2020 to 2050 1075
Figure 20.24 Water withdrawal scenarios for LAC and the World 1076
Figure 20.25 Share of total energy use by source in LAC from 2020 to 2050 1077
Figure 20.26 Projected trends in agricultural demand and production in LAC from 2020–2050 1078
Figure 20.27 Implications of the Current Trends, Behaviour-focused and Technology-focused Scenario pathways for key environmental system indicators 1080
Figure 20.28 Primary energy use for the three pathways in Western Europe and Other Groups 1089
Figure 20.29 Agricultural demand for the three pathways in Western Europe and Other Groups 1091
Figure 20.30 Terrestrial biodiversity for the three pathways in Western Europe and Other Groups 1092
Figure 20.31 Air pollution for the three pathways in Western Europe and Other Groups 1093
Figure 20.32 Pumpkins or Parks – Behaviour-focused pathway implications 1097
Figure 20.33. Behavioural-LIFE focused path showing two directions 1099
Figure 20.34 Implications from a positive and a negative approach to a technological pathway 1100
Figure 20.35 Transboundary issues, virtual water, and the food-water-energy nexus 1101
Figure 20.36 Projected dynamics of telecoupling in crop and energy trades under current trends, behavioural- focused transformation and technology-focused transformation 1104

21 Driving the transformations

Figure 21.1 How to accelerate a sustainable transformation 1129
Figure 21.2 Three categories of agents of change actors 1137
Figure 21.3 Six networks of actors in housing decarbonization in Romania: handlers, controllers intelligence gatherers, deliverers, non-governmental, clients 1141
Figure 21.4 The power-interest matrix with examples from the five GEO-7 systems 1142
Figure 21.5 Agents of change in the food system 1144
Figure 21.6 How varying theoretical lenses describe motivations or motivators 1146

List of Boxes

1 Introduction

Box 1.1 Global environmental crises: the urgency of transformative action 18

3 Air

Box 3.1 Various examples of air pollution during the COVID-19 pandemic 124
Box 3.2 Local and Indigenous practices in biomass burning 134
Box 3.3 Air pollution from fires caused by the conflict in Gaza 136

4 Land and Soils

Box 4.1 Key findings on land and soils from assessments published since GEO-6 166

5 Oceans and coasts

Box 5.1 Ecological and social consequences of shifts in Sargassum ecology 231
Box 5.2 Example of how selected international agreements apply to different sectors and activities 243

8 Interlinkages across environmental changes, scales and geographic regions and subregions

Box 8.1 Where has the agriculture in Eastern Europe come from? 381

Box 8.2 Forest fuel exports in Eastern Europe 385
Box 8.3 Geothermal energy in Eastern Europe 386
Box 8.4 The influence of conflicts in the EE region on the environment 391

10 Continuation of current trends – global implications
Box 10.1 Narrative of the SSP2 Middle of the road scenario Source: O'Neill et al. 2017 506
Box 10.2 Impacts of the global environmental crises on crop yields 510
Box 10.3 Land restoration pledges under different conventions 515
Box 10.4 Countries' response to the Kunming-Montreal Global Biodiversity Framework 518
Box 10.5 Climate tipping points may be reached much earlier than generally assumed 523
Box 10.6 Implications of the global environmental crises on the mental health of Indigenous Peoples 529

11 Transformation pathways towards achieving global goals – global implications
Box 11.1 The Behaviour-focused Transformation Narrative 549
Box 11.2 The Technology-focused Transformation Narrative 550

12 Transforming systems – principles and levers in action
Box 12.1 Calls for system transformations to address environmental challenges sanctioned by the international community 617
Box 12.2 Examples of unintended consequences of environmental interventions in complex systems 618
Box 12.3 Examples of scaling in food systems 620
Box 12.4 Examples of marginal improvement in sociotechnical transitions 621
Box 12.5 Examples of radical innovations 622
Box 12.6 Examples of generalization and diffusion in socio-technical transitions 623
Box 12.7 Examples of phase-out 623

14 Solution pathways for the transformation of economic and financial systems
Box 14.1 Nature-based solution (+ adaptation): Great Green Wall (GGW) Initiatives in the Sahara, Africa 725

15 Solution pathways for transformation towards circularity
Box 15.1 Waste management and the zero-waste cities programme in China 793
Box 15.2 Circular practices used by Indigenous Peoples and traditional or local communities 794

16 Energy System Transformation Pathways
Box 16.1 Climate adaptation for energy systems 840

18 Solution pathways enabling a sustainable and resilient environment for systems transformation
Box 18.1 Biodiversity conservation and enhanced ecosystem services 921
Box 18.2 Features of nature-based solutions 927
Box 18.3 Locally led adaptation actions 931
Box 18.4 Drivers and principles to ensure a future sustainable bioeconomy 935
Box 18.5 Bioenergy and Carbon Capture and Storage: concerns for the environment 939
Box 18.6 Adaptive and transformative governance 943

19 Implications for Different Economic Development Contexts
Box 19.1 Case study: France's development cooperation profile 970
Box 19.2 Case study: Sustainable Banking and Finance Network 971
Box 19.3 Case study: Circular Economy Approaches for the Electronics Sector in Nigeria 975
Box 19.4 Modelling food and land system in Australia 982
Box 19.5 European Green Deal initiatives for environmentally responsible sourcing 990
Box 19.6 Social media voices influence on air quality improvement in China 992

Box 19.7 Human-wildlife coexistence, Chitwan National Park, Nepal 994

20 Regional Dimensions of the Transformative Solutions for the Global Environmental Crises

Box 20.1 The green hydrogen economy in regional development. The case of Namibia 1030
Box 20.2 A carbon footprint integrating all ecosystem elements: application to Indigenous Knowledge systems of pastoral livestock production in the Sahel 1032
Box 20.3 Climate change adaptation needs 1048
Box 20.4 Transformation pathways for China 1053
Box 20.5 Indigenous Knowledge, technology, behaviour and governance: Sustainable whaling 1095
Box 20.6 The Inflation Reduction Act as an example of financial-system change 1097

21 Driving the transformations

Box 21.1 Adaptation can strengthen integration and acceleration across systems 1130
Box 21.2 Aspects of desired futures according to Indigenous Peoples. 1131
Box 21.3 Data, barriers and lock-ins 1135
Box 21.4 Definitions of health 1145
Box 21.5 Costa Rica's government makes bold investments in public health, education, and environmental protection 1145
Box 21.6 The multiple benefits of nature 1146
Box 21.7 Nature-positive economy and the Aymara people 1147
Box 21.8 Participatory and inclusive governance reforms that can support a multidimensional transformation. 1151

List of Tables

1 Introduction

Table A.1 Key findings and similarities from previous relevant reports. Reports dealing with the assessment of the global environment or its various aspects published since launching the 6th edition of the Global Environment Outlook (GEO-6, 2019a). 22

2. Historical, current, and projected drivers and pressures of environmental change

Table 2.1 Investment needs: Summary 54

Global Environment Crises Chapeau

Table C.1 Potential for interactions between climate change and pollution 92
Table C.2 Potential for interactions between climate change and biodiversity 94
Table C.3 Potential for interactions between climate change and land degradation 95
Table C.4 Potential for interactions between pollution and biodiversity loss 96
Table C.5 Potential for interactions between pollution and land degradation 97
Table C.6 Potential for interactions between biodiversity and land degradation 98
Table 3.1 WHO 2005 and 2021 Air Quality Guidelines 144

7 Implication of Environmental Crises on the Socioeconomic Dimensions of the Sustainable Development Goals

Table 7.1 The impact of environmental crises on food security 311
Table 7.2 The impacts of environmental crises on SDG 3. 313
Table 7.3 The impacts of environmental crises on various energy sources. 318
Table 7.4 Impacts of global environmental crises on infrastructure and industries. 324
Table 7.5 SDG funding gap compared to global military spending, economic losses from the climate crisis,

and benefits to the global economy from ecosystems 331

8 Interlinkages across environmental changes, scales and geographic regions and subregions

Table 8.1 The three environmental priorities identified for each region in GEO-7 355
Table 8.2 Anticipated climate change-induced GDP losses by 2030 for temperature increases between 1°C and 4°C 369
Table 8.3 Trade among the five United Nations regions (2017–2021) (unit: billion US$) 426
Table 8.4 Foreign direct investment in the five United Nations regions during 2017–2021 (unit: billion US$) 426
Table 8.5 Human migration among the five United Nations regions in 2021 (unit: million persons) 426
Table 8.6 International tourism among the five United Nations regions from 2017 to 2021 (unit: million persons) 426
Table 8.7 Implications of four selected telecoupling types on natural and human systems 428

9 Scenario methodology: Current Trends and Transformation Pathways

Table 9.1 Goals to be achieved in the two transformation pathways 472

11 Transformation pathways towards achieving global goals – global implications

Table 11.1 Decomposition of GDP impact on key factors per Transformation pathway compared to the current trends 561
Table 11.2 Required system transformations between 2020 and 2050 to meet the goals set out in Sections 9.3 578
Table 11.3 Summary of possible synergies (green) and risks or trade-offs (red) that need to be negotiated to meet all the goals described in Section 9.3 and Table 9.1, repeated in the "diagonal" 580

12 Transforming systems – principles and levers in action

Table 12.1 Juxtaposing three perspectives on system transformation 627

14 Solution pathways for the transformation of economic and financial systems

Table 14.1 Synergies and trade off which other systems 737

16 Energy System Transformation Pathways

Table 16.1 Synergies and trade-offs with other systems 844

17 Food Systems Transformation Pathways

Table 17.1 Overall goals of the food system transformation 863

18 Solution pathways enabling a sustainable and resilient environment for systems transformation

Table 18.1 Goals to enable sustainable and resilient environment system for nature, circularity, energy and food 917
Table 18.2 Projected biomass feedstock requirements 940

19 Implications for Different Economic Development Contexts

Table 19.1 Summary of opportunities for different economic groups by system 995

20 Regional Dimensions of the Transformative Solutions for the Global Environmental Crises

Table 20.1 Regional environmental priorities identified in Chapter 8 1025
Table 20.2 Drivers and actions for each transformation pathway 1037
Table 20.3 Annual production, demand, and extraction for different materials 1046
Table 20.4 A Recycling rate for different materials 1047
Table 20.5 Actions for Asia and the Pacific Countries 1055

Table 20.6 Levers and policy recommendations for Eastern Europe 1067
Table 20.7 Land cover dynamics related results, response options and regional considerations 1082
Table 20.8 Freshwater Quality and Availability related results, response options and regional considerations.. 1084
Table 20.9 Coastal and Marine Resources-related results, response options and regional considerations..... 1086
Table 20.10 Main actions for each system 1102

21 Driving the transformations

Table 21.1 Actor categories and their roles 1125
Table 21.2 Illustrative examples of different types of barriers across the five key systems 1132
Table 21.3 Categories of actors, their definitions and roles 1138
Table 21.4 Explaining how agents of change are motivated to action through the various theoretical 'lenses described in Figure 21.6 1143
Table 21.5 Using motivators to align the interests of governments, the public, and the private sector to drive transformations 1149

As the Global Environment Outlook 7 reminds us: now is the time for courage and creativity

António Guterres

Secretary-General of the United Nations

Foreword

Life is all about choices. Some are of little consequence. Some are life-altering. Humanity now faces perhaps the biggest choice it will ever make: continue down the road to a future devastated by climate change, dwindling nature, degraded land, and polluted air, land and water, or change direction to secure a healthy planet, healthy people and prosperity for all.

The Global Environment Outlook, Seventh Edition: A Future We Choose, the product of 287 multi-disciplinary scientists from 82 countries, tells us what we stand to gain by choosing the latter path – a path that tackles the interconnected crises of climate change, biodiversity loss and land degradation, and pollution and waste as one.

By investing in a global transformation of systems from energy to food, we can avoid nine million premature deaths by 2050 – many of them from decreased air pollution. We can lift 200 million people out of undernourishment and 150 million people out of extreme poverty by 2050. We can give 300 million more people access to safely managed water sources by 2050. And so much more. Yes, this will involve up-front costs, but there is long-term return on investment: the global macroeconomic benefits of this path appear in 2050, grow to US$20 trillion per year by 2070 and boom thereafter.

If we choose to stay on the current path – powering our economies with fossil fuels, extracting virgin resources, destroying nature, polluting the environment – the damages would stack up. Climate change would cut four per cent off annual global GDP by 2050, claim many lives and increase forced migration. Amazon forest dieback and ice-sheet collapse would become more likely. Hundreds of millions more hectares of natural lands would be lost. Vital species such as pollinators would be decimated. Food availability would fall. Urban air pollution would continue, with fine particulate matter alone causing around four million premature deaths annually. Solid waste, currently over two billion tonnes per year, would almost double, turning our world into a toxic garbage dump.

Sometimes a choice is no real choice at all.

To take the first path, we need interlinked, whole-of-society and whole-of-government approaches to reshape economy and finance, materials and waste, energy, food and, of course, the environment. This new journey begins with moving beyond GDP as a measure of economic well-being – instead using inclusive indicators that also track the health of human and natural capital, so that economic and business decisions are made from a position of full knowledge. It continues with a transition to circular economy models that reduce material footprints; a rapid decarbonization of the energy system; a shift towards sustainable diets, reduced waste and improved agricultural practices; and expanding protected areas and restoring degraded ecosystems – all backed by behavioural, social and cultural shifts that include respect for Indigenous Knowledge and Local Knowledge.

Change is always difficult, more so when it is on such a massive scale. But change we must. There are two futures ahead of humanity. Let us choose the right one.

Inger Andersen
Executive Director
United Nations Environment Programme

Preface by GEO-7 Co-Chairs

A Planet in Peril, A Call for Action

The fifth session of the United Nations Environment Assembly (UNEA-5) adopted, in March 2022, Resolution 5/3 on the Future of Global Environment Outlook (GEO). In this resolution, Member States established the objectives, core function and next steps in developing the GEO process and the seventh edition of the GEO - UNEP's flagship report. This was informed by two preceding years of analysis and consultations undertaken by UNEP under the auspices of the intergovernmental Steering Committee on the Future of the GEO. The latter was established pursuant to Resolution 4/23 adopted at the fourth session of UNEA.

The seventh edition of the Global Environment Outlook (GEO-7) continues UNEP's tradition of delivering comprehensive, science-based information and knowledge, critical to guiding policy and action towards environmental sustainability. This is done with the aim of addressing the multiple, complex environmental challenges humanity faces today. It provides a set of integrated and actionable solution pathways which are tailored to the needs of Member States and other stakeholders to support the necessary global transition to a sustainable, equitable, and resilient future for all.

A scientific assessment of the global environment demands collaboration across a vast array of scientific disciplines. Over 280 scientists– representing every geographic region and balanced in terms of gender distribution – contributed their specific expertise to writing this landmark assessment: the Global Environment Outlook (GEO-7). Hundreds more reviewed the chapters of the report and provided constructive peer-review comments.

This seventh edition of GEO examines two overarching themes:

1. The historic, current and projected status of the interconnected global environmental crises of climate change, biodiversity loss, land degradation and desertification, and pollution and waste, what causes them, and what are their impacts on human well-being.

2. Potential Solution Pathways necessary to address these crises successfully through the simultaneous and systemic transformation of the interconnected human systems of (i) economics/finance, (ii) materials/waste, (iii) energy and (iv) food, as well as through (v) improved environmental management.

This GEO-7 main report, released at the Seventh UN Environment Assembly (UNEA-7) in December 2025, situates environmental challenges within broader socio-economic and political landscapes, while translating complex systemic data, information and knowledge into clear, actionable insights needed by national and subnational governments, Multilateral Environmental Agreements (MEAs), and other stakeholders, to tackle adequately the afore-mentioned global environmental crises. The report's findings are poised to shape the agenda and deliberations of Member States and Stakeholders at UNEA-7.

At the country level, GEO-7's conclusions will guide the integration of environmental sustainability into national development agendas, strategies and policies, ensuring alignment with the universally agreed Sustainable Development Goals (SDGs) and related Internationally Agreed Environmental Goals.

Building on prior assessments by IPCC, IPBES, and earlier GEO reports, GEO-7 casts the widest net yet, encompassing the interconnected global environmental crises. It draws on diverse knowledge systems—from natural, social, cultural and behavioral sciences to scenario modelling, economics, and Indigenous Knowledge and Local Knowledge—to present a truly holistic view of the world's environment.

Decades of global assessments—both led by the UN and independent ones—have painted a stark picture:

the degradation of the global environment is continuous and accelerating every time. These assessment reports reveal how human systems, energy, food, materials/waste and prevailing economic models, drive cumulative environmental harm, and in turn are adversely affected by environmental degradation. While international treaties, like the Multilateral Environmental Agreements, often state what must be achieved by 2050, they seldom recommend how we can get there—leaving critical gaps in policy, governance, technology, and behavioral pathways across varied contexts.

UNEP's previous global environmental assessment, the GEO-6 report launched in 2019, as well as numerous other major reports confirmed that the world missed the Aichi Biodiversity Targets and is off track to meet the SDGs and the Paris Agreement's climate goals. Without swift, transformative action, humanity risks a 3 °C rise in global temperatures, rampant pollution, and catastrophic biodiversity loss. Governments have recognized these threats and have called for immediate, sustained responses, but the pace and scale of the interventions needed has been inadequate to date.

In direct response, GEO-7 focuses on solutions to complement the diagnosis. It equips policymakers with practical guidance on designing, implementing, and governing transformative policies, addressing timing socio-economic co-benefits and trade-offs, and unintended consequences. Acknowledging political and economic constraints, financing shortfalls, misaligned policies, vested interests, educational gaps, and fragmented governance, the GEO-7 assessment report provides concrete solution pathways to overcome these barriers.

The report opens with a rigorous review of the status of Earth's air, land, oceans, and freshwater natural systems—alongside the crises of climate change, biodiversity loss and land degradation, and pollution and waste. This analysis integrates robust scientific evidence with Indigenous Knowledge and Local Knowledge. For instance, Arctic communities' sea-ice monitoring deepens our understanding of climate anomalies, while Indigenous Peoples' fire-stewardship practices demonstrate nature-based approaches to wildfire mitigation and biodiversity conservation.

The GEO-7 report introduces two target-seeking scenarios that align with global goals through transformative solutions across all human systems. It then presents a new transformation framework based on six core principles and operationalized through seven actionable steps—designed to generate multiple solution pathways for each system.

The report explores how these systems' transformations can be addressed simultaneously, accelerated and effectively governed to meet the targets of internationally agreed environmental goals, while realizing socio-economic benefits. It continues by weaving together scenario insights and policy responses, clarifying the roles of governments, communities, the private sector, and civil society in driving systemic change.

Finally, the report outlines how transformation strategies can be adapted to suit regional contexts and the specific needs of various socio-economic country groupings, While many actions are similar from one country to another, and from one region to another, GEO-7 identifies some specific regional challenges and opportunities for action.

Looking Ahead

- Governments can pilot GEO-7's transformational framework in subnational contexts—cities, provinces, or watershed basins—to test its seven actionable steps in real-world settings.

- National ministries and other government entities could align their climate strategies, land use planning, and biodiversity action plans with the GEO's target-seeking scenarios, accelerating their 2030 and 2050 national commitments and targets.

- Academia and civil society should collaborate on monitoring progress towards targets, applying Indigenous Knowledge and Local Knowledge to refine policy interventions.

- Private-sector stakeholders should collaborate in resource-mobilization partnerships that channel finance towards nature-based

- solutions, green infrastructure, and circulareconomy initiatives.

This preface sets the stage for an evidence-driven, action-oriented journey towards a healthier, safer, and more equitable planet for all. The pages that follow will guide the reader through both the sobering challenges and the transformative opportunities that lie ahead.

The GEO-7 emphasizes not just what needs to be done, but how actions that address the issues and challenges can be implemented in a socially and economically acceptable manner. If we are to avoid a catastrophe for humanity, actions need to be taken now – the next five years are critical.

Grounded in our shared responsibility for sustainable development, we urge all Member States and stakeholders to act decisively. Time is running out. This report shows that the cost of action is far less than the cost of inaction – the health of the planet deserves no less. To neglect this moment is to betray the promise we owe to tomorrow's citizens.

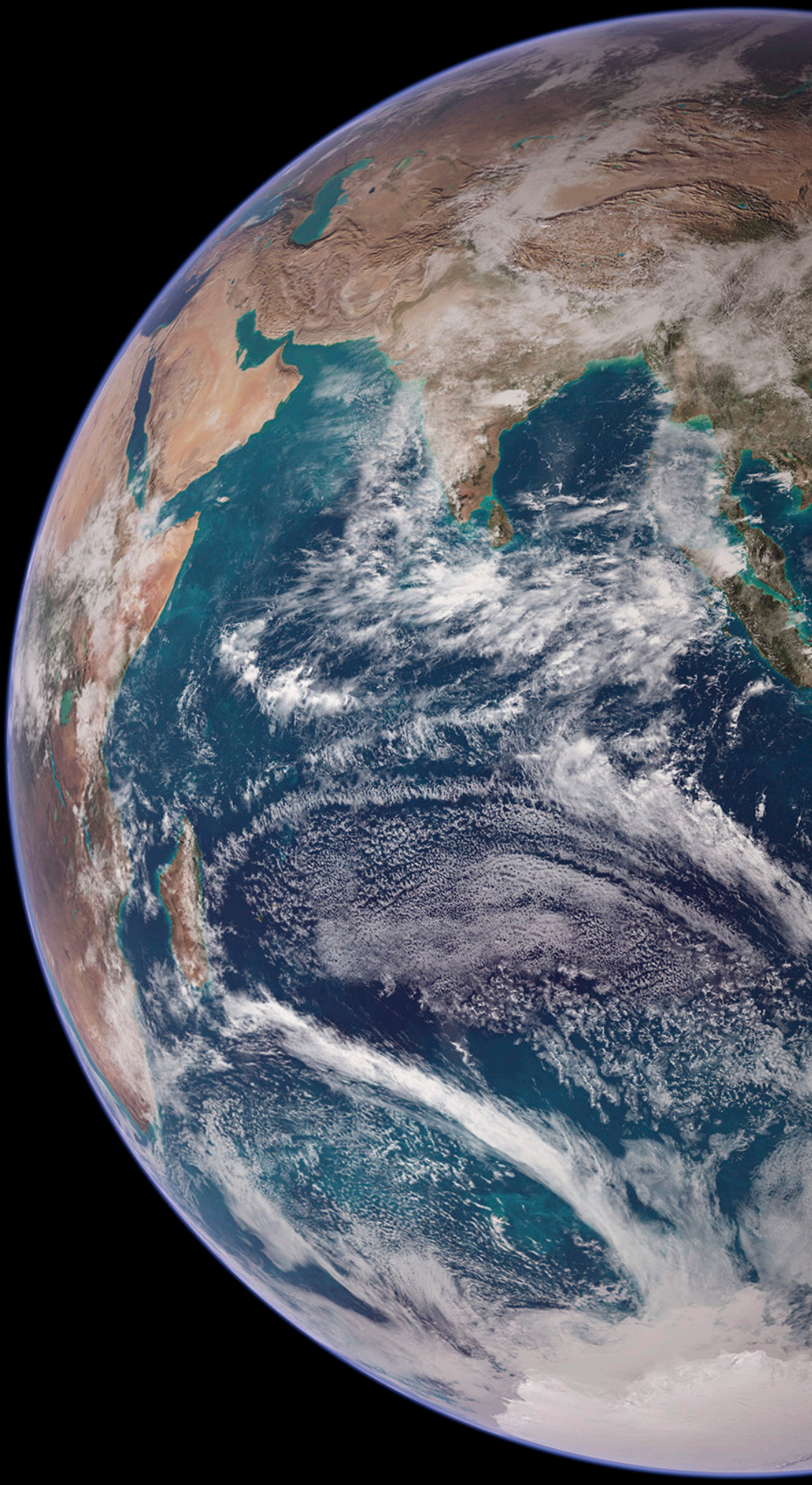
Edgar E. Gutiérrez-Espeleta

Nyovani Madise

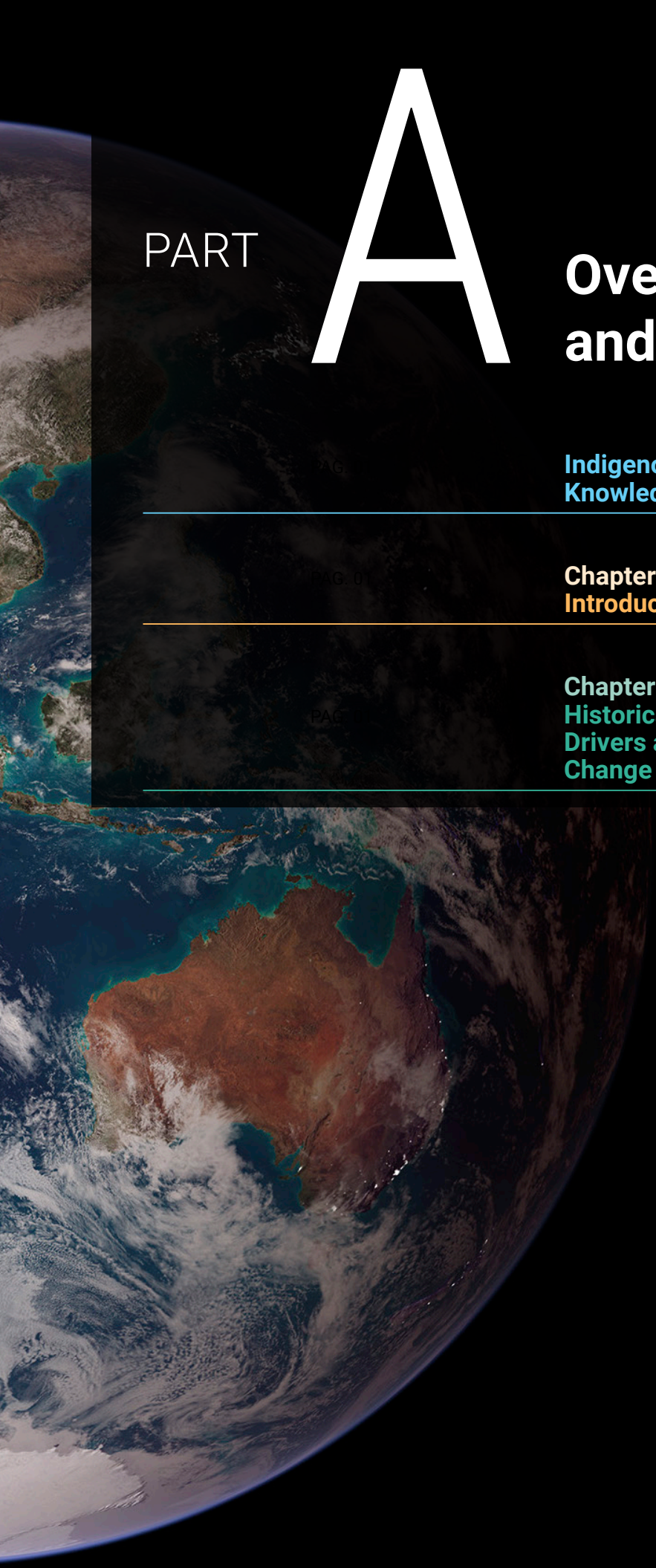
Ying Wang

Robert Watson

Credit: GreensandBlues/Envato



Credit: NASA Visible Earth



PART A

Overview and Context

Indigenous Knowledge and Local Knowledge Chapeau A

Chapter 1
Introduction

Chapter 2
Historical, Current, and Projected Drivers and Pressures of Environmental Change

Coordinating Lead Authors: Sarah-Lan Mathez-Steifel (Centre for Development and Environment, University of Bern and Wyss Academy for Nature, University of Bern); Aibek Samakov (University of Central Asia);

Lead Authors: Eduardo Erazo Acosta (Universidad de Nariño); Janelle Baker (Athabasca University); Isa Elegbede (Lagos State University,); Jyotsna Krishnakumar (Keystone Foundation); Jinlong Liu (Renmin University of China); Yolanda López -Maldonado (Indigenous Science); William Armand Mala (University of Yaoundé); Juliana Merçon (Universidad Veracruzana); Didacus Namanya (Ministry of Health); Valerie Nelson (National Resource Institute, University of Greenwich); Maria Cristina Tirado-von der Pahlen (SHE Foundation, University of California); Kamal Kumar Rai (ITT-Nepal, Indigenous Knowledge and Peoples Networks, Society for Wetland Biodiversity Conservation, NIFB); Kamaljit K Sangha (Charles Darwin University); Thomas Thornton (University of Alaska); Carol Zavaleta-Cortijo (Universidad Peruana Cayetano Heredia and Indigenous Peoples Observatory Network (IPON))
Contributing Lead Authors: Claudio Belis (European Commission, Joint Research Centre), Indu Murthy (CSTEP; Center for Study of Science, Technology and Policy), Mulako Kabisa (University of the Witwatersrand - Global Change Institute), Stephan Harrison (University of Exeter)

Fellows: Senankpon Stephane Marcel Tcheton (University of Witwatersrand); Victoria Del Pilar Chicmana Zapata (Universidad Peruana Cayetano Heredia)

The Indigenous Knowledge and Local Knowledge (IK & LK) Authors worked on all of the five IK & LK chapeaux in the GEO-7 report.

Indigenous Knowledge and Local Knowledge Chapeau A

Indigenous Peoples perspectives on environmental change and its causes can inform understanding of the global environmental crises of climate change, biodiversity loss, land degradation and desertification, and pollution and waste. Indigenous scholars, leaders and elders, as well as non-Indigenous researchers have identified capitalism, globalization, imperialism, colonialism and patriarchy as underlying causes of these global environmental crises (Whyte 2017; McGregor, Whitaker and Sritharan 2020; Smith 2021). Imposed natural resource extraction and conservation have become synonymous with the displacement of [Indigenous] peoples and animals, the denial of access to or destruction of lands and natural resources, and the elimination of traditional livelihoods and ways of life (United Nations 2021). Extractive and industrial activities, such as oil and gas extraction, unsustainable agriculture, uncontrolled lumbering, unrestricted overfishing, mining, and dams have resulted in severe environmental injustices with Indigenous Peoples disproportionately affected (Owen et al. 2023). False solutions to environmental challenges include conservation and climate mitigation policies that redesignate Indigenous lands, again disproportionately affecting Indigenous Peoples (A/HRC/54/31; United Nations 2021; IK & LK Dialogues 2025). Enforcing respect for Indigenous Peoples human rights, ensuring representation in decision-making, and promoting shifts in values towards care for all life are essential principles for sustainability and for future generations (United Nations 2021; IPBES 2022).

There is a rich diversity of Indigenous languages, values, traditions, practices and worldviews while they share affinities with lands, peoples, and cultures, however, Indigenous Peoples also share experiences and legacies of colonialism (IK & LK Dialogues 2025). These ways of knowing and doing build on reciprocal connections with the land and nature and with divine presence (Philippine Indigenous Peoples and Biodiversity Coalition 2024. Indigenous Peoples biocultural knowledge is generated relationally, shaped by values and through practice (IK & LK Dialogues 2025).

Indigenous Peoples ways of knowing and being persist and have significant potential for sustainability transformations (Ford et al. 2020; Arora and Stirling 2023; IPBES 2024). Indigenous Peoples do not conceive of nature as external to humans, nor as comprising mechanistic systems, or as a passive entity available primarily for exploitation and management (Polheim et al. 2024). Indigenous sciences do not position

Credit: NaturesCharm/Envato

humans as exceptional or as having authority, superiority, or ownership over other beings. Instead, many Indigenous sciences position humans as part of (entangled with) the world. (Ahenakew 2016; Stein et al. 2024). Two-Eyed Seeing or Indigenous-led Etuaptmumk in Mi'kmaw, is a methodology that effectively draws upon and gives value to both Indigenous Knowledge and positivist science (Bartlett, Marshall, and Marshall, 2012). Increased support for Indigenous-led research based on the application of Two-Eyed Seeing is needed (Smith 2017).

Centring Indigenous biocultural perspectives, governance, and science that value all life represents an important avenue for future sustainability (Gallegos 2015; Merçon et al. 2019; Burke et al. 2023; Datta et al. 2025). Indigenous Peoples ways of knowing and being assign spiritual and sacred value to all life. Practices such as eating or fishing are constituted relationally, often with species treated as kin and guided by reciprocity (Salmon 2000; Topa and Narvaez 2022). Respect for life cycles and their continuity is a sacred example of the Agdal systems of the Amazigh of North Africa (IK & LK Dialogues 2025). Lands and water are living places, perceived as inhabited by ancestral humans and non-humans who demonstrate how to live well together on a shared, finite planet (Bakawa Country et al. 2016; Stewart-Harawira 2020; McGregor, Whitaker and Sritharan 2020; Luque-Lora 2023; Chakraborty 2025). Multiple Indigenous concepts for convivial and sacred co-dwelling exist, as set out by Andean *Sumak Kawsay* and Southern African *Ubuntu* (IPBES 2022; IK & LK Dialogues 2025).

References

Ahenakew, C. (2016). Grafting Indigenous Ways of Knowing onto Non-Indigenous Ways of Being: The (Underestimated) Challenges of a Decolonial Imagination. International Review of Qualitative Research 9(3), 323-340. https://doi.org/10.1525/irqr.2016.9.3.323

Arora, S. and Stirling, A. (2023). Colonial modernity and sustainability transitions: A conceptualization in six dimensions. Environmental Innovation and Societal Transitions 48(100733). https://doi.org/10.1016/j.eist.2023.100733

Bartlett, C., Marshall, M. and Marshall, A. (2012). Two-Eyed Seeing and other lessons learned within a co-learning journey of bringing together indigenous and mainstream knowledges and ways of knowing. Journal of Environmental Studies and Sciences 2(4), 331-340. https://doi.org/10.1007/s13412-012-0086-8

Burke, L., Díaz-Reviriego, I., Lam, D.P.M. and Hanspach, J. (2023). Indigenous and local knowledge in biocultural approaches to sustainability: a review of the literature in Spanish. Ecosystems and People 19(1). https://doi.org/10.1080/26395916.2022.2157490

Bakawa Country, Wright, S., Suchet-Pearson, S., Lloyd, K., Burarrwanga, L., Ganambarr, R. et al. (2016). Co-becoming Bawaka:Towards a relational understanding of place/space. Progress in Human Geography 40(4), 455-475. https://doi.org/10.1177/0309132515589437

Chakraborty, S. (2025). Sacred Landscapes: The Intersection of Indigenous Women's Spirituality and Environmental Protection in Canada. In Gender, Environment, and Human Rights: An Intersectional Exploration (pp. 117-128). IGI Global.

Datta, R., Hurlbert, M., Kibria, A., Singha, R., Kairy, B., & Chatterjee, S. (2025). Rethinking and relearning disaster adaptations from and within Indigenous land-based perspectives. London: Routledge. https://doi.org/10.4324/9781003536345

Ford, J.D., King, N., Galappaththi, E.K., Pearce, T., McDowell, G. and Harper, S.L. (2020). The Resilience of Indigenous Peoples to Environmental Change. One Earth 2(6), 532-543. https://doi.org/10.1016/j.oneear.2020.05.014

Gallegos, L. (2015). Sketch of a Decolonial Environmentalism : Challenging the Colonial Conception of Nature through the Biocultural Perspective. Inter-American Journal of Philosophy 6(1), 32. http://www.csstoday.com/Item/10383.aspx

IK & LK Dialogues (2025). Indigenous Knowledge and Local Knowledge Dialogues. Global Environment Outlook 7. Mexico City: Indigenous Knowledge and Local Knowledge Dialogues - Copit Arxives (2025)

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2022). Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://www.ipbes.net/the-values-assessment

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2024). Summary for Policymakers of the Thematic Assessment Report on the Interlinkages among Biodiversity, Water, Food and Health of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. McElwee, P.D., Harrison, P. A., van Huysen, T. L., Alonso Roldán, V., Barrios, E., Dasgupta, P., DeClerck, F., Harmáčková, Z. V., Hayman, D. T. S., Herrero, M., Kumar, R., Ley, D., Mangalagiu, D., McFarlane, R. A., Paukert, C., Pengue, W. A., Prist, P. R., Ricketts, T. H., Rounsevell, M. D. A., Saito, O., Selomane, O., Seppelt, R., Singh, P. K., Sitas, N., Smith, P., Vause, J., Molua, E. L., Zambrana-Torrelio, C., and Obura, D. (ed.). http://dx.doi.org/10.5281/zenodo.13850290

Luque-Lora, R. (2023). The Trouble with Relational Values. Environmental Values 32(4), 411-431. https://doi.org/10.3197/096327122X16611552268681

McGregor, D., Whitaker, S. and Sritharan, M. (2020). Indigenous environmental justice and sustainability. Current Opinion in Environmental Sustainability 43, 35-40. https://doi.org/10.1016/j.cosust.2020.01.007

Merçon, J., Vetter, S., Tengö, M., Cocks, M., Balvanera, P., Rosell, J.A. et al. (2019). From local landscapes to international policy: contributions of the biocultural paradigm to global sustainability. Global Sustainability 2, e7. https://doi.org/10.1017/sus.2019.4

Owen, J.R., Kemp, D., Lechner, A.M. et al. Energy transition minerals and their intersection with land-connected peoples. Nat Sustain 6, 203–211 (2023). https://doi.org/10.1038/s41893-022-00994-6

Polheim, A., Manuel-Navarrete, D., Goebel, J. and Loos, J. (2024). Embodying relationality through immersive sustainability solutions with Indigenous communities in the Ecuadorian Amazon. Sustainability Science 19(4), 1445-1457. https://doi.org/10.1007/s11625-024-01523-4

Salmon, E. (2000). Kincentric Ecology: Indigenous Perceptions of the Human-Nature Relationship. Ecological Applications 10(5). http://dx.doi.org/10.2307/2641288

Smith, L.T. (2021). Decolonizing Methodologies. Research and Indigenous Peoples. Third edn. London: Bloomsbury Publishing. https://www.bloomsbury.com/us/decolonizing-methodologies-9781786998125/

Stein, S., Ahenakew, C., Valley, W., Sherpa, P.Y., Crowson, E., Robin, T. et al. (2024). Toward more ethical engagements between Western and Indigenous sciences. FACETS(9), 1-14. https://doi.org/10.1139/facets-2023-0071

Stewart-Harawira, M. W. (2020). Troubled waters: Maori values and ethics for freshwater management and New Zealand's fresh water crisis. Wiley Interdisciplinary Reviews: Water, 7(5), e1464. https://doi.org/10.1002/wat2.1464

The Philippines Indigenous Peoples Biodiversity Strategy and Action Plan (IPBSAP) (2024). Report of the Philippine Indigenous Peoples and Biodiversity Coalition'. Available at https://transformativepathways.net/philippine-indigenous-peoples-biodiversity-strategy-and-action-plan/

The Philippine Indigenous Peoples Biodiversity Strategy and Action Plan - Transformative Pathways

Topa, W. and Narvaez, D. (2022). Restoring the kinship worldview: Indigenous voices introduce 28 precepts for rebalancing life on planet earth. Berkeley: North Atlantic Books

United Nations (2021). State of the world's Indigenous Peoples. Right to Lands, Territories and Resources. New York. https://digitallibrary.un.org/record/3924462/files/state-of-worlds-indigenous-peoples-vol-v-final.pdf

United Nations, Human Rights Council (2023). Report of the Special Rapporteur on the rights of Indigenous Peoples, José Francisco Calí Tzay. Green financing – a just transition to protect the rights of Indigenous Peoples 15 September. A/HRC/54/31. https://docs.un.org/en/A/HRC/54/31

Whyte, K. (2017). Indigenous Climate Change Studies: Indigenizing Futures, Decolonizing the Anthropocene. English Language Notes 55(1), 153–162. https://doi.org/10.1215/00138282-55.1-2.153

01 Introduction

Coordinating Lead Authors: Leila Dagher (Lebanese American University), Jan Plesnik (Nature Conservancy Agency of the Czech Republic)

Lead Authors: Valerie Nelson (National Resource Institute, University of Greenwich)

Contributing Author: Sofia Belardinelli (University of Padova)

Fellows: Sofia Belardinelli (University of Padova)

Hurricane Milton over the Gulf of Mexico, 8 October 2024.

Credit: NASA Visible Earth

1.1 Acting now for a healthy planet: initiating transformative change

All life on Earth, including humanity, is facing an unprecedented threat, represented by the convergence of human-induced global environmental crises: the crisis of climate change, the crisis of biodiversity loss, land degradation and desertification, and the crisis of pollution and waste. These crises are interlinked and mutually reinforcing, pushing planetary systems towards uncharted territory where there is a growing likelihood that several tipping points may soon be irreversibly crossed. Despite numerous political commitments and repeated calls for action, the world is still not on track to meet internationally agreed objectives for responding to these crises.

Previous reports, including key findings from the Sixth Global Environment Outlook (GEO-6) report, explicitly show that global environmental crises are continuing at an accelerating rate, are worsening, and the costs of inaction are rapidly increasing. Meanwhile, the window for effective and timely action is closing (Dinerstein et al. 2019; Evans 2021; Muluneh 2021; Visseren-Hamakers et al. 2021; Leadley et al. 2022; Persson et al. 2022; Wilkinson et al. 2022; Chaplin-Kramer et al. 2023). These calls for immediate action are prioritized by the United Nations 2030 Agenda for Sustainable Development and its 17 SDGs and by several Multilateral Environment Agreements, including the Convention on Biological Diversity's Kunming-Montréal Global Biodiversity Framework (United Nations 2015; United Nations Environment Programme [UNEP] 2019a; Secretariat of the Convention on Biological Diversity 2022a; Secretariat of the Convention on Biological Diversity 2022b).

Transformative change is necessary to safeguard planetary and human health and well-being, as well as to address deepening inequalities caused by the unbalanced consequences of global environmental crises, which primarily affect the world's most vulnerable populations. Achieving the environmental, social and economic goals that can ensure a sustainable and just future for all will require a transformation of the interconnected systems of economics and finance, energy, food, material resources, and the environment.

The Seventh Global Environment Outlook (GEO-7) outlines an actionable roadmap for enabling such transformations. The report provides a comprehensive assessment of the latest information on the current state of the global environment and expected future trends. The report informs decision makers and all citizens worldwide that achieving sustainability and transformative change in a timely and equitable manner is both necessary and feasible.

The report calls on all actors, governments, non-governmental and multilateral organizations, the public, including Indigenous Peoples, civil society, academia and professional organizations, as well as the private sector to acknowledge the urgency of the global environmental crises and to collaborate in the co-design and implementation of integrated policies, strategies and actions. Such coordinated actions can initiate a process of change that transforms socio-ecological systems. Equitable and just transformations fundamentally require a shift away from the concentration of power and wealth, away from short-term decisions prioritizing individual and material gains, and away from the disconnection from and domination over nature. This shift involves values moving away from extractivism and unsustainable patterns of consumption towards regenerative socio-ecological systems based on reciprocity and care (O'Brien et al. 2024).

Indigenous Peoples' care for peoples, lands and nature demonstrates the latter. GEO-7 has sought to address Indigenous Knowledge, providing dedicated space as well as attention to it throughout the text and going beyond integration into scientific framings. This attention recognizes that Indigenous Peoples' ways of knowing and being have significant value. Approaches such as Two-Eyed Seeing, Etuaptmumk in Mi'kmaw, are practical Indigenous methodologies for bringing Indigenous Knowledge and science into balanced participation. Based on long-term observations and relations with the land, as well as scientific knowledge, these approaches weave together new knowledge while recognizing the inherent value of each. Indigenous Peoples' values and ways of being, such as Sumak Kawsay from Ecuador or Ubuntu from Southern Africa, prioritize collective well-being for all life, challenging dominant formations of resource extraction and appropriation. These ways of knowing, being and relating are thus highly valuable when considering the nature of sustainability transformations and how to achieve them.

Credit: Sun-Shock/Envato

Led by an Indigenous Knowledge and Local Knowledge Task Force and drawing from the findings of three dialogues held as part of this process, GEO-7 provides space for the articulation of Indigenous and local knowledge in five stand-alone chapeaus or sections. These provide Indigenous perspectives on the global environmental crises and solution pathways responses, as well as being included within many of the other chapters in the assessment.

Recognizing the need for more far-reaching change, the report outlines the key guiding principles, long-term thinking and planning, pluralism, participation and inclusion required for governing the transformation that can inform new policy designs for current times. It also outlines the levers, or domains of intentional action, for implementing these principles. The identified levers are Economic and financial, Individual and collective action, Knowledge and innovation, Governance, and Capabilities. Acting within these areas and following transformation principles can overcome barriers and generate options for transformative actions.

To illustrate the feasibility of transformative change to achieve globally agreed environmental goals, GEO-7 has also developed two contrasting target-seeking scenarios, which model possible alternative trajectories of systems transformations and explore the scale and effort required to achieve the goals. GEO-7 Behaviour-focused Transformation Pathway Scenario envisions a profound transformation in society´s values, beliefs, and norms, accompanied by a significant decrease in consumption, particularly in affluent countries. GEO-7 Technology-focused Transformation Pathway Scenario envisions massive investments in technology and development, aiming at efficiency and clean-technology gains in an economically globalized, commodified, and urbanized world. The scenario analysis indicates that the long-term benefits of transformative change—ecological, social, and economic—would far outweigh the associated costs of its implementation.

GEO-7 also identifies several near- and long-term "solution pathways" within the five key human systems of economics and finance, energy, food, materials resources, and the environment, that, if applied, can deliver the most social and environmental benefits. Implemented through whole-of-government and whole-of-society approaches, these systemic solutions have the potential to secure a healthy global environment as the continued foundation of societies and people's well-being and health.

Recognizing the complexity of achieving transformative change at the global level, the report explores how

Credit: MaplesImages/Envato

system-wide transformations and solution pathways may vary across national and regional contexts. It provides tailored pathways and scenarios for countries with different economic contexts (high-income, medium-income, and low-income), and takes into account regional specificities, emphasizing the importance of regional cooperation and international partnerships in developing context-specific strategies and enabling equitable progress worldwide. GEO-7 also explores how the transformation process can be accelerated while ensuring that the solutions implemented in onesystem do not have adverse consequences in other systems.

1.2 A solution-focused approach for sustainability transformations

The report is the Seventh in a series of GEOs, a process established as part of the follow-up to the adoption of Agenda 21 in 1992 (UNEP 1995). The first GEO was released in 1997. Since the launch of the latest GEO in 2019 (UNEP 2019a), several global environmental assessment reports have been published, most notably the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (2023), the UN Global Sustainable Development Report (2023), the World Meteorological Organization United in Science Report (2023), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) "Values Assessment" (2022), and the IPBES Transformative Change Assessment Report (O'Brien et al. 2024) (**Appendix 1.1**).

GEO-7 was prepared in response to a request from the fifth United Nations Environment Assembly [UNEA-5]. According to Resolution 5/3, the core function of the GEO process is to provide, every four years, an intergovernmental, expert-led, authoritative global assessment with regional specificities that analyses and tracks trends, evaluates the effectiveness of global policy responses and assesses future perspectives. At the same time, it evaluates the drivers of environmental change and the interactions across these environmental themes while benefiting from but not duplicating existing assessments (UNEP 2022).

1.2.1 New ways of thinking and acting for systems transformations

In the past, different assessments have been criticized for their findings being too abstract for policymakers

and practitioners to implement in a practical manner (Jabbour et al. 2017; Kowarsch et al. 2017; Hallegatte et al. 2024). Moreover, they fell short of providing sufficient guidance on the best policy, governance, technology or behavioural approaches to achieve these often-ambitious targets, thus aiming at the *what* without guidance on the *how*. Therefore, and due to the urgent need to address the global environmental crises of climate change, biodiversity loss and land degradation, and pollution and waste, the primary focus of GEO-7 is not the description of facts, the assessment of state, changes and trends in globalfeatures, patterns and processes or possible opportunities, but on evidence-based and adaptive solutions. By addressing key policy questions, it can serve as a basis for sound and effective policymaking. To meet these ambitions, the report provides readers with substantial innovations.

Historically, one of the most widely used causal and conceptual frameworks for describing the interactions between human and ecological systems has been the Driver-Pressure-State-Impact-Response (DPSIR) framework. This causal framework is used to describe various interactions between human society and the environment at multiple scales and is generally well accepted to manage environmental problems (Carr et al. 2007; Ness et al. 2010; Tscherning et al. 2012; UNEP 2017; Risch et al. 2019; Gupta et al. 2020). Within GEO-7, the analysis of historical, current and projected drivers and pressures of global environmental change builds on the DPSIR model but with a re-modelling and expansion. This report provides a more in-depth exploration of the Drivers and Pressures, analysing their interlinkages and intersections with the global environmental crises (*Chapter 2, Figure 2.1*). Moreover, it outlines the implementation of a system-wide transformative change through the identified solution pathways. Additionally, GEO-7 recognizes that there are other ways of understanding human-nature interactions, such as within Indigenous Peoples relational thinking and practice, which has valuable lessons for sustainability.

The governance of human systems transformations requires new ways of thinking, being, and acting. This implies, among other things, breaking away from established, unsustainable planning and decision-making, and envisioning new solution pathways. It also involves embracing participatory, pluralist and inclusive governance structures that involve all relevant stakeholders and evaluating conditions for their feasibility.

GEO-7 offers a new framework for designing and implementing interventions to drive system transformations, combining theoretically grounded requirements for whole-system transformations with operational steps for developing solution pathways. The framework is designed to be future-proof, ensuring that the challenges, complexities, and implications of system transformations are anticipated. This accelerates the pace of deliberate, transformative change at a systemic level across temporal and spatial scales. This methodology is adaptive and integrates interdependencies involving synergies and trade-offs between and within systems. Through an iterative, holistic decision-making process, this methodology accounts for possible effects of resistances, shocks and risks. Thus, it provides guidance for designing transformative solution pathways. The 7-step methodology developed in GEO-7 focuses on identifying the system goals, solutions, levers, actors, and actions needed to achieve the desired transformations.

1.2.2 Scenarios, pathways and strategies for realizing transformative change

The GEO-7 scenario analysis shows that internationally agreed goals related to the global environmental crises can be achieved with significant benefits for people and the planet. Both transformation scenarios require unprecedented and coordinated transformations of key human systems. Furthermore, both scenarios depend on effective governance addressing inequality and inequity, high levels of technological development, and well-regulated markets where externalities are appropriately identified and consequently priced. Implementing the multiple coordinated strategies is extremely urgent. It requires orchestrating coordinated actions across diverse systems, sectors and regions, and gaining societal acceptance of specific solutions, such as changes in consumption patterns and human behaviour. For example, avoiding inefficient and unnecessary resource use and embracing the concept of circularity creates multiple synergies across systems to address planetary crises and improve human well-being.

The report confirms that three complementary perspectives can be applied to system transformation: a) a socio-ecological perspective focusing on various interactions of environmental and social components and situating intentional transformative actions within the nested practical and personal spheres; b) a socio-technical perspective aiming at the mutual shaping

Credit: Dmitry_Rukhlenko/Envato

of technology and society, commonly representing systems as partially coherent bundles of technology, policies, science, culture, and industry and markets; and c) a socioeconomic perspective highlighting the interactions of economic and social systems and the scope for institutional frameworks and response structures that modify these systems. These perspectives differ in terms of how system boundaries are drawn, how the dynamics and future pathways of transformations are represented, and the insights for governance. Key principles that can guide transformations are presented in the report, including adaptability, inclusion, and plurality.

1.2.3 A plurality of forms of knowledge can support the achievement of desired sustainable futures

Plurality means recognizing different forms of knowledge in seeking sustainability transformations, such as scientific knowledge and Indigenous Knowledge and Local Knowledge. The latter can contribute to transformations towards sustainable futures by providing valuable concepts of human-nature relations, values based on the ethics of care, and practices such as ways of caring for lands, people, and nature. Indigenous Peoples and other communities that maintain historical connections to living territories often have a deep, relational understanding of lands and ecologies. Importantly, Indigenous Peoples do not separate nature from humans but rather recognize that humans and nature are entangled and interdependent, with these relations underpinned by obligations and values of reciprocity and care, and imbued with spiritual significance. These relational rather than instrumental interactions with nature, based on the ethics of care for territories and all life, enable humans and non-humans to flourish with broader relevance for sustainability transformations.

Fundamental shifts for the desired sustainable futures identified by Indigenous Peoples in the Second Dialogue for GEO-7 include: a) territorial and life care; b) sustainable, social and solidarity economy; c) just energy transitions with equitable access; d) education that fosters intergenerational transmission of Indigenous Knowledge and Local Knowledge and the revitalization of Indigenous Knowledge, cultures, and languages; and e) strengthening Indigenous forms of organization, alliances and networks. Instead of dismissing Indigenous Peoples' ways of knowing, being, and relating, or seeking to integrate them into scientific framings and paradigms, sustainability transformations will be better served by giving greater space to Indigenous perspectives and representation in decision-making processes and defending the human rights of Indigenous Peoples.

Finally, the GEO process should identify inter-governmentally defined needs and terms to support capacity-building, knowledge generation and policymaking. The report aims at providing support services for addressing those needs. Therefore, GEO-7 has started implementing a set of supporting services

such as capacity building, technology transfer, knowledge generation, and support for policymaking. These activities are intended to assist all actors – from governments to civil society, organizations, and communities, as well as businesses and enterprises – in implementing these ambitious transformations. The supporting services approach is an outgrowth of the two year process to define the Future of GEO, which recognized that implementing the findings of the GEO assessment requires additional support.

1.3 Realizing transformative change: solution pathways and driving the transformation

To secure a sustainable future, transformative change must move beyond intent to action. The GEO-7 report outlines five interconnected solution pathways for achieving this transformation: transforming economic and financing systems, implementing circular economy principles, transforming the energy system, transforming the food system, and managing environmental systems. The pathways prioritize innovation, regional perspectives, and strategies to accelerate progress. They are not isolated; their synergies amplify the impacts, ensuring solutions that are effective, equitable, and inclusive. The urgency of this transformation demands unprecedented ambition and coordination across governments, societies, and knowledge systems. From an Indigenous Peoples' perspective, it is clear that efforts to achieve sustainability transformations should not involve 'false solutions' such as green capitalism, that continue to reproduce business-as-usual and undermine their human rights, but should instead entail shifts towards care and reciprocity and recognition of their rights to self-determination and representation in policymaking as rights-holders.

1.3.1 Transformation of economic and financing systems

Economic and financial systems must evolve by phasing out socially and environmentally harmful substances, pricing externalities such as pollution, moving beyond Gross Domestic Products as the sole measure of progress, and redirecting financial flows towards sustainability. Innovations such as the EU's Sustainable Europe Investment Plan and New Zealand's well-being budgets demonstrate how fiscal reforms can align economies with environmental goals. In developing regions, international financing can enable leapfrogging to sustainable models, with equity ensured through compensatory mechanisms for vulnerable populations.

1.3.2 Implementing circular economy principles and practices

Circular economy principles focus on minimizing waste and maximizing resource efficiency. Urban mining in Japan, which recovers metals from electronics, and Africa's informal recycling networks showcase scalable practices, as do Indigenous Peoples' care economies based on the principle of abundant sufficiency. These efforts reduce the need for raw extraction, support sustainable bio-economies, and create jobs, particularly in resource-scarce areas. Additionally, integrating circularity into energy and food systems amplifies these benefits.

1.3.3 Transforming the global energy system

Transforming the energy system hinges on decarbonization, scaling renewable sources like solar and wind and improving efficiency. Cost-competitive technologies, advanced energy storage, and smart grids drive this shift. Africa's abundant solar potential and Europe's leadership in wind energy highlight regional strengths. The electrification of transport and industry further reduces emissions, demonstrating that innovation delivers both environmental and economic benefits.

1.3.4 Transforming the food system

Food system transformation calls for dietary shifts toward plant-based options, more efficient production, waste reduction, and alternative proteins like lab-grown meat. Precision farming, regenerative agriculture, and novel proteins can reduce environmental footprints. Asia's rice-based diets and Latin America's cattle-heavy regions can adopt tailored sustainable practices, while technologies like food waste apps enhance security and resilience globally. Indigenous Peoples' food systems offer holistic biocultural solutions to sustainability.

1.3.5 Managing environmental systems

Managing environmental systems in ways that enhance sustainability involves implementing nature-friendly solutions and incorporating Indigenous Peoples' governance and care for living territories. Monitoring through the use of artificial intelligence can more effectively track the health of ecosystems. Community-

Credit: avanti_photo/Envato

led conservation in Africa and the Amazon can restore biodiversity cost-effectively. Respecting Indigenous Peoples' rights and building on Indigenous Knowledge and Local Knowledge and practices can enhance the effectiveness, equity and cultural relevance of conservation, also supporting climate adaptation.

1.3.6 Regional perspectives

Regional perspectives emphasize context-specific solutions. Africa excels in solar and circular waste systems, Latin America's Amazon Fund protects forests, Asia builds green urban hubs, and Europe leads in wind and policy innovation. Equity and justice remain critical: technology transfers and support for marginalized groups can strengthen inclusive progress, as can respect for human rights, including the rights of Indigenous Peoples.

1.3.7 Accelerating the transformation

Accelerating transformation requires urgent action, as noted throughout GEO-7. Policy innovations, such as a carbon tax in Sweden, technology-scaling through research, and cultural and value shifts via education, including the recognition of the agency and rights of non-humans, are key drivers. Strong governance, involving whole-of-government and whole-of-society approaches, is essential and also recognizes Indigenous Peoples' rights to self-determination. Private sector innovation, public-private partnerships, and education build momentum. Barriers such as vested interests and funding gaps can be overcome through blended finance and transparent communication, while remote sensing and citizen science facilitate adaptive management.

1.3.8 Unified pathways for shaping a sustainable future

The five solution pathways chart a course to sustainability, integrating economic and financial, energy, food, material resources, and environmental systems. Innovations, from green finance and

Indigenous Peoples' governance of lands to alternative proteins, unlock their potential, bolstered by regional insights and accelerated through policy, technology and collaboration.

The call to action is clear: act now, with boldness and equity, to forge a just and sustainable future where prosperity and planetary health coexist. The GEO-7 report equips us with the vision and tools to make this systemic transformation real, ensuring a resilient world for all.

All the pathways outlined are interconnected: renewables reduce emissions, circularity mitigates ecosystem strain, and dietary shifts free up land for people and nature. Digitalization that addresses equity and justice can enhance efficiency across all areas of operation. In conclusion, the transformative scenarios of behavioural and technological change, along with the five solution pathways, offer a roadmap to sustainability, blending strategies to radically transform the economic and financial, energy, food, material resources, and environmental systems. The beneficial outcomes multiply when these solutions address transformation principles such as justice, pluralism, and Indigenous Peoples' perspectives. With bold, equitable action, the GEO-7 report envisions a resilient future where prosperity and planetary health thrive together.

1.4 Structure of GEO-7

The report is divided into five parts. Each section begins with an Indigenous Knowledge and Local Knowledge chapeau that sets out Indigenous Peoples' perspectives on each of the five sections.

Part A: Overview and Context (chapters 1 and 2) sets the scene and the context while also covering the Drivers and Pressures of environmental change.

A global environmental crises chapeau expands on the global environmental crises and their interrelationships and how feedback among crises aggravates their pressures but also highlights opportunities for solution pathways with co-benefits.

Part B: State and Trends of the Environment (chapters 3 to 8) describes the State and Trends of the environment and the impacts of environmental degradation on human systems. It also analyzes the state of the environment from a regional and subregional perspective and emphasizes the urgent need for change.

Part C: Outlooks (chapters 9 to 11) presents a methodological approach for developing target-seeking scenarios, utilizing both qualitative and quantitative methods. Subsequently, it presents and discusses an explorative scenario to discuss the likely environmental and socioeconomic implications of a continuation of these trends, as well as two target-seeking scenarios to show what is needed to achieve internationally agreed goals related to the global environmental crises.

Part D: Solution Pathways towards Transformation (chapters 13 to 18), introduces the methodological approach to solution-focused pathways, followed by a detailed overview of five different solution pathways for transformation.

Finally, Part E: Implications for Regions and Groups of Countries and Driving the Transformations (chapters 19 to 21) presents some implications, regional similarities and differences, and a concluding section.

Box 1.1: Global environmental crises: the urgency of transformative action

Global environmental assessments conducted by international organizations in collaboration with the global scientific community provide critically important insights into environmental change and its underlying causes.

Environmental action is urgently needed to sustain a liveable planet. Work on planetary boundaries, which draws upon Earth system science, identifies some processes that are critical for maintaining the stability and resilience of the Earth system as a whole and shows that boundaries are being exceeded (Rockström et al. 2009; Steffen et al. 2015; Steffen et al. 2018; Richardson et al. 2023; Caesar et al. 2024).

The framework update on planetary boundaries reveals that they are closely related and generate cascading effects upon one another. Seven of the nine boundaries—biogeochemical flows, freshwater change, land system change, biosphere integrity, climate change, novel entities and ocean acidification—have already been crossed, suggesting that Earth is now well outside of the safe operating space for humanity (Richardson et al. 2023).

The current global environmental crises are primarily a result of processes such as technological innovation, economic growth, and increased environmental impacts on natural systems. This ensemble of processes has been termed The Great Acceleration, which began in the second half of the 20th century and is unique in the history of human existence (Costanza et al. 2007; Steffen et al. 2007; McNeill and Engelke 2014; Steffen et al. 2015; Dasgupta 2021; Head et al. 2022; Shoshitaishvili 2021).

Credit: Freedomnaruk/Envato

Box 1.1: Global environmental crises: the urgency of transformative action (cont.)

Given that the health of people is closely connected to the health of animals and our shared environment, as encapsulated by the "One Health" concept, promoting a healthy planet should be the collective pursuit of all. The impacts of climate change, the unsustainable use of natural resources, the pollution of air, land and water, the unsound management of chemicals and waste, and the resulting loss of biodiversity and decline in benefits provided by ecosystems all interfere with achieving a healthy, equitable, and sustainable planet (Adla et al. 2022; Bastien-Olvera et al. 2023; Lenton et al. 2023).

Effective action is needed to address the underlying causes of unsustainability, and this action must be transformative. The definition of transformative change is evolving in academic debates and science-policy assessments (Fisher et al. 2022). In recent years, GEO-6, IPBES, and IPCC, for example, have defined transformative change respectively as:

"The process whereby positive development results are achieved and sustained over time by institutionalizing policies, programmes and projects within national strategies. It should be noted that this embodies the concept of institutionally sustained results – consistency of achievement over time. This is in order to exclude short-term, transitory impact" (UNEP 2019a).

"Fundamental, system-wide reorganization across technological, economic and social factors, including paradigms, goals and values" (IPBES 2019).

"A system-wide change that requires more than technological change through consideration of social and economic factors that, with technology, can bring about rapid change at scale" (IPCC 2023).

The most comprehensive assessment of transformative changes is provided by the recent IPBES Assessment on Transformative Change, which focuses on biodiversity (O'Brien et al., 2024). It highlights

Credit: IciakPhotos/Envato

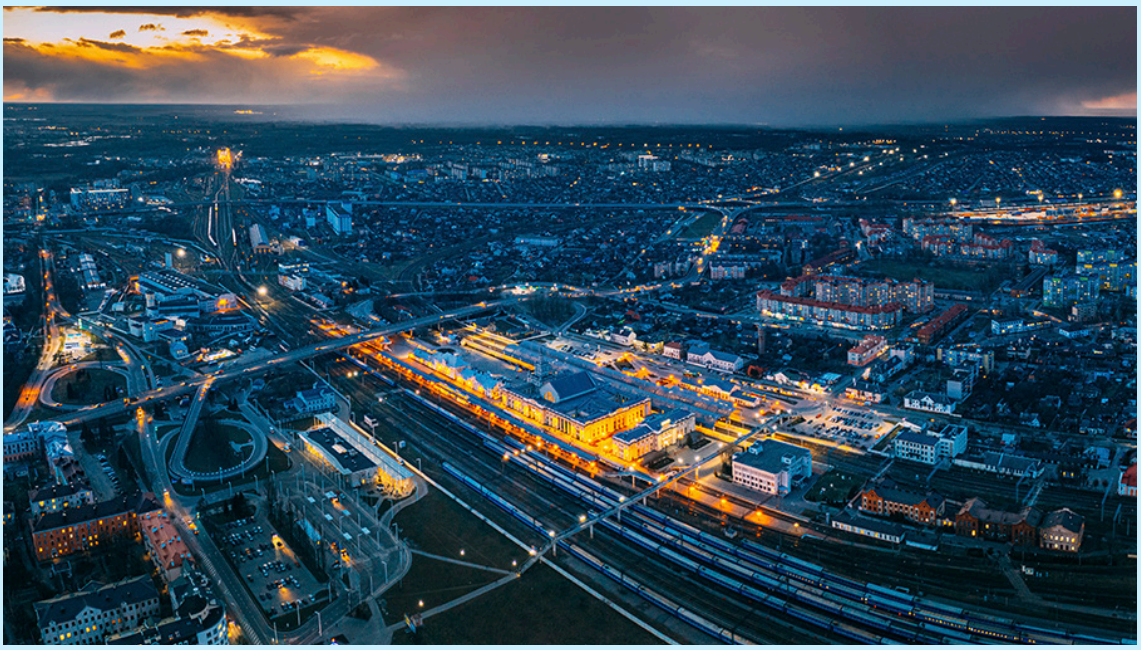
Box 1.1: Global environmental crises: the urgency of transformative action (cont.)

three underlying causes: disconnection from and domination over nature, the concentration of power and wealth, and the prioritization of short-term decision-making based on individual and material gain. It recommends certain types of changes as ways forward, such as economic system transformations moving away from growth and structural and sociocultural worldviews and values shifting from domination to care (O'Brien et al. 2024).

Well-designed and effective policies and actions undertaken by diverse actors are likely to be part of such transformative change. Shifting from 'incremental' to 'transformative' change demands a radical reassessment of the existing frameworks of economic, political, and social systems (Iversen et al. 2018). Indigenous Peoples' ways of knowing, being, and relating offer valuable practices for caring for land, people, and ecologies in ways that align with an ethics of care and challenge extractivism, appropriation, and treating nature as separate from humans and a resource for human use and benefit. Indigenous scholars and representatives have identified "…ongoing processes of colonialism, dispossession, capitalism, imperialism/globalization and patriarchy…" as the root causes of our current global environmental crises and environmental injustices (McGregor, Whitaker and Sritharan 2020; IK & LK Dialogues 2025). These insights merit consideration for achieving sustainability.

Transforming human systems, the economic and financial, energy, food, material resources, and environmental systems together with sociocultural and behavioural shifts, would contribute significantly to creating a world with a stable climate while also delivering equity and justice for all life on Earth and future generations.

Transformation processes can promote equity and justice by following key principles of inclusion, participation and plurality; by seeking to address socioeconomic and power imbalances related to gender, class, ethnicity, religion, age, indigeneity, disability, and by recognizing that geographic aspects can interact in multiple ways with environmental problems and exacerbate in policy design (UNEP 2019b; UNEP 2021; UNDP 2020). Additional care should be taken for those who are particularly vulnerable to environmental degradation, in line with human rights and considering emerging nature rights and representation.



Credit: Great_bru/Envato

Appendix 1.1 Key findings from previous global environmental assessments since 2019

Organization/ Author(s) and year	Title	Evaluation of Step or Procedure Check List
IPBES 2019	*Global Assessment Report on Biodiversity and Ecosystem Services*	Globally, nature is declining at rates unprecedented in human history. The decline in biodiversity, a direct result of human activity, has been accelerating despite awareness that this poses a significant threat to human well-being.
IPCC 2019	*IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*	Over the last decades, global warming has led to the widespread shrinking of the cryosphere. Since 1993, the rate of ocean warming has more than doubled and by absorbing more CO_2, the ocean has undergone increasing surface acidification. A loss of oxygen has occurred from the surface to 1000 m.
UNEP 2019a	*Global Chemicals Outlook, 2nd edition*	Hazardous chemicals and other pollutants, including plastic waste and pharmaceutical pollutants, continue to be released in large quantities and accumulate in the environment, underscoring the need to prevent future legacies through sustainable materials management and circular business models.
WRI 2019	*Creating a sustainable food future*	As the global population grows and incomes grow across the developing world, overall food demand is projected to increase by more than 50 per cent till 2050.
Eggleton 2020	*The State of the World's Insects*	Recent studies have indicated a worrying decline in insect species, especially in flying insects in the northern temperate region due to agricultural intensification, urbanization, overuse of pesticides, and global climate change. However, there is too little data to warrant the belief that all insects are declining everywhere.
FAO & UNEP 2020	*The state of the world's forests*	Deforestation and forest degradation continue to occur at alarming rates, contributing significantly to the ongoing loss of biodiversity.
Royal Botanical Gardens Kew [RBGK] 2020 **(Antonelli *et al.* 2020)**	*State of the world's plants and fungi*	Two in five plants are estimated to be threatened with extinction.
SCBD 2020	*Global Biodiversity Outlook, 5th edition*	Biodiversity decline has been continuing: at the global level, none of the 20 Aichi Targets have been fully achieved, though six targets have been partially achieved.
UNDP 2020	*Human Development Report*	Humans are destabilizing the planetary systems on which they rely for their survival.
IPCC & IPBES 2021 **(Pörtner *et al.* 2021)**	*IPBES-IPCC Co-sponsored workshop Biodiversity and Climate Change. Scientific outcome*	Climate and biodiversity are inextricably connected with each other and with human futures.
International Resource Panel [IRP] 2021	*Building biodiversity*	Four principles of natural resource management – value-chain transparency, integrated landscape planning, nature-based and circular solutions, and recognize nature's benefits – can help countries effectively implement biodiversity policy.
Ramsar Convention 2021	*Global Wetland Outlook. Special edition 2021*	Although wetlands are critical to delivering on global commitments related to biodiversity, climate change, and sustainable development, their deterioration continues.
United Nations Office of Legal Affairs 2021	*The Second World Ocean Assessment*	Many pressures from human activities continue to degrade the ocean, including those associated with climate change, unsustainable fishing, the introduction of invasive alien species, atmospheric pollution causing acidification and eutrophication, excessive inputs of nutrients and hazardous substances, increasing amounts of anthropogenic noise, and ill-managed coastal development and extraction of natural resources.

Organization/ Author(s) and year	Title	Evaluation of Step or Procedure Check List
UNEP 2021	*Making peace with nature*	Humankind faces three crises: climate change, biodiversity loss and pollution. Environmental changes are undermining hard-won development gains by incurring significant economic costs and resulting in millions of premature deaths annually. They are impeding progress towards ending poverty and hunger, reducing inequalities, and promoting sustainable economic growth, work for all and peaceful and inclusive societies.
Birdlife International 2022	*State of the World's Birds 2022*	One in eight bird species is threatened with extinction, and the status of the world's birds continues to deteriorate: species are moving ever faster towards extinction.
FAO 2022	*The State of Food and Agriculture 2022*	If implemented correctly, agricultural automation can contribute to inclusive and sustainable agrifood systems.
Global Mangrove Alliance [GMA] 2022	*The State of the World's Mangroves 2022*	Halting loss means bringing global mangrove losses to zero by 2030, equating to 168 km^2 of avoided loss of mangroves. Restoring half refers to the recorded losses since 1996 and equates to some 4,092 km^2 of restoration.
International Energy Agency [IEA] 2022	*World Energy Outlook 2022*	Seventy million people who recently gained access to electricity will likely lose it. As markets rebalance, renewables, supported by nuclear power, see sustained gains; the upside for coal from today's crisis is temporary. The increase in renewable electricity generation is sufficiently rapid to outpace growth in total electricity generation, thereby reducing the contribution of fossil fuels to power.
IPCC 2022	*IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems*	People currently use one-quarter to one-third of land's potential net primary production for food, feed, fibre, timber, and energy. Global population growth and changes in per capita consumption of food, feed, fibre, timber, and energy have led to unprecedented rates of land and freshwater use, with agriculture currently accounting for approximately 70 per cent of global freshwater use.
UNCCD 2022	*Global Land Outlook, 2nd edition*	Two in five plants are estimated to be threatened with extinction.
Wetlands International 2022	*We need wetlands*	Since 1970, 35 per cent of the world's wetlands have been lost.
World Wildlife Fund [WWF] 2022	*Living Planet Report*	An average decline of 69 per cent was found in almost 32,000 selected wildlife populations between 1970 and 2018.
Finn et al. 2023	*More losers than winners: Investigating Anthropocene defaunation through the diversity of population trends*	There is a widespread global erosion of species, with 48 per cent undergoing declines, while 49 per cent and 3 per cent of species currently remain stable or are increasing, respectively.
Independent Group of Scientists appointed by the Secretary-General 2023	*Global Sustainable Development Report 2023*	Overall progress towards the 2030 Agenda and its Sustainable Development Goals has been severely disrupted over the last three years, yet every inch of progress matters and counts. Transformations are possible and inevitable.
IPBES 2023	*Thematic Assessment Report on invasive alien species and their control*	Invasive alien species pose major global threats to nature, economies, food security and human health. For example, they have played a key role in 50 per cent of global plant and animal extinctions.

Organization/ Author(s) and year	Title	Evaluation of Step or Procedure Check List
IPCC 2023	*Synthesis Report of the IPCC Sixth Assessment Report (AR6)*	Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with the average global surface temperature reaching 1.1°C above 1850-1900 levels in 2011-2020. Global greenhouse gas emissions have continued to increase. Human-caused climate change is already affecting many weather and climate extremes in every region across the globe.
Lenton et al. 2023	*The Global Tipping Points Report 2023*	Climate change and nature loss could soon cause the crossing of tipping points in the natural world. These tipping points pose threats of a magnitude that humanity has never faced before.
MacAlister et al. 2023	*Global Water Security 2023 Assessment*	Alarmingly, most of the world's population lives in water-insecure countries today. Out of 7.78 billion people living in 186 countries, over 0.61 billion people, or 8 per cent, are critically water-insecure and 5.52 billion, 72 per cent, are water-insecure. In addition, 0.65 billion people, eight per cent, live in moderately water-secure countries.
UNEP 2023a	*Environmental Effects of Stratospheric Ozone Depletion, UV Radiation, and Interactions with Climate Change 2022 Assessment Report*	The Montreal Protocol has prevented significant increases in surface UV-B radiation, with the greatest benefits at high latitudes.
UNEP 2023b	*Global Framework on Chemicals*	Pollution is the world's most significant risk factor for disease and premature death, with pollution from chemicals contributing to millions of deaths, illnesses and disabilities each year. The sound management of chemicals and waste is essential for achieving the goals of the 2030 Agenda for Sustainable Development.
World Economic Forum [WEF] 2023	*The Global Risks Report 2023*	Natural ecosystems are past the point of no return.
WMO 2023a	*United in Science 2023*	Human-induced climate change is affecting life-sustaining systems. Looking beyond the 2030 time frame, new technological solutions and gradual changes in consumption patterns are needed at all levels.
WMO 2023b	*Provisional State of the Global Climate 2023*	The global mean near-surface temperature to October in 2023 was around 1.40 ± 0.12 °C above the 1850–1900 average. Based on the data to October 2023, it is virtually certain that 2023 will be the warmest year in the 174-year observational record. The past nine years, 2015–2023, will be the nine warmest years on record.
FAO 2024	*The State of World Fisheries and Aquaculture 2024*	Fishery resources continue to decline due to overfishing, pollution, poor management, and other factors, but the number of landings from biologically sustainable stocks is on the rise. Aquaculture has great potential to feed and nourish the world's growing population, but growth must be sustainable.
Health Effects Institute 2024	*State of Global Air 2024 Special Report*	In 2021, air pollution contributed to 8.1 million deaths – more than 1 in 8 deaths worldwide, being the second leading risk factor for death among children under 5 in 2021, after malnutrition.
IUCN 2024	*Red List of Mangrove Ecosystems*	Fifty per cent of the world's mangrove areas are at risk of collapse, and one out of five of these ecosystems are at severe risk of collapse.
Sachs et al. 2024	*Sustainable Development Report 2024*	On average, only 16 per cent of the SDG targets are on track to be met globally by 2030, with the remaining 84 per cent showing limited progress or a reversal of progress.
UNEP 2024b	*Food Waste Index Report 2024*	Previous estimates of consumer food waste significantly underestimated its scale. Food waste generates an estimated 8–10 per cent of global greenhouse gas emissions (including from both loss and waste), and it takes up the equivalent of nearly 30 per cent of the world's agricultural land.

Organization/ Author(s) and year	Title	Evaluation of Step or Procedure Check List
UNEP 2024c	*Global Waste Management Outlook 2024*	Every year across the globe, more than two billion tonnes of municipal solid waste is generated. For a liveable future, the current pattern of resource use needs to be halted with urgency, and zero waste and circular economy strategies must be implemented to protect the human rights of future generations.
UNEP 2024d	*Global Resources Outlook 2024*	Extraction and processing of material resources account for over 55 per cent of greenhouse gas emissions and 40 per cent of particulate matter's health-related consequences. If land-use change is considered, climate effects grow to more than 60 per cent, with biomass contributing the most at 28 per cent, followed by fossil fuels at 18 per cent, and then non-metallic minerals and metals, together at 17 per cent. Biomass from crops and forestry also accounts for over 90 per cent of the total land-use-related biodiversity loss and water stress. All environmental impacts are on the rise.
United Nations Educational, Scientific and Cultural Organization [UNESCO] 2024	*The United Nations World Water Development Report 2024: Water for Prosperity and Peace*	Climate change, geopolitical unrest, pandemics, mass migration, hyperinflation and other crises can exacerbate water access inequalities. In nearly all cases, the poorest and most vulnerable groups are those who suffer the most significant risks to their well-being.

References

Adla, K., Dejan, K., Neira, D. and Dragana, Š. (2022). Chapter 9 - Degradation of ecosystems and loss of ecosystem services. In One Health. Prata, J.C., Ribeiro, A.I. and Rocha-Santos, T. (eds.). Academic Press. 281-327. https://www.sciencedirect.com/science/article/pii/B9780128227947000083

Antonelli, A., Fry, C., Smith, R.J., Eden, J., Govaerts, R.H.A., Kersey, P. et al. (2023). State of the World´s Plants and Fungi. Royal Botanic Gardens, Kew. https://doi.org/10.34885/wnwn-6s63

Bastien-Olvera, B.A., Conte, M.N., Dong, X., Briceno, T., Batker, D., Emmerling, J. et al. (2023). Unequal climate impacts on global values of natural capital. Nature. https://doi.org/10.1038/s41586-023-06769-z

BirdLife International (2022). State of the World's Birds. BirdLife International. https://www.birdlife.org/papers-reports/state-of-the-worlds-birds-2022/

Caesar, L., Sakschewski, B., Andersen, L.S., Beringer, T., Braun, J. D. Dennis, J.D., et al. (2024). Planetary Health Check Report 2024. Potsdam, Germany: Potsdam Institute for Climate Impact Research. https://d1gwxouzo4hr10.cloudfront.net/planetaryhealthcheck2024_report.pdf.

Carr, E.R., Wingard, P.M., Yorty, S.C., Thompson, M.C., Jensen, N.K. and Roberson, J. (2007). Applying DPSIR to sustainable development. International Journal of Sustainable Development & World Ecology 14(6), 543-555. https://www.doi.org/10.1080/13504500709469753

Chaplin-Kramer, R., Neugarten, R.A., Sharp, R.P., Collins, P.M., Polasky, S., Hole, D. et al. (2023). Mapping the planet's critical natural assets. Nature Ecology & Evolution 7(1), 51-61. https://doi.org/10.1038/s41559-022-01934-5

Costanza, R., Graumlich, L., Steffen, W., Crumley, C., Dearing, J., Hibbard, K., ... & Schimel, D. (2007). Sustainability or collapse: what can we learn from integrating the history of humans and the rest of nature? AMBIO: A Journal of the Human Environment, 36(7), 522-527

Crutzen, P.J. (2002). Geology of mankind. Nature 415(6867), 23-23. https://doi.org/10.1038/415023a

Crutzen, P.J. (2006). The "Anthropocene". In Earth System Science in the Anthropocene. Ehlers, E. and Krafft, T. (eds.). Berlin, Heidelberg: Springer Berlin Heidelberg. 13-18. https://doi.org/10.1007/3-540-26590-2_3.

Crutzen, P.J. and Stoermer, E.F. (2000). The "Anthropocene". Global Change NewsLetter 41. https://inters.org/files/crutzenstoermer2000.pdf

Dasgupta, P. (2021). The Economics of Biodiversity: The Dasgupta Review. London: HM Treasury. https://assets.publishing.service.gov.uk/media/602e92b2e90e07660f807b47/The_Economics_of_Biodiversity_The_Dasgupta_Review_Full_Report.pdf

Dinerstein, E., Vynne, C., Sala, E., Joshi, A.R., Fernando, S., Lovejoy, T.E. et al. (2019). A Global Deal For Nature: Guiding principles, milestones, and targets. Science Advances 5(4), eaaw2869. https://www.doi.org/10.1126/sciadv.aaw2869

Eggleton, P. (2020): The State of the World's Insects. Annual Review of Environment and Resources 45: 8.1-8.22. https://www.annualreviews.org/docserver/fulltext/energy/45/1/annurev-environ-012420-050035.pdf?expires=1725119572&id=id&accname=guest&checksum=

Evans, M.C. (2021). Re-conceptualizing the role(s) of science in biodiversity conservation. Environmental Conservation 48(3), 151-160. https://www.doi.org/10.1017/S0376892921000114

Finn, C., Grattarola,F. and Pinchera-Donoso, D. (2023): More losers than winners: investigating Anthropocene defaunation through the diversity of population trends. Biological Reviewers 98, 1732-1748. https://onlinelibrary.wiley.com/doi/full/10.1111/brv.12974

Fisher, E., Brondizio, E. and Boyd, E. (2022). Critical social science perspectives on transformations to sustainability. Current Opinion in Environmental Sustainability 55, 101160. https://doi.org/10.1016/j.cosust.2022.101160

Food and Agriculture Organization (2022). The State of Food and Agriculture 2022. Leveraging automation in agriculture for transforming agrifood systems. Rome: FAO. https://doi.org/10.4060/cb9479en

Food and Agriculture Organization (2024). The State of World Fisheries and Aquaculture 2024. Blue Transformation in Action. Rome: FAO. https://doi.org/10.4060/cd0683en

Food and Agriculture Organization and United Nations Environment Programme (2020). The State of the World's Forests 2020. Forests, biodiversity and people. Rome. https://doi.org/10.4060/ca8642en

Gibbard, P., Walker, M., Bauer, A., Edgeworth, M., Edwards, L., Ellis, E. et al. (2022). The Anthropocene as an Event, not an Epoch. Journal of Quaternary Science 37(3), 395-399. https://www.doi.org/10.1002/jqs.3416

Global Mangrove Alliance (2022). The State of the World's Mangroves 2022. Global Mangrove Alliance. https://www.mangrovealliance.org/mangrove-forests/

Hallegatte, S., Godinho, C., Rentschler, J., Avner, P., Dorband, I.I., Knudsen, C. et al. (2024). Within Reach: Navigating the Political Economy of Decarbonization. Climate Change and Development Series. Washington, DC: World Bank. https://www.doi.org/10.1596/978-1-4648-1953-7

Head, M.J., Steffen, W., Fagerlind, D., Waters, C.N., Poirier, C., Syvitski, J. et al. (2022). The Great Acceleration is real and provides a quantitative basis for the proposed Anthropocene Series/Epoch. Episodes Journal of International Geoscience 45(4), 359-376. https://www.doi.org/10.18814/epiiugs/2021/021031

Health Effects Institute (2024). State of Global Air 2024. Special Report. Boston, MA: Health Effects Institute. https://www.stateofglobalair.org/resources/report/state-global-air-report-2024

IK & LK Dialogues (2025). Indigenous Knowledge and Local Knowledge Dialogues. Global Environment Outlook 7. Mexico City: CopIt-arXives. https://copitarxives.fisica.unam.mx/SC0011EN/SC0011EN.php

Independent Group of Scientists appointed by the Secretary-General (2023). Global Sustainable Development Report 2023. New York: United Nations. https://desapublications.un.org/publications/global-sustainable-development-report-2023

Intergovernmental Panel on Climate Change (2014). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-PartA_FINAL.pdf

Intergovernmental Panel on Climate Change (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. https://www.ipcc.ch/srocc/

Intergovernmental Panel on Climate Change (2022). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Cambridge, UK and New York, NY, USA: IPCC. https://doi.org/10.1017/9781009157988

Intergovernmental Panel on Climate Change (2023). AR6 Synthesis Report: Climate Change 2023. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/sixth-assessment-report-cycle/

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2016). The methodological assessment report on scenarios and models of biodiversity and ecosystem services. Bonn, Germany. https://digitallibrary.un.org/record/3793989

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2018). The IPBES assessment report on land degradation and

restoration. Bonn, Germany: Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://zenodo.org/records/3237393

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES secretariat. https://zenodo.org/record/6417333

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2022). Methodological assessment of the diverse values and valuation of nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES Secretariat. . https://zenodo.org/record/7687931

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2023). Thematic Assessment Report on invasive alien species and their control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES Secretariat. https://zenodo.org/records/11629357

International Energy Agency (2022). World Energy Outlook 2022. Paris: International Energy Agency. https://www.iea.org/reports/world-energy-outlook-2022

International Resource Panel (2021). Building biodiversity. The natural resource management approach. Paris. https://wedocs.unep.org/bitstream/handle/20.500.11822/35972/BDNR.pdf

International Union for Conservation of Nature (2024): Red List of Mangrove Ecosystems. Gland, Switzerland, IUCN. https://iucn.org/resources/conservation-tool/iucn-red-list-ecosystems/red-list-mangrove-ecosystems

Iversen, K., Islam, S.N. and U.N. Department of Economic Social Affairs (2018). From "Structural Change" to "Transformative Change": Rationale and Implications. https://digitallibrary.un.org/record/3859024

Jabbour, J. and Flachsland, C. (2017). 40 years of global environmental assessments: A retrospective analysis. Environmental Science & Policy 77, 193-202. https://doi.org/10.1016/j.envsci.2017.05.001

Keys, P.W., Galaz, V., Dyer, M., Matthews, N., Folke, C., Nyström, M. et al. (2019). Anthropocene risk. Nature Sustainability 2(8), 667-673. https://www.doi.org/10.1038/s41893-019-0327-x

Kowarsch, M., Jabbour, J., Flachsland, C., Kok, M.T.J., Watson, R., Haas, P.M. et al. (2017). A road map for global environmental assessments. Nature Climate Change 7(6), 379-382. https://www.doi.org/10.1038/nclimate3307

Leadley, P., Gonzalez, A., Obura, D., Krug, C.B., Londoño-Murcia, M.C., Millette, K.L. et al. (2022). Achieving global biodiversity goals by 2050 requires urgent and integrated actions. One Earth 5(6), 597-603. https://www.doi.org/10.1016/j.oneear.2022.05.009

Lenton, T.M., Armstrong McKay, D.I., Loriani, S., Abrams, J.F., Lade, S.J., Donges, J.F., Milkoreit, M. et al. (2023). The Global Tipping Points Report 2023. University of Exeter, Exeter, UK. https://global-tipping-points.org/

MacAlister, C, Baggio, G, Perera, D, Qadir, M, Taing, L, Smakhtin, V.(2023). Global Water Security 2023 Assessment. Hamilton, Canada. United Nations, University Institute for Water, Environment and Health, http://inweh.unu.edu/publications/

McGregor, D., Whitaker, S. and Sritharan, M. (2020). Indigenous environmental justice and sustainability. Current Opinion in Environmental Sustainability 43, 35-40. https://doi.org/10.1016/j.cosust.2020.01.007

McNeill, J.R. and Engelke, P. (2014). The Great Acceleration: An Environmental History of the Anthropocene since 1945. Harvard University Press. https://www.jstor.org/stable/j.ctvjf9wcc

Millennium Ecosystem Assessment (2005). Ecosystems and Human wellbeing: A Framework for Assessment. Washington, DC: Island Press. https://www.millenniumassessment.org/en/Framework.html#download

Muluneh, M.G. (2021). Impact of climate change on biodiversity and food security: a global perspective—a review article. Agriculture & Food Security 10(1), 36. https://doi.org/10.1186/s40066-021-00318-5

Ness, B., Anderberg, S. and Olsson, L. (2010). Structuring problems in sustainability science: The multi-level DPSIR framework. Geoforum 41, 479-488. https://doi.org/10.1016/j.geoforum.2009.12.005

Nobel Foundation (2021). Our Planet, Our Future. An urgent call for action. https://www.nobelprize.org/uploads/2021/05/Statement-3-June-DC.pdf

O'Brien, K., Garibaldi, L., Agrawal, A., Bennett, E., Biggs, O., Calderón Contreras, R. et al. (2024). IPBES Transformative Change Assessment: Summary for Policymakers. Zenodo. https://zenodo.org/records/14513975

Persson, L., Carney Almroth, B.M., Collins, C.D., Cornell, S., de Wit, C.A., Diamond, M.L. et al. (2022). Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. Environmental Science & Technology 56(3), 1510-1521. https://www.doi.org/10.1021/acs.est.1c04158

Pörtner, H.-O., Scholes, R.J., Agard, J., Archer, E., Bai, X., Barnes, D. et al. (2021). IPBES-IPCC co-sponsored workshop report on biodiversity and climate change. https://zenodo.org/record/5101133

Ramsar Convention on Wetlands (2021). Global Wetland Outlook: Special Edition 2021. Gland, Switzerland. https://www.global-wetland-outlook.ramsar.org/report-1

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F. et al. (2023). Earth beyond six of nine planetary boundaries. Science Advances 9(37), eadh2458. https://www.doi.org/10.1126/sciadv.adh2458

Risch, D., Norris, T., Curnock, M. and Friedlaender, A. (2019). Common and Antarctic Minke Whales: Conservation Status and Future Research Directions. Frontiers in Marine Science 6. https://doi.org/10.3389/fmars.2019.00247

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F. et al. (2009). A safe operating space for humanity. Nature 461(7263), 472-475. https://doi.org/10.1038/461472a

Rockström, J., Gupta, J., Qin, D., Lade, S.J., Abrams, J.F., Andersen, L.S. et al. (2023). Safe and just Earth system boundaries. Nature 619(7968), 102-111. https://doi.org/10.1038/s41586-023-06083-8

Rutz, C., Loretto, M.-C., Bates, A.E., Davidson, S.C., Duarte, C.M., Jetz, W. et al. (2020). COVID-19 lockdown allows researchers to quantify the effects of human activity on wildlife. Nature Ecology & Evolution 4(9), 1156-1159. https://doi.org/10.1038/s41559-020-1237-z

Sachs, J.D., Lafortune, G. Fuller, G. (2024). The SDGs and the UN Summit of the Future. Sustainable Development Report 2024. Paris: SDSN, Dublin: Dublin University Press. doi:10.25546/108572. https://doi.org/10.25546/108572

Secretariat of the Convention on Biological Diversity (2020). Global Biodiversity Outlook 5. Montreal. https://www.cbd.int/gbo/gbo5/publication/gbo-5-en.pdf

Secretariat of the Convention on Biological Diversity (2022a). Expert input to the post-2020 global biodiversity framework: Transformative actions on all drivers of biodiversity loss are urgently required to achieve the global goals by 2050. Montreal: Convention on Biological Diversity. https://www.cbd.int/doc/c/5735/c241/efeeac8d7685af2f38d75e4e/sbstta-24-inf-31-en.pdf

Secretariat of the Convention on Biological Diversity (2022b). Kunming-Montreal Global Biodiversity Framework. Montreal: Convention on Biological Diversity. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf

Shoshitaishvili, B. (2021). From Anthropocene to Noosphere: The Great Acceleration. Earth's Future 9(2), e2020EF001917. https://doi.org/10.1029/2020EF001917

Steffen, W., Crutzen, P.J. and McNeill, J.R. (2007). The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature. AMBIO: A Journal of the Human Environment 36(8), 614-621. https://www.doi.org/10.1579/0044-7447(2007)36[614:TAAHNO]2.0.CO;2

Steffen, W., Grinevald, J., Crutzen, P. and McNeill, J. (2011). The Anthropocene: conceptual and historical perspectives. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 369(1938), 842-867. https://www.doi.org/10.1098/rsta.2010.0327

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M. et al. (2015). Planetary boundaries: Guiding human development on a changing planet. Science 347(6223), 1259855. https://www.doi.org/10.1126/science.1259855

Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D. et al. (2018). Trajectories of the Earth System in the Anthropocene. Proc Natl Acad Sci U S A 115(33), 8252-8259. https://www.doi.org/10.1073/pnas.1810141115

Tan, J., Duan, Q., Xiao, C., He, C. and Yan, X. (2023). A brief review of the coupled human-Earth system modeling: Current state and challenges.

The Anthropocene Review, 20530196221149121. https://www.doi.org/10.1177/20530196221149121

Tscherning, K., Helming, K., Krippner, B., Sieber, S. and Paloma, S.G.Y. (2012). Does research applying the DPSIR framework support decision making? Land Use Policy 29(1), 102-110. https://doi.org/10.1016/j.landusepol.2011.05.009

United Nations (2015). Transforming our world. The 2030 Agenda for Sustainable Development. New York, NY. https://sdgs.un.org/sites/default/files/publications/21252030per cent20Agendaper cent20forper cent20Sustainableper cent20Developmentper cent20web.pdf

United Nations (2022). The human right to a clean, healthy and sustainable environment. Resolution 76/300. New York (NY). https://documents-dds-ny.un.org/doc/UNDOC/GEN/N22/442/77/PDF/N2244277.pdf?OpenElement

United Nations Convention to Combat Desertification (2022). The Global Land Outlook, 2nd edition. Bonn. https://www.unccd.int/sites/default/files/2022-04/UNCCD_GLO2_low-res_2.pdf

United Nations Development Programme (2020). Human Development Report 2020. The Next Frontier: Human Development and the Anthropocene. New York (NY). https://hdr.undp.org/content/human-development-report-2020

United Nations Development Programme (2022). Environmental Justice: Securing Our Right to a Clean, Healthy and Sustainable Environment. New York: United Nations Development Programme. https://www.undp.org/publications/environmental-justice-securing-our-right-clean-healthy-and-sustainable-environment

United Nations Educational, Scientific and Cultural Organization (2024): The United Nations World Water Development Report 2024: Water for Prosperity and Peace. Paris: United Nations Educational, Scientific and Cultural Organisation. https://www.unwater.org/publications/un-world-water-development-report-2024

United Nations Environment Programme (1995). Proceedings of the Governing Council at its 18th session: Governing Council of the United Nations Environment Programme. Nairobi. https://digitallibrary.un.org/record/204256

United Nations Environment Programme (2017). Towards a pollution-free planet: background report. Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/21800/UNEA_towardspollution_longper cent20version_Web.pdf?sequence=1&isAllowed=y

United Nations Environment Programme (2019a). Global Environment Outlook, 6th edition (GEO-6). Healthy planet, Healthy people. Nairobi https://www.doi.org/10.1017/9781108627146

United Nations Environment Programme (2019b). Global Chemicals Outlook II. From legacies to innovative solutions: Implementing the 2030 Agenda for Sustainable Development – Synthesis Report. Nairobi. https://www.unep.org/resources/report/global-chemicals-outlook-ii-legacies-innovative-solutions

United Nations Environment Programme (2021). Making Peace with Nature: A scientific blueprint to tackle the climate, biodiversity and pollution emergencies. Nairobi: United Nations Environment Programme. https://www.unep.org/resources/making-peace-nature

United Nations Environment Programme (2023a) Environmental Effects of Stratospheric Ozone Depletion, UV Radiation, and Interactions with Climate Change 2022 Assessment Report. Nairobi. https://ozone.unep.org/system/files/documents/EEAP-2022-Assessment-Report-May2023.pdf

United Nations Environment Programme (2023b) Global Framework on Chemicals - For a Planet Free of Harm from Chemicals and Waste. https://www.chemicalsframework.org/page/text-global-framework-chemicals

United Nations Environment Programme (2024b). Food Waste Index Report. Nairobi. https://www.unep.org/resources/publication/food-waste-index-report-2024

United Nations Environment Programme (2024c) Global Waste Management Outlook 2024: Beyond an age of waste – Turning rubbish into a resource. Nairobi. https://doi.org/10.59117/20.500.11822/44939

United Nations Environment Programme (2024d) Global Resources Outlook 2024: Bend the Trend – Pathways to a liveable planet as resource use spikes. International Resource Panel. Nairobi. https://wedocs.unep.org/20.500.11822/44901

United Nations Environment Programme and International Science Council (2024). Navigating New Horizons: A global foresight report on planetary health and human wellbeing. United Nations Environment Programme. https://wedocs.unep.org/xmlui/handle/20.500.11822/45890

United Nations Office of Legal Affairs (2021). The Second World Ocean Assessment. United Nations. https://www.un-ilibrary.org/content/books/9789216040062

Visseren-Hamakers, I.J., Razzaque, J., McElwee, P., Turnhout, E., Kelemen, E., Rusch, G.M. et al. (2021). Transformative governance of biodiversity: insights for sustainable development. Current Opinion in Environmental Sustainability 53, 20-28. https://doi.org/10.1016/j.cosust.2021.06.002

Wetlands International (2022). We need wetlands. The urgent case for global wetland targets. Ede, the Netherlands. https://www.wetlands.org/publication/we-need-wetlands-the-urgent-case-for-global-wetland-targets/

Wilkinson, J.L., Boxall, A.B.A., Kolpin, D.W., Leung, K.M.Y., Lai, R.W.S., Galbán-Malagón, C. et al. (2022). Pharmaceutical pollution of the world's rivers. Proceedings of the National Academy of Sciences 119(8), e2113947119. https://www.doi.org/10.1073/pnas.2113947119

World Bank (2024). Global Economic Prospects. Washington, D.C.: World Bank. http://documents.worldbank.org/curated/en/099003106112426991/IDU1bc56b5c41f04914acb194181b46ce62466fe

World Economic Forum (2023). The Global Risks Report 2023, 18th edition. Insight Report. Cologny/Geneva. https://www3.weforum.org/docs/WEF_Global_Risks_Report_2023.pdf

World Meteorological Organisation (2023a). United in science 2023. Geneva. https://library.wmo.int/records/item/68235-united-in-science-2023

World Meteorological Organisation (2023b). Provisional State of the Global Climate 2023. Geneva: World Meteorological Organisation. https://wmo.int/sites/default/files/2023-11/WMOper cent20Provisionalper cent20Stateper cent20ofper cent20theper cent20Globalper cent20Climateper cent202023.pdf

World Resources Institute (2019). Creating a sustainable food future. A menu of solutions to feed nearly 10 billion people by 2020. Washington, D.C. https://www.wri.org/research/creating-sustainable-food-future

World Wildlife Fund for Nature (2022). Living Planet Report 2022 – Building a nature-positive society. Gland, Switzerland. https://wwfint.awsassets.panda.org/downloads/embargo_13_10_2022_lpr_2022_full_report_single_page_1.pdf

02 Historical, Current, and Projected Drivers and Pressures of Environmental Change

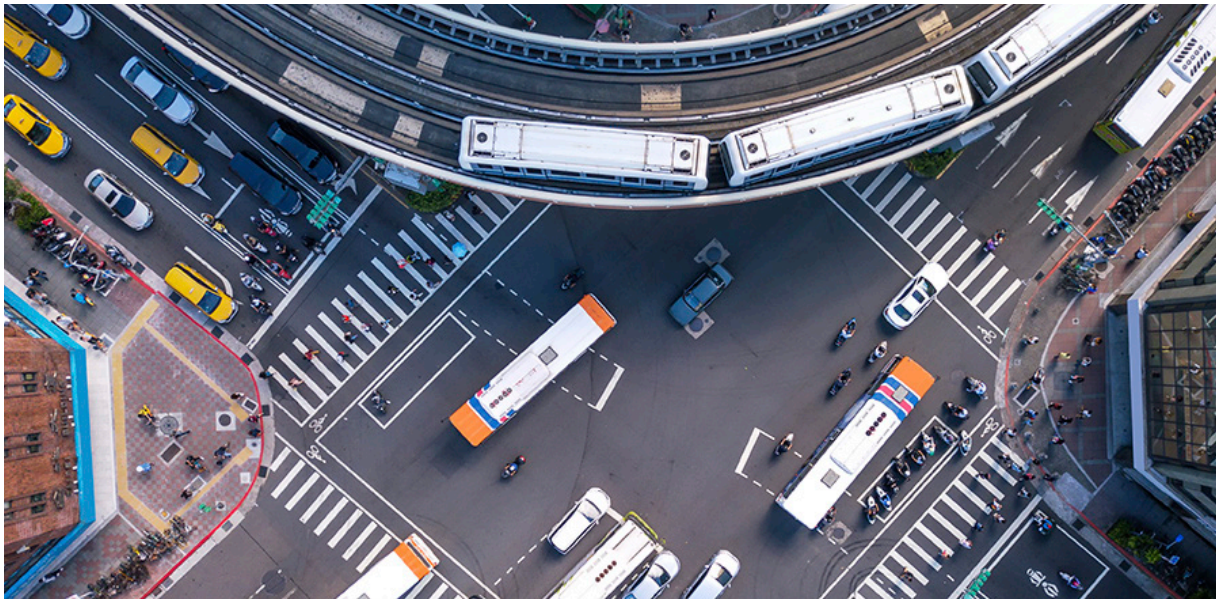
Coordinating Lead Authors: Jacob Park (University of Johannesburg/Vermont State University)

Lead Authors: Susana Beatriz Adamo (CIESIN-Columbia Climate School-Columbia University), Quosay Awad Ahmed (University of Khartoum), Ricardo O. Barra (University of Concepcion), Jonathan Davies (University of British Columbia), Jagath Premakumara Dickella Gamaralalage (Institute for Global Environmental Strategies), Rozana Himaz (University College London), Miho Kamei (Institute for Global Environmental Strategies), Jinlong Liu (Renmin University of China), David Lopez-Carr (University of California), Indu K Murthy (Center for Study of Science, Technology and Policy), Evans Osabuohien (Covenant University/DePECOS Institutions and Development Research Centre-DIaDeRC), Adina Manuela Relicovschi (European Investment Bank), Chao Ren (The University of Hong Kong), Roopesh Kevin Sungkur (University of Mauritius), Thomas F. Thornton (University of Alaska), Chiara Varazzani (Organisation for Economic Cooperation and Development), Samanta Villegas (Jocotoco Conservation Foundation), Le Yu (Tsinghua University)

Fellows: Raphael Villela Almeida (Institute for Applied Economic Research, IPEA), Astride Messaga Maffo (Institut de Formation et de Recherche Demographiques, IFORD)

Credit: south_nostalgia/Envato

Chapter summary



Credit: tampatra/Envato

A growing economy, increasing population and changing lifestyles are driving the demand for goods and services, such as materials, energy, and food. However, the current systems for producing and consuming these resources are unsustainable. They are shaped by poor governance structures and policies, particularly in the areas of economics and finance, as well as behaviours and technologies that promote land-use change, resource exploitation, greenhouse gas emissions, pollution, and the spread of invasive alien species. These pressures contribute to the interconnected global environmental crises of climate change, biodiversity loss, land degradation and desertification and pollution and waste. Addressing these challenges and achieving internationally agreed goals requires a deep understanding of how these drivers interact and how to transform the economic and financial, material resources, energy and food systems to manage their environmental consequences effectively.

Drivers of change

The global human population grew from 3 billion in 1960 to 8 billion people in 2022, and is projected to reach 9.7 (10.1 – 9.3) billion people by 2050 and 10.2 (9.3 – 11.1) billion people by 2100 (*well established*). Rising per capita wealth, combined with population growth and prevailing patterns of production and consumption, is likely to generate demand for goods and services that exceeds the planet's capacity to safeguard the global environment's vitality and to support sustainable and equitable human development. However, levels and forms of consumption vary widely across and within countries, depending on factors such as the level of development and income {2.2.1}.

Global population growth rate was 0.9 per cent in 2022 and is projected to decline to 0.42 per cent (0.32-0.52 per cent) by 2050 (*well established*). Many countries anticipate declining populations in the coming decades, creating opportunities for a natural and social "depopulation dividend". A further decrease in the UN projected medium fertility rate could reduce the global population in 2100 from 10.2 billion to 7 billion (United Nations 2022). Ensuring universal access to education and healthcare, particularly by advancing girls' and women's education and empowerment, as well as reducing natural resource consumption, is essential for protecting environmental sustainability for future generations {2.2.1}.

Global gross domestic product increased from US$9.14 trillion in 1960 to US$93.35 trillion in 2023 (adjusted to 2015 US dollars), and is expected to more than double

by 2050, with the fastest growth occurring in emerging economies (*well established*). Per capita gross domestic product has increased fourfold since 1960 and is expected to double again by 2050 (*well established*). There is an urgent need to reform economic policies to address current and future global environmental crises and to introduce new measures for human development in economic decision-making. The significant disparities in economic progress across regions highlight the importance of incorporating social equity and environmental factors into development strategies that better balance economic growth with environmental sustainability (*established but incomplete*) {2.2.2}.

Understanding how lifestyles impact environmental issues is crucial for promoting effective environmental action (*well established*). Since 1960, per capita consumption has quadrupled, and by 2023, advanced economies are consuming 70 per cent more than the global average. This growth is partly driven by a shift toward more resource-intensive lifestyles, fuelled by increasing per capita incomes (*well established*). By adopting demand-side strategies in key sectors such as buildings, transportation, and food, it is possible to achieve a substantial reduction in global greenhouse gas emissions, ranging from 40 per cent to 70 per cent by 2050 (*well established*). Complementing these strategies, initiatives that incorporate core values of caring for nature, Indigenous Knowledge, and Local Knowledge that protect the environment, along with leveraging sociocultural drivers, building trust, and shaping social norms, offer avenues to foster sustainable behaviours, mitigate climate change, and lay the groundwork for a more sustainable future for generations to come (*well established*) {2.2.5; 10.3; 12.2; 12.3}.

Governance and environmental quality are directly and indirectly interlinked, and the lack of a clear alignment between governance structures and environmental goals often contributes to or exacerbates environmental degradation (*well established*). Weak implementation of general governance practices that contribute to environmental degradation includes issues such as corruption control, governmental effectiveness, transparency, and accountability measures. Improving policymaking and enforcement is essential and requires urgent action to address the limited access to reliable and comprehensive information, low public awareness, and the need for more inclusive public engagement. Additionally, there is a deficiency in sustainability-related disclosures and reporting in both the public and private sectors (*well established*). Since whole-of-government and whole-of- society approaches are necessary to achieve agreed environmental and social goals, national cross-government coordination will be crucial for developing and implementing the required policies, along with international coordination {2.2.6}.

Supply chains for clean energy technologies are becoming more susceptible to issues related to the acquisition and distribution of critical minerals. This vulnerability leads to land degradation, harm to biodiversity, and increased climate-related conflicts, such as water stress for local communities, resulting from competition for global resources (*virtually certain*). Key clean energy technologies such as solar PV, wind, electric vehicles, batteries, electrolysers, and heat pumps are expanding rapidly. They are expected to drive the fastest growth in global electricity demand (*well established*) {2.2.3}.

Digital transformation can support the efficient distribution of resources, balance supply and demand, and drive the development of innovative city solutions. These efforts can positively impact the achievement of the SDGs and promote social inclusion (*well established*). However, these advances, especially in artificial intelligence, are occurring much more rapidly than traditional regulatory and legislative processes, which can also increase social risks and ethical challenges. Their lifecycle environmental impacts, for example, are uncertain, with energy and water demands expected to rise globally (*virtually certain*) {2.2.3}.

Urbanization is rapidly expanding worldwide, with 55 per cent of people now residing in urban areas. By 2030, this number is expected to increase to 60 per cent, and by 2050, 68 per cent of the global population is projected to live in cities (*well established*). Developing countries, especially in Asia and Africa, are undergoing significant growth (*well established*). Urbanization can foster economic opportunities while also bringing significant economic, social, and environmental pressures (*well established*). Urbanization has the potential to reduce per capita environmental impact through economies of scale, but so far, it has typically increased resource use due to residents' higher incomes and demand for goods and services (*well established*) {2.2.4}.

The number of natural event-driven shocks threatening over 10,000 people – through death, injury, or homelessness – has more than tripled in the past 40 years *(well established)*. They accounted for half of all

Credit: Shaiith/Envato

shocks in 1980, increasing to two-thirds by 2022. The effects of shocks on the environment, exacerbated by climate change, have led to widespread and irreversible damage in terrestrial, freshwater, cryospheric, and coastal and open-ocean ecosystems (*well established*) {2.2.7}.

Pressures that affect the global environment

Land-use changes mainly involve shifts between cropland and forest, accounting for about 30 per cent of all observed transitions. From 2000 to 2020, cropland area expanded slightly worldwide, mostly due to growth in Sub-Saharan Africa, Southeast Asia, and parts of Latin America. Meanwhile, North America, Europe, and Eastern Asia saw decreases in cropland (*established but incomplete*). However, the expansion of cropland and plantations has sometimes led to deforestation in certain areas, impeding biodiversity, ecosystem services, Indigenous Peoples' livelihoods, and carbon storage. While global forest areas have decreased, some progress has been made in reducing deforestation in specific regions. However, some policies aimed at mitigating deforestation have resulted in human rights and Indigenous Peoples' rights violations, underscoring the need for a more inclusive evaluation (*well established*) {2.3.1}.

Indigenous Peoples' traditional lands sustain much of the world's biological and cultural diversity, but are facing increasing pressure (*well established*). Indigenous Knowledge and Local Knowledge systems support numerous adaptations, interspecific relationships, and stewardship practices that enhance environmental productivity, species abundance, distribution, richness, ecosystem functioning, and social-ecological resilience (*well established*). Indigenous populations and their unique connections to their environments are threatened by global environmental change drivers and pressures. Efforts by Indigenous communities to defend their lands and waters are frequently met with penalties, intimidation, and violence. To counter these dangers, it is urgent to protect and clearly define Indigenous lands and uphold Indigenous Peoples' rights over those territories (*well established*) {2.2.1, 2.2, 2 2.2.3}.

The excessive and unsustainable use of both finite and renewable natural resources—such as fisheries, mineral deposits, and fossil fuel reserves—puts pressure on environmental systems (*well established*). Overfishing, habitat destruction, and illegal wildlife trade are accelerating biodiversity loss at unprecedented levels. The growing demand for rare earth elements and minerals, driven by urban growth and technological advancements, depletes finite reserves while causing

Credit: pilens/Envato

ecological damage and raising ethical concerns. Wood harvesting contributes to deforestation and emissions, despite efforts to promote sustainability. Overuse of freshwater, pollution, and poor management drain vital supplies {2.3.2}.

Global anthropogenic emissions of greenhouse gases – primarily carbon dioxide, methane, and nitrous oxide – reached a record high in 2023 of nearly 60 gigatons of CO_2 equivalent, driving unprecedented climate change. Of all sectors, 79 per cent of emissions originated from energy, industrial processes, transport, and buildings collectively, while 22 per cent came from agriculture, forestry, and land-use change. The pace of greenhouse gas emissions was moderated due to the increased adoption of renewable energy sources, such as solar and wind (International Energy Agency (IEA), 2023a). Although emissions from deforestation stayed high, efforts in afforestation and reforestation helped create a carbon sink, partially offsetting these emissions (*well established*) {2.3.3.1}.

The number of chemicals released into the environment, including plastics, has grown over time, with an estimated 350,000 chemicals available globally (Wang et al. 2020), and new threats arise, such as the forever chemicals (poly and perfluorinated chemicals) (*well established*). While some countries have strict regulations for new chemicals, many do not, which limits our ability to anticipate or currently measure adverse environmental and human health effects of these new chemicals on a global scale. Capabilities for improving our chemical risk assessments are being continuously developed, although they are not yet fully established {2.3.3.2}.

Invasive alien species are non-native plants and animals that are introduced outside their natural habitat and cause damage to ecosystems, human health, or the economy. The spread and introduction of these alien species are accelerating, driven by global trade and increased connectivity between regions and ecosystems (*well established*). Over 3,500 alien species with harmful impacts have been documented. Invasive alien species (IAS) have multiple adverse effects: they can spread diseases, outcompete native species, and decrease ecosystem function, especially in freshwater and island ecosystems (*well established*). Indigenous Peoples as well as local communities can view IAS as part of the landscape (*established but incomplete*) and have rights to self-determination in their management. Some IAS have positive impacts on quality of life, but most impacts are negative (*established but incomplete*) {2.3.4}.

2.1 Introduction

This chapter examines the historical, current, and future drivers, exploring how they interact and how they have influenced the demand for resources such as food, energy, and water. This demand, in turn, has caused ongoing pressures on the global environment. With a particular focus on solutions, this assessment draws on a comprehensive review of the IPCC, IPBES, IRP, GSDR, and previous GEO reports, as well as the Driver-Pressure-State-Impact-Response (DPSIR) Framework.

The DPSIR framework is an evolving conceptual and causal model. Alternative models of human-environment interactions exist, especially among the world's Indigenous Peoples. Indigenous models typically reject the human-environment and culture-nature dichotomies, instead viewing people as part of Earth Systems alongside other-than-human beings and forces. This relational approach often relies on respectful and reciprocal relationships between humans and the environment, aiming to maintain balance and sustainability. The DPSIR framework also rests on the idea that ecosystems and climate conditions have remained relatively stable over the past 11,700 years, allowing for the development of agriculture, cities, and modern societies. This assumption can shape how change and sustainability are understood in scientific frameworks.

In contrast, in the context of Indigenous systems, sustainability stems from Indigenous histories of influencing and adapting – or not – to environmental changes over extended periods in specific landscapes. In this grounded context, the abstract language of "systems" and "drivers" may not fully capture the lived experience or ways of understanding change (Gupta et al. 2020).

Indigenous perspectives on the current global environmental crises were highlighted through several dialogues convened with Indigenous Peoples for the GEO-7. Key causes behind environmental changes and their consequences, as observed within communities across major continents, include industrial development and pollution, degradation or displacement of local habitats and species, disruption of Indigenous relationships and practices that maintain ecosystem balance, and an increase in extreme events such as flooding that threaten local populations. Indigenous participants emphasized that these root causes of the global environmental crises must be addressed through education, policy, and practice by including Indigenous cultural and spiritual voices, values, and ways of knowing and sustaining the diversity and quality of life on Earth as part of living well (IK & LK Dialogues 2025).

This chapter will describe the GEO-7 conceptual and methodological approach and highlight the likely relevance of GEO findings for other multilateral environmental agreements and processes. The chapter also examines the historical, current, and projected drivers and pressures of global environmental change, including the core assessment of human-environment interactions. It expands on the Driver-Pressure-State-Impact-Response (DPSIR) framework (see 1.2.1) and explores the interconnections between the drivers, pressures, and the "global environmental crises" **(Figure 2.1)** as defined by GEO-7. Formally, the global environmental crises are the crisis of climate change, the crisis of biodiversity loss, land degradation and desertification, and the crisis of pollution and waste. This chapter will treat land degradation with particular emphasis, as it represents intersections of the crises by featuring different facets.

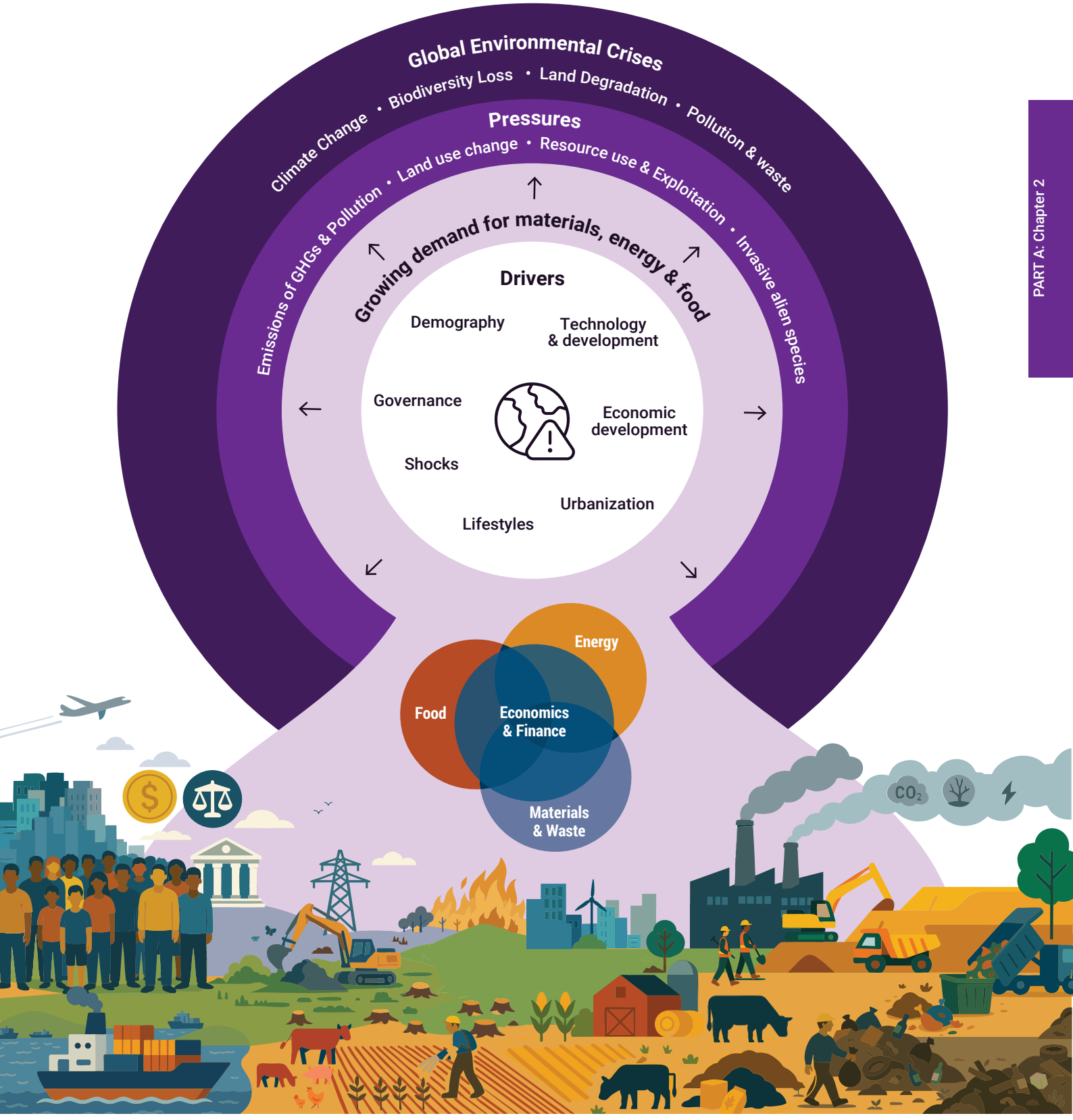
The key elements of Chapter 2 include drivers (2.2), such as population and demographics, economic development, technology and development, urbanization, lifestyles, governance, and shocks, as well as pressures (2.3), including land-use change, resource use and exploitation, emissions such as greenhouse gases and other pollutants, and invasive alien species. It also covers the interlinkages among drivers, pressures, and environmental crises (2.4). **Figure 2.1** visually illustrates these critical nexuses and interconnections among drivers, pressures, systems, and global environmental crises described in this report.

2.2 Drivers of change

2.2.1 Demography

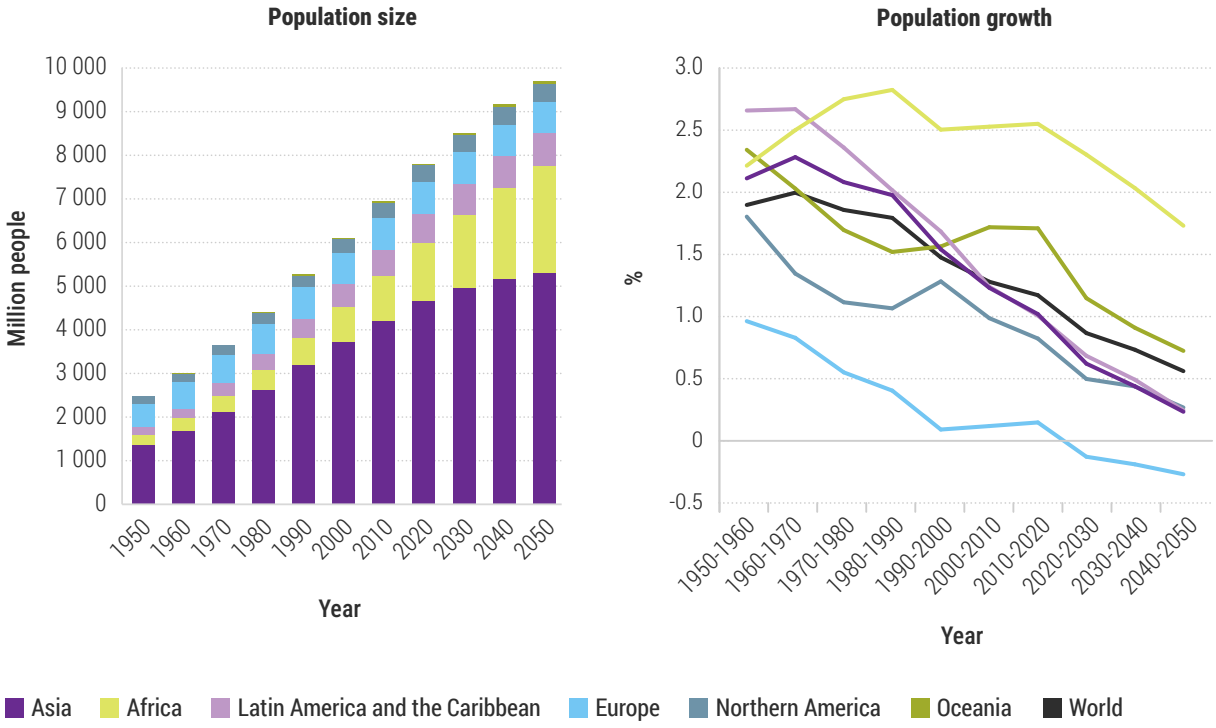
On November 15, 2022, the world population reached 8 billion people (United Nations Population Fund 2022). **Figure 2.2** illustrates how the global population has changed from 1950 to 2020, its projection to 2050, and the regional variations. The figure also shows the historical and projected growth rates for the global and regional populations during the same period (United Nations 2022). Despite the general decline in growth rates, the world population will continue to grow because

Figure 2.1: Transforming key human systems is essential to address the global environmental crises



Note: the figure shows that the ensemble of drivers results in an ever-increasing demand for materials, energy and food, which is being met using environmentally unsustainable production and consumption systems, embedded in economic, financing and governance systems which themselves are unsustainable. This results in ever-increasing pressures of emissions of greenhouse gases and pollutants, land-use change, resource use and exploitation, and invasive alien species, which in turn are the underlying causes of the global environmental crises. Therefore, addressing the global environmental crises requires transforming the dominant economics/finance, materials/waste, energy and food systems.

Figure 2.2: Past and future trends in global and regional population size and growth, 1950-2050



Source: United Nations (2022a)

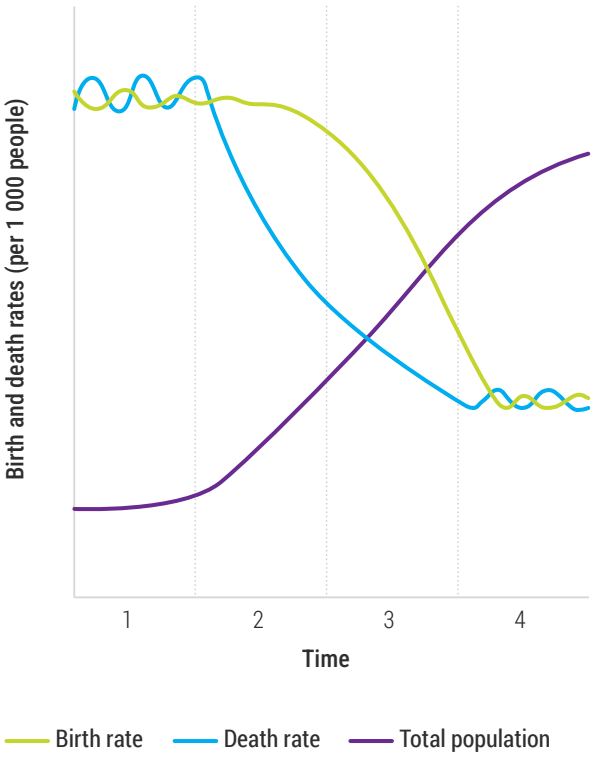
the age structure includes a high proportion of people of reproductive age. This phenomenon is known as "population momentum" (Guo et al. 2020). This trend is true for all regions except Europe.

Globally, there are approximately 476 million Indigenous Peoples. While they make up only 6 per cent of the world's population, they represent about 19 per cent of people living in extreme poverty (International Labour Organization [ILO] 2019, p. 20).

Births and deaths for the global population, as well as migration for regional, national, and local populations, each contribute differently to population growth (Deuster et al. 2023). This results in varying demographic trends across regions. The demographic transition theory (**Figure 2.3**) categorizes these contributions into stages that form a timeline. This framework has been used to describe population changes worldwide and within specific countries and regions (Regional division from the United Nations: Africa, Asia, Europe, Latin America and the Caribbean, North America, Oceania).

In summary, the demographic transition involves a shift from high fertility and mortality rates to low fertility and mortality rates (Delventhal, Fernández-

Figure 2.3: Stages of the demographic transition and the interplay of birth, deaths and total population



Source: Chorley (2015)

Villaverde, and Guner, 2021). The "demographic transition theory" describes how mortality, fertility, and growth rates change as societies transition between different demographic regimes. Initially introduced by American demographer Frank W. Notestein in the mid-20th century, this theory has been further developed by many scholars (United Nations Populations Fund 2019). In stage one, both birth and death rates are high, leading to slow population growth. During stage 2, death rates fall while birth rates stay high, causing rapid population growth. As birth rates begin to decline in stage 3, the growth rate slows. This pattern continues into stage 4, where both birth and growth rates are low, resulting in slow population growth again (Sloggett 2015; UNFPA 2019).

Trends for selected demographic indicators for the 2020-2050 period are presented in **Figure 2.4**. These numbers show the current state to 2020 and illustrate how populations in different regions are expected to change by 2050.

Regional or local differences in demographic trends and population growth result in the concentration of population in certain areas, such as cities and coastal regions. Expected changes in the spatial distribution of the world population between 2015 and 2030 are displayed in **Figure 2.5** using population densities. Larger declines are spread over extensive areas, while larger increases are concentrated in a reduced number of areas, notably on the coasts, Sub-Saharan Africa, and South and South-East Asia.

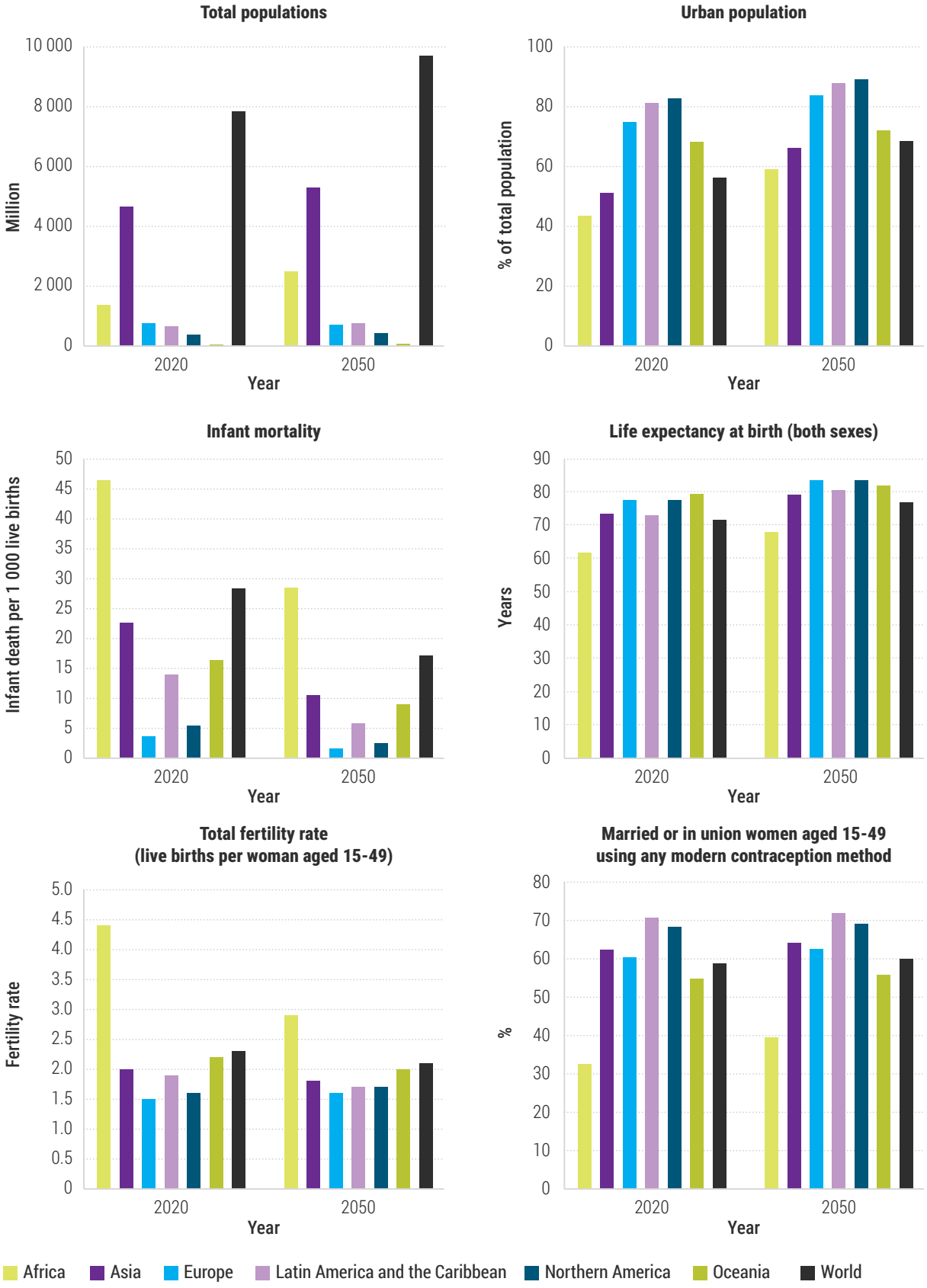
In summary, major demographic trends such as population growth and decline, population ageing, urbanization, and international migration shape our world. These trends are significant because population size, distribution, and composition, as well as demographic processes of fertility, mortality, and migration, are closely connected to the level and type of effects on natural resources and the environment (United Nations 2015; Khan et al. 2021; Wang, Wang and Li 2022). Changes in the size, age structure, and spatial distribution of populations present both challenges and opportunities. By effectively managing these challenges and leveraging the opportunities, we can accelerate progress towards inclusive and sustainable development, create pathways to eradicate poverty, improve access to social protection, healthcare, and education, promote gender equality, advance more sustainable production and consumption patterns, and safeguard the environment.

Direct effects of demographic trends include agricultural activities and commodities, waste and pollution, and overall consumption patterns of food, water, energy, and other resources. Indirect impacts include, for example, the contribution of corporate agriculture to greenhouse gas (GHG) emissions causing climate change. However, it is crucial to recognize that levels and forms of consumption, such as conspicuous consumption in high-income countries or groups versus meeting basic needs in low-income countries or groups, differ widely by region and country, and within them, and are linked to development level and income (Oswald, Owen and Steinberger 2020).

While the fertility-mortality balance determines global population growth and size, impacts on natural resources can also arise from migration and other forms of population mobility. Rural-rural migration directly affects natural resources negatively by clearing land for agriculture. Rural-urban migration, both domestic and international, directly affects resources through urbanization and urban expansion as land-use change, especially in early stages of urbanization when migration to cities usually increases. Finally, international migration has an indirect effect, either positive or negative, through remittances, which can be used for development or to increase and diversify consumption (Caulfield et al. 2019; Radel et al. 2019).

Among the major global environmental crises – climate change, biodiversity loss and land degradation, and pollution and waste – population growth is most evidently a key factor in biodiversity decline. This is largely due to increased demand for food production, which leads to agricultural expansion and land degradation (Cafaro, Hansson and Götmark 2022). As the population grows and consumption rises, fewer resources and less habitat are available for non-human species (Crist 2019). Overpopulation occurs when the total human population multiplied by per capita consumption surpasses the capacity of sustainable ecosystems and resources. Although the global human population continues to grow, per capita consumption is increasing at a faster rate. To the extent that people are disrupting natural habitats and degrading ecosystem services for future generations, despite regional heterogeneity, some research suggests that most of the world's nations may be considered overpopulated (Lianos and Pseiridis 2016; Tucker 2019).

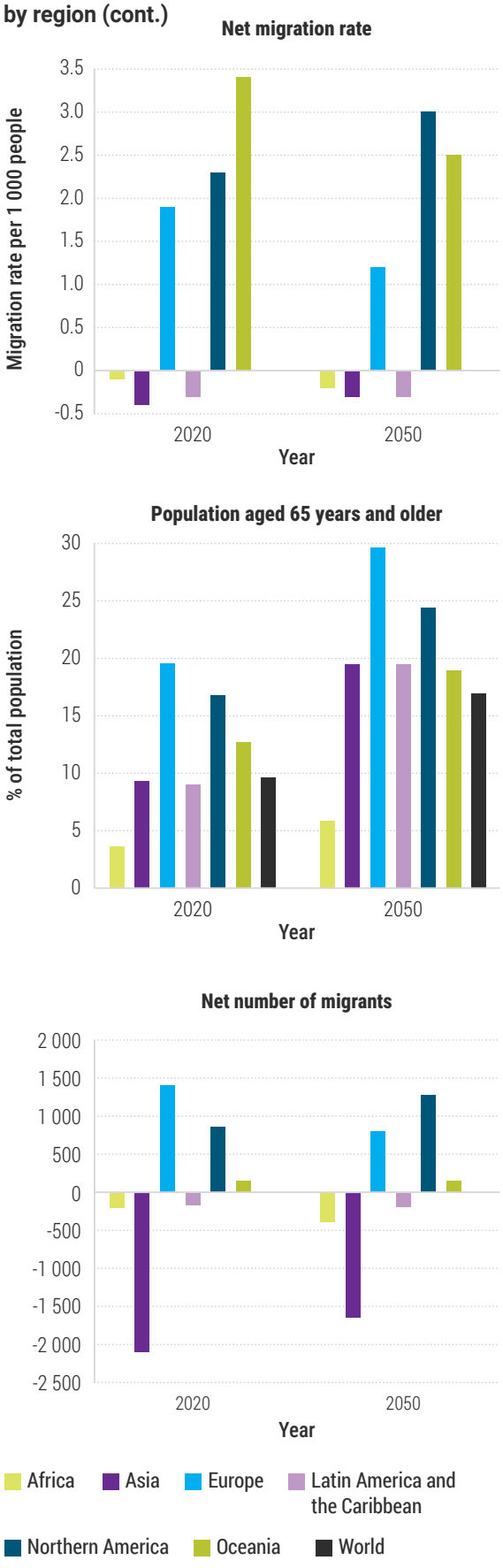
Figure 2.4: Trends in selected key demographic indicators in 2020 (estimated) and 2050 (projected) by region



Note: The estimates for 2020 and projections to 2050 use medium fertility variant

Source: United Nations (2018; 2022a; 2022b)

Figure 2.4: Trends in selected key demographic indicators in 2020 (estimated) and 2050 (projected) by region (cont.)



Source: United Nations (2018; 2022a; 2022b)

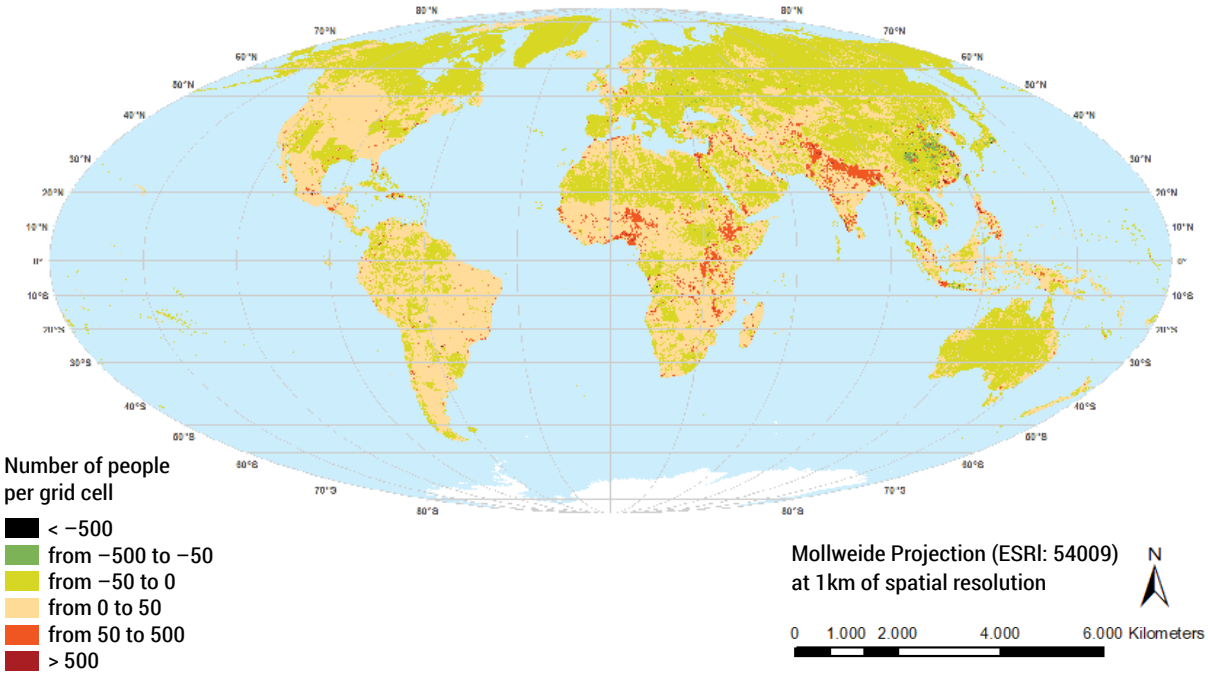
The Global Assessment Report on Biodiversity and Ecosystem Services finds that agricultural expansion is the primary driver of land-based biodiversity loss, while overfishing is the leading cause of marine biodiversity declines (IPBES 2019). Both are worsened by an increasing human population through higher consumption and production. Rising rural populations lead to the conversion of wildlands into farmland, particularly among small farm households (Lopez-Carr and Burgdorfer 2013), while growing urban populations increase demand for animal protein, which is increasingly produced by large export farms (Marques et al. 2019). Although just under one-third of the Earth's land remains forested, population growth and higher consumption are reducing this area, with an estimated 10 million hectares cleared annually between 2015 and2020, or about 0.25 per cent of the total land area each year (Food and Agriculture Organization of the United Nations [FAO] 2022).

Population dynamics not only affect the environment but are also sensitive to environmental changes. For example, climate extremes increase population displacement in vulnerable regions, especially in Africa and Asia (Intergovernmental Panel on Climate Change [IPCC] 2023). Heat exposures are mainly caused by a combination of higher temperatures and population growth. Likewise, nearly half the global population faces water scarcity due to climate and non-climate factors, a proportion expected to rise because of climate change (Koutroulis et al. 2019; Seneviratne et al. 2021).

Although declining populations may present short-term economic difficulties, the current global population greatly exceeds levels compatible with maintaining biodiversity and ensuring sustainable human well-being, especially considering recent consumption patterns (O'Neill et al. 2018; Rees 2020). Some studies suggest that Earth could support a larger population, but recent research indicates that a sustainable world, even with improved consumption and production, should not surpass two to three billion people (Lianos and Pseiridis 2016; Dasgupta et al. 2019; Tucker 2019; Tamburino and Bravo 2021). However, UN projections (2019b) show that reducing fertility by half a child below the most likely UN medium variant rate would decrease the global population in 2100 by over 3.2 billion, from 10.2 billion to about 7 billion in the low-fertility scenario (United Nations 2022).

Further research is necessary to understand the links between population dynamics and biodiversity loss to

Figure 2.5: Projected changes in population density between 2015 and 2030



Note: The raster map depicts projected changes in population density between 2015 and 2030. Population density is defined as the number of people per square kilometre, which in this case is the size of the grid cell or pixel. Greenish shades indicate areas where population density is expected to decline, while reddish shades indicate areas where population density is expected to increase.

Data source: European Commission (2024)

determine how many people the world's countries can support while maintaining viable wildlife populations (Rust and Kehoe 2017). Nonetheless, many countries, especially those with higher consumption rates, anticipate declining populations in the coming decades, creating opportunities for wildland restoration – a natural and social "depopulation dividend" – provided that unsustainable consumption does not increase simultaneously (Matanle 2017).

Countries that promote the multiple health and economic benefits of smaller family sizes have been effective in reducing populations, whereas countries that have failed to implement such programmes continue to experience high population growth (Wyman and Yao 2017; Turner 2021). Universal access to modern contraception offers a potential win-win situation for women's empowerment and the environment (Cottingham, Germain and Hunt 2012; Engelman and Johnson 2019). Smaller family sizes can be encouraged through tax and benefits policies, as well as media outreach (Hornik and McAnany 2001; La Ferrara, Chong and Duryea 2012; Ryerson 2012; Cafaro 2021).

Such efforts are a moral duty that also yield environmental benefits for both nature and people. They can coexist with environmental conservation efforts. In fact, population-environment-health synergies have demonstrated how improving human health and livelihoods can align with protecting biodiversity (Lopez-Carr and Ervin 2017). In high-income countries, where populations are slowing or declining but per capita consumption remains high, reducing the use of natural resources – especially fossil fuels and animal protein – would significantly support environmental sustainability. Later chapters will explore other key environmental challenges and explore policies that can promote human well-being while preserving the resources and ecosystem services vital to everyone.

2.2.2 Economic Development

Economic development is a fundamental driver of environmental change. Key measures of economic development include gross domestic product (GDP) per capita, the Human Development Index (HDI), and growth in productivity, trade, labour force, and investment (World Bank 2023a). These measures align closely with projections from shared socioeconomic pathways, which consider factors such as physical and human capital, employment, energy demand, natural resources, and total factor productivity (Dellink et al. 2017). Shared socioeconomic pathway factors influence productivity growth and investment,

while the labour force, population (2.2.1), and technology development (2.2.3) also play important roles in economic development.

Trend in Economic Development by per capita GDP over the past six decades

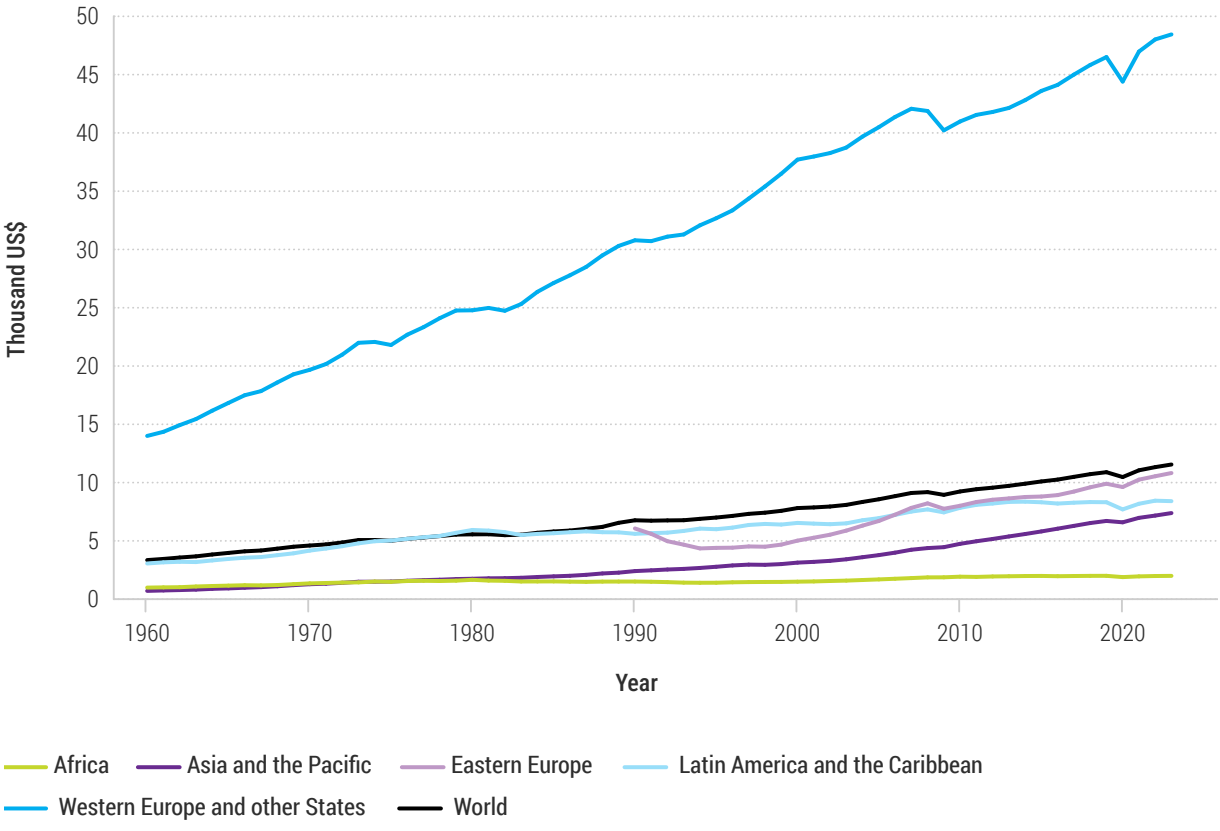
Global GDP increased by over 7,000 per cent between 1960 and 2024 (Systems Change Lab 2025). Although this growth has led to positive societal gains, it has also been linked to significant social and environmental impacts, including two major downturns: the 2007-2008 global financial crisis and the 2020 COVID-19 pandemic (**Figure 2.6**). The data in **Figure 2.6** shows a generally steady trend in economic development, as measured by GDP per capita. However, substantial disparities persist across different regions. The African states have shown the least marginal improvement, followed by Asia and the Pacific states, which experienced noticeable growth starting in the late 1980s and early 1990s, which continued to widen through the 2000s. The Eastern European states and Western Europe and other states experienced similar patterns.

Trend in Economic Development as trade over the last six decades

The international trade trends shown in **Figure 2.7** from 1960 to 2023 reveal variations across various regions of the world. The importance of trade as a key element of economic development is well established in the literature. This is particularly important because it aligns with international logistics, different modes of international travel, and the global value chain, which all exert a driving force on economic activities, energy use, and the environment over the medium and long term (Akinyemi et al. 2019; Efogo, Wonyra and Osabuohien 2022). To avoid cluttering the analysis with multiple graphs, total trade – defined as the sum of exports and imports relative to GDP, and serving as a broad measure of trade openness – is plotted acro various economic group. This indicator is crucial as it reflects the comparative openness of an economy.

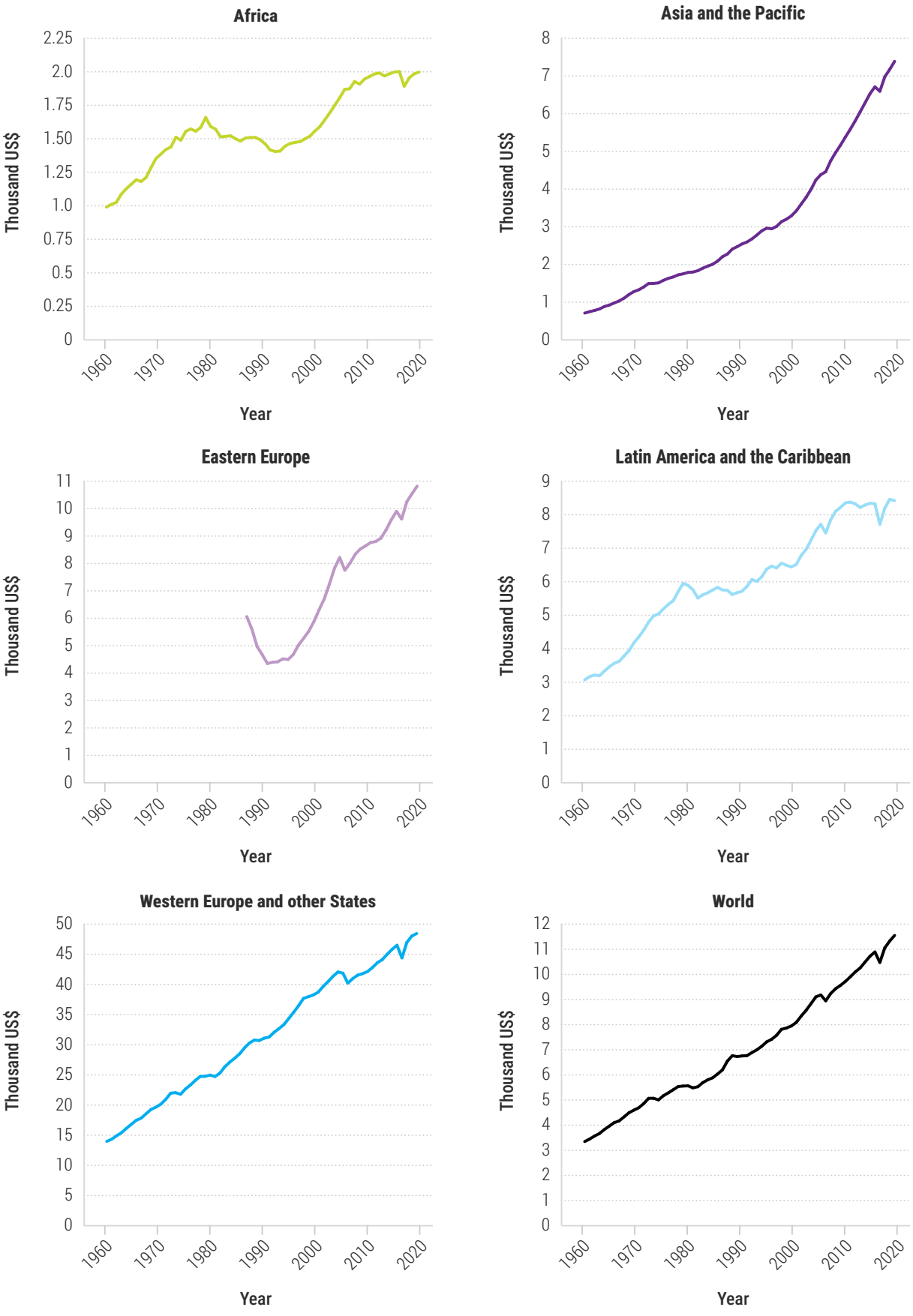
From the early years of the graphs (1960s to 1980s), it is clear that African States generally appear more open to trade than others. However, starting around 1990, when

Figure 2.6: Trends of per capita GDP (constant 2015 thousand US$) in the world and UN regions from 1960 to 2023



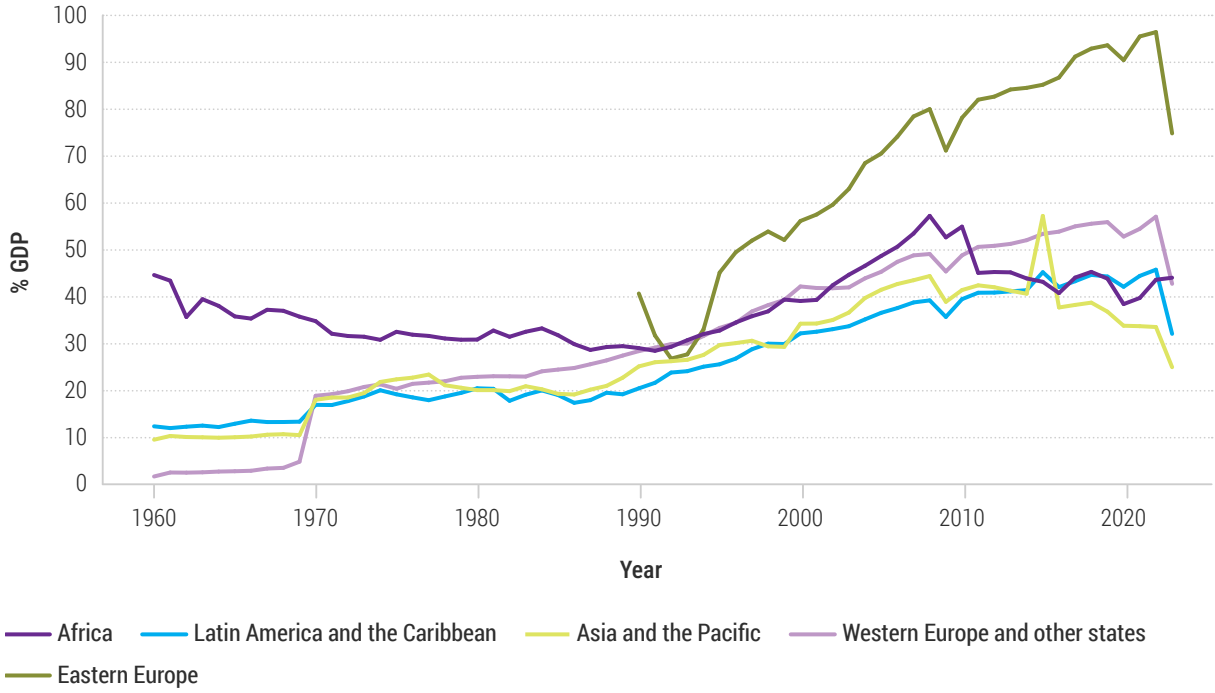
Source: World Development Indicators, World Bank (2025)

Figure 2.6: Trends of per capita GDP (constant 2015 thousand US$) in the world and UN regions from 1960 to 2023 (cont.)



Note: A distinct vertical axis scale is applied to each regional panel to better highlight the shape and evolution of the regional trajectories, e.g., steady growth, fluctuation and deceleration

Figure 2.7: Trends of Trade Openness across UNEP Regions (1960-2023)



Source: World Bank | World Development Indicators

data from Eastern European States became available, different trend patterns emerge across the regions (2000-2023). The data suggests that Eastern European States have the highest trade openness, followed by Western European and Other States, Latin American and Caribbean States, with African States closely behind. Since trade openness is calculated using GDP as the denominator, this may influence the reported values. Despite this, the key insight from Figure 2.7 is that trade, as a part of economic development, likely interacts with environmental factors.

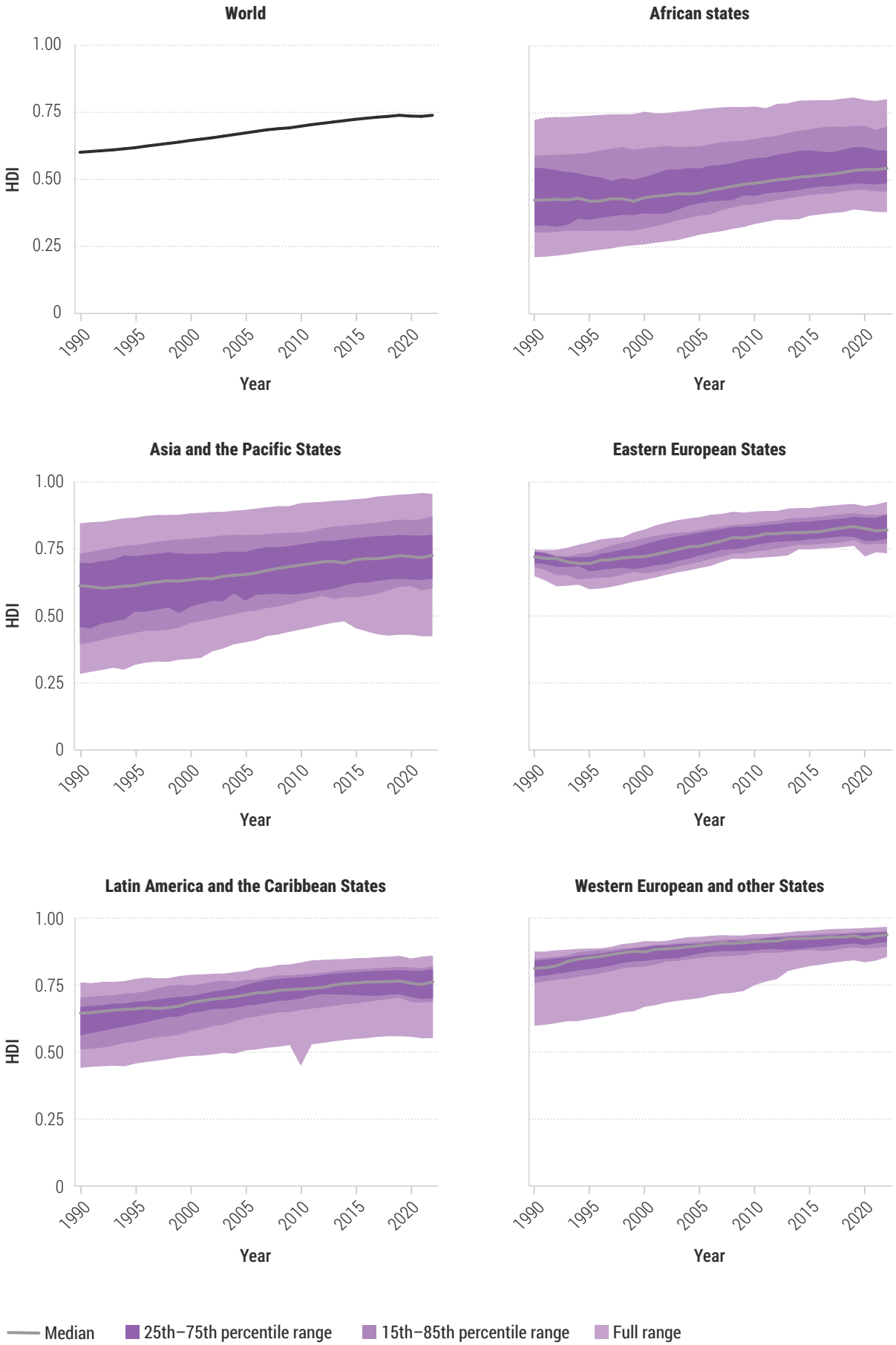
Enabling new metrics of human development in economic policymaking

HDI measures overall progress in three key aspects of human development, offering a broader perspective than GDP per capita. It encompasses health and longevity, knowledge, and a decent standard of living (United Nations Development Programme [UNDP] 2024). Currently, the global level of human development is rated as high on UNDP's development scale. HDI data, starting from 1990—the year it was first introduced—are shown in **Figure 2.8**.

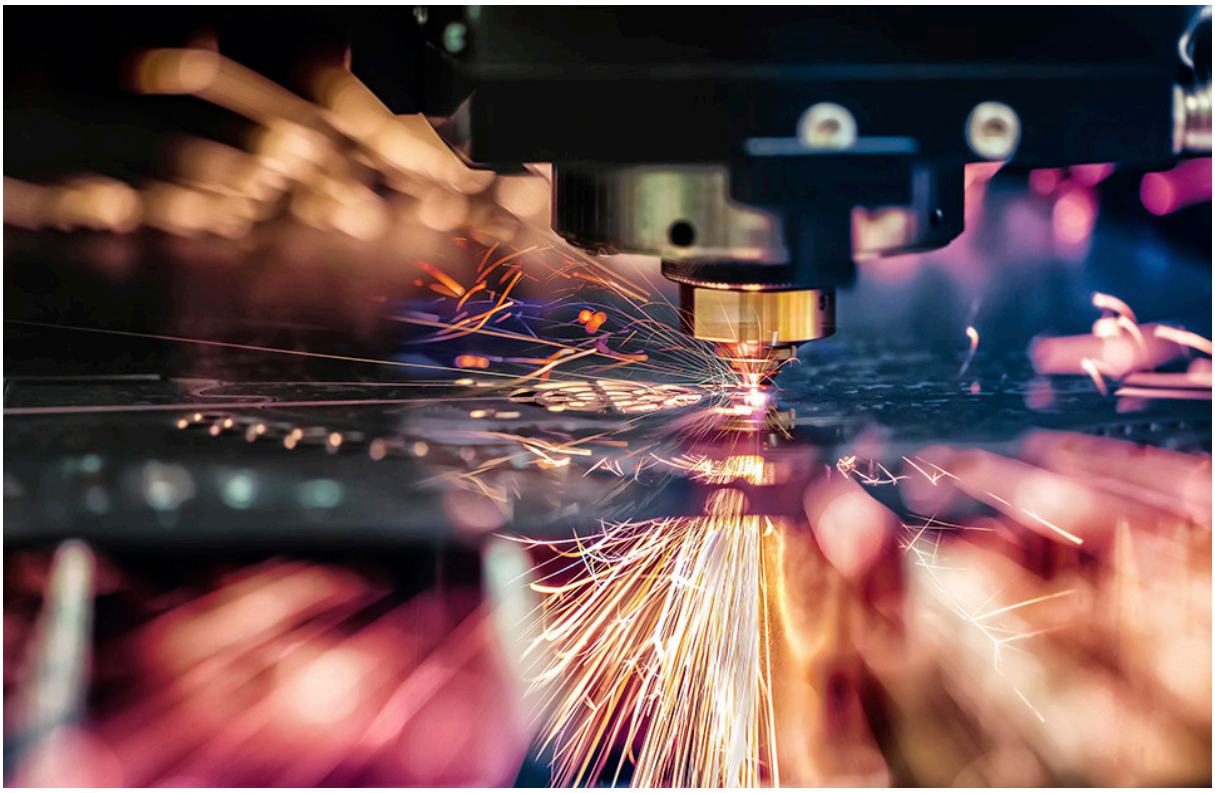
The HDI estimated for the world increased from 0.601 to 0.739 from 1990 to 2022. The increase was observed across all the time series, except during the COVID-19 pandemic, as it declined from 0.739 in 2019 to 0.736 by 2020, and then to 0.735 in 2021. Despite the similarity with the overall global trend, it is important to highlight observable disparities across the UNEP regions. For the African states, the statistical median of the HDI distribution increased from 0.425 to 0.543, with the amplitude – the difference between the highest and the lowest – declining from 0.543 to 0.422. In the Asia-Pacific region, the median increased from 0.613 to 0.726, with a slight decline in the amplitude from 0.562 to 0.536. For the Eastern European states, it increased from 0.721 to 0.821, with an observable increase in the amplitude, from 0.099 to 0.183). For the Latin American region, the median increased from 0.645 to 0.762, while the amplitude exhibited a slight decline from 0.319 to 0.308. In the Western European and other states, the median increased from 0.811 to 0.937, with the amplitude declining from 0.277 to 0.112.

The scenarios might represent shocks such as wars and natural disasters that caused major declines in HDI. Such shocks include the 2014 war in Yemen among Asia-Pacific countries, the 2010 earthquake in Haiti in Latin America, and the war in Ukraine conflict in Eastern Europe beginning in 2022 that led to a notable HDI decrease in Ukraine, among others (UNDP 2024).

Figure 2.8: Human Development Index (HDI)



Source: United Nations Development Division | Human development Reports



Credit: cookelma/Envato

2.2.3 Technology and Development

Technologies play a dual role, helping to mitigate risks while also contributing to various environmental threats. Scientific and technological advancements must enhance regional adaptive capacity and strengthen the responses to future climate risks. Integrating Indigenous Knowledge and Local Knowledge into climate adaptation and mitigation efforts can lead to novel place-based solutions and innovations that can inform other regions.

Projection of future trends and the possible transition

By 2024, over 107 countries committed to achieving net-zero emissions within this 21st century, covering roughly 82 per cent of the world's emissions (United Nations Environment Programme [UNEP] and International Resource Panel [IRP] 2024). Recent extreme weather events have highlighted the potential rise in future energy demand, the vulnerability of supply systems, and the urgent need for bold actions to cut global GHGs. Resilient supply chains for manufacturing clean energy technologies are key to the global energy transition. The major clean energy technologies such as solar PV, wind, electric vehicles, batteries, electrolysers, and heat pumps have been growing fourfold since 2015, reaching beyond US$700 billion in 2023 (IEA 2024a). However, the clean energy transition to these technologies is projected to drive rapid growth in global electricity demand. As a result, more than 30 countries plan to expand their use of nuclear power, and there are other initiatives to accelerate the development of less mature technologies, including carbon capture, utilization, and storage, to meet the net-zero target (IEA 2024b).

These supply chain systems rely heavily on critical minerals and their geographic distributions. The end-use sector also consumes large amounts of energy embedded in materials, such as cement for infrastructure, steel for vehicles, and chemicals for fertilizers and consumer goods (IEA 2023b). Deep decarbonization requires more system integration across different sectors and production processes. There needs to be a better balance between supply and demand (Davis et al. 2018). Another key challenge is the shortening of innovation cycles, as only half of the technology to achieve carbon neutrality is already on the market, while the other half is still in research and development (Smith et al. 2019).

Food supply per capita has increased by more than 30 per cent since the 1960s, accompanied by a significant rise in nitrogen fertilizers and water use for irrigation.

This has led to agrifood systems emitting one-third of all global GHG emissions (IPCC 2019; FAO 2020; Crippa et al. 2021). Additionally, climate change has already affected food security and Indigenous food sovereignty, with certain extreme weather events becoming more frequent (IPCC 2019). A more integrated approach is needed, including increasing productivity, improving resilience, and reducing emissions, which is also a major challenge for safeguarding food, water, and natural systems. Nature-based solutions have great potential to sequester carbon, improve water retention, increase soil productivity, create local food production, and ultimately restore local evapotranspiration and climate cycles (United Nations 2023a; United Nation Convention to Combat Desertification [UNCCD] 2025).

The expansion of mobile technologies, remote-sensing services, and distributed computing has enhanced smallholders' access to essential services (FAO 2019). The COVID-19 pandemic underscored the need to reshape distribution networks and ownership structures to boost supply chain resilience. A territorial market approach can help revitalize local and regional production, thereby improving food system equity (High Level Panel of Experts on Food Security and Nutrition [HLPE] 2020). The trade in services has also advanced, aided by the emergence of new services. Additionally, innovative and smart financial instruments and platforms have been developed to facilitate cross-border transactions (Anser 2023). Besides increasing transparency, technological financial innovations also improve risk management and promote greater financial inclusion.

Digital transformation enhances the efficient allocation of resources, balances supply and demand, and facilitates smart-city solutions. Smart cities can comprise interconnected intelligent environments that learn from human activity patterns and adapt to behavioural changes (Batty 2018; Kandt and Batty 2021). Likewise, smart grids optimize electricity distribution using digital communication and sensing technologies, enabling the integration of renewable, green energy sources into existing electricity networks (IEA 2020).

Digital transformation and artificial intelligence (AI) are rapidly transforming society, supporting scientific progress, decision-making, social engagement, and planetary health used in climate models (Eyring et al. 2024) and the UNDP Human Development Report 2025 (UNDP 2025). AI-generated suggestions for shifting to renewable energy and AI-based forest monitoring are just some examples of how AI can be used to address urgent global environmental challenges. However, their lifecycle environmental consequences remain uncertain. For instance, the use of minerals, energy, and water is expected to rise worldwide, along with increased production of e-waste and pollution (UNEP 2024). Human rights should also be protected throughout the entire lifecycle to ensure security and reduce the digital divide and gender inequality (United Nations Educational, Scientific and Cultural Organization [UNESCO] 2021). The necessary ethical framework and governance for such emerging technologies remain unclear. Technology contributes to prosperity and maximizes well-being and social welfare when it is equally accessible and supported by an adequate social safety net (Acemoglu and Johnson 2023; AI Safety Summit 2023).

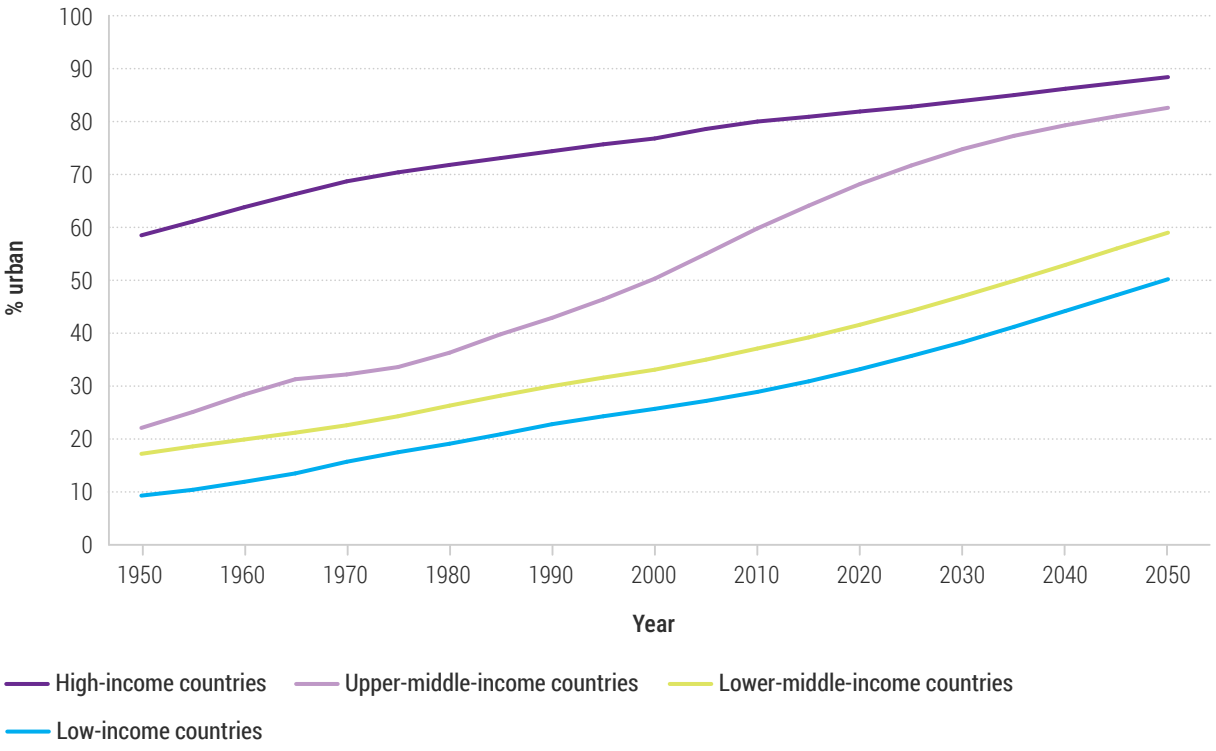
2.2.4 Urbanization

Urbanization takes many forms around the world, reflected in demographic variations such as city size, population density, growth rates, age structure, and mobility patterns (Ritchie, Samborska and Roser 2018; De Haas, Castles and Miller 2019; Sun et al. 2020). Spatially, urban areas expand unevenly, from compact cores to sprawling suburbs, creating diverse landscapes (Dadashpoor, Azizi and Moghadasi 2019). Urbanization trajectories also vary, with some regions facing rapid growth and inadequate infrastructure, while others grapple with population decline and economic downturns (Wolff and Wiechmann 2018; Meng and Long 2022). While urbanization can drive sustainable development (United Nations 2020), when poorly planned it can lead to significant environmental, social and economic challenges, emphasizing the need for effective development strategies.

Urbanization Trends

Urban areas accommodate most of the population compared to rural regions, with about 55 per cent living in urban areas in 2018, projected to reach 68 per cent by 2050 (United Nations 2019a). It is important to note that the definition of urban areas varies globally, and a standardized approach including demographic features and density grids is vital for precise policy analysis and environmental management (Organisation for Economic Cooperation and Development [OECD] and

Figure 2.9: Percentage of population residing in urban areas by income group, 1950-2050



Source: United Nations (2019a)

European Commission 2020; EU, FAO, UN-Habitat, OECD, World Bank 2021).

High-income countries tend to have a larger share of urban residents, whereas lower-middle and low-income countries are expected to undergo rapid urbanization in the coming decades (**Figure 2.9**).

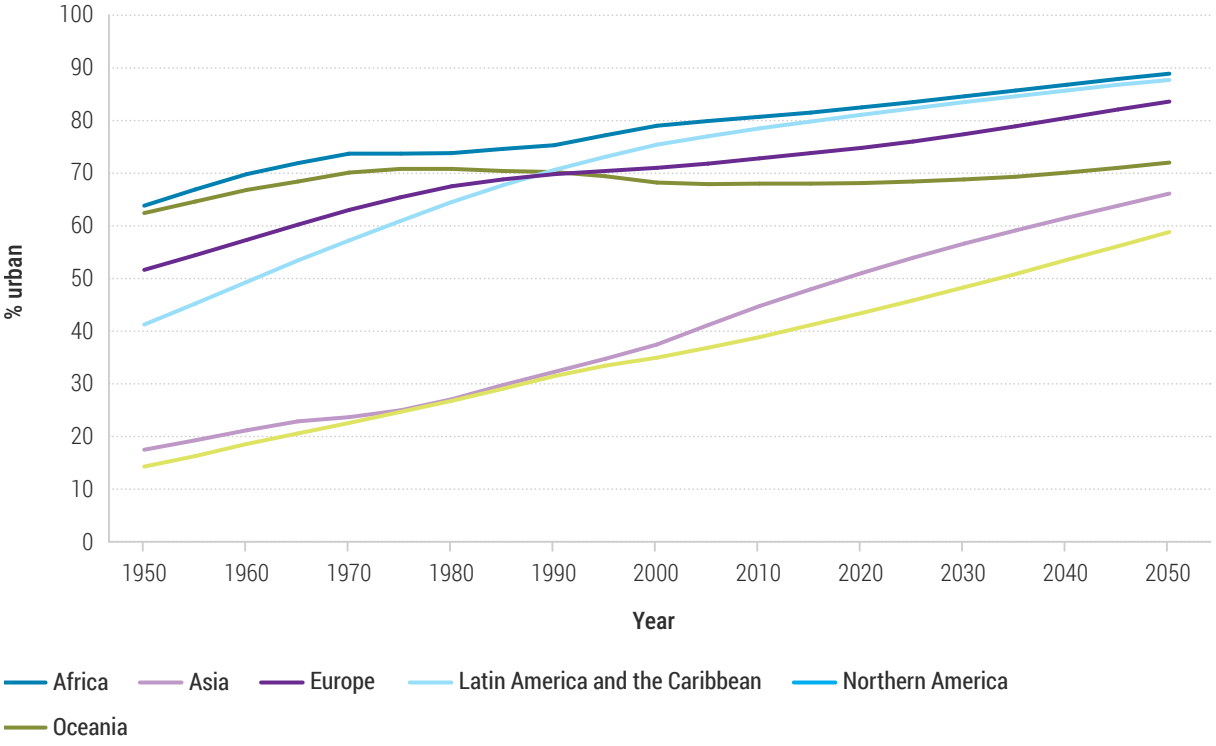
Likewise, urbanization levels vary significantly across regions (**Figure 2.10**). Northern America at 82 per cent and Latin America and the Caribbean at 81 per cent have high urbanization rates, followed by Europe at 74 per cent and Oceania at 68 per cent. Conversely, Asia at 50 per cent and Africa at 43 per cent are mainly rural but are expected to collectively accommodate 74 per cent of the global urban population by 2050.

Although urbanization is expected to increase in many areas, some nations are forecast to see a decrease in their urban populations. These projections emphasize that future urban growth will mainly occur in lower and low-middle-income countries across Asia and Africa (**Figure 2.11**).

Cities display significant demographic variations in both space and time. **Figure 2.12** demonstrates this diversity, showing that nearly half of the world's urban population lives in settlements with fewer than 500,000 residents, while about one in eight resides in 33 megacities with over 10 million people. Projections for 2030 estimate there will be 43 megacities, mainly in developing regions. At the same time, some cities in low-fertility Asian and European countries have experienced population declines (United Nations 2019a).

Urban growth is primarily driven by three factors – towns transforming into cities, city expansion, and increasing city density. Densification alone accounts for 50 to 60 per cent of the growth in urban populations. Wealthier countries generally have lower city densities, whereas lower-income countries often have densities nearly four times higher. For instance, North America has an average density of 1,700 inhabitants per km², while Sub-Saharan Africa and South Asia surpass 8,000 inhabitants per km². In high- and upper-middle-income countries, larger cities tend to be denser, but in low-income nations, high density is common across cities due to smaller housing units and policies that restrict urban sprawl (OECD and European Commission 2020).

Figure 2.10: Percentage of population residing in urban areas by geographic region, 1950-2050



Source: United Nations (2019)

Challenges and issues faced by cities in different urbanization level

A. Economic challenges

Cities worldwide face economic, social, and environmental challenges at various stages of urbanization. Income inequality is especially severe in highly urbanized cities, particularly megacities in developing countries. Some local governments try to reduce urban-rural disparities by promoting entrepreneurial clusters (Guo et al. 2020). Employment pressures also present significant challenges, especially during crises such as COVID-19 (Su et al. 2022). In low-income regions, inadequate infrastructure and high urban poverty rates exacerbate unemployment and hinder economic resilience (Filho et al. 2019). Cities heavily reliant on specific industries, such as resource-based economies, are also vulnerable to economic fluctuations (Tan 2021).

B. Social challenges

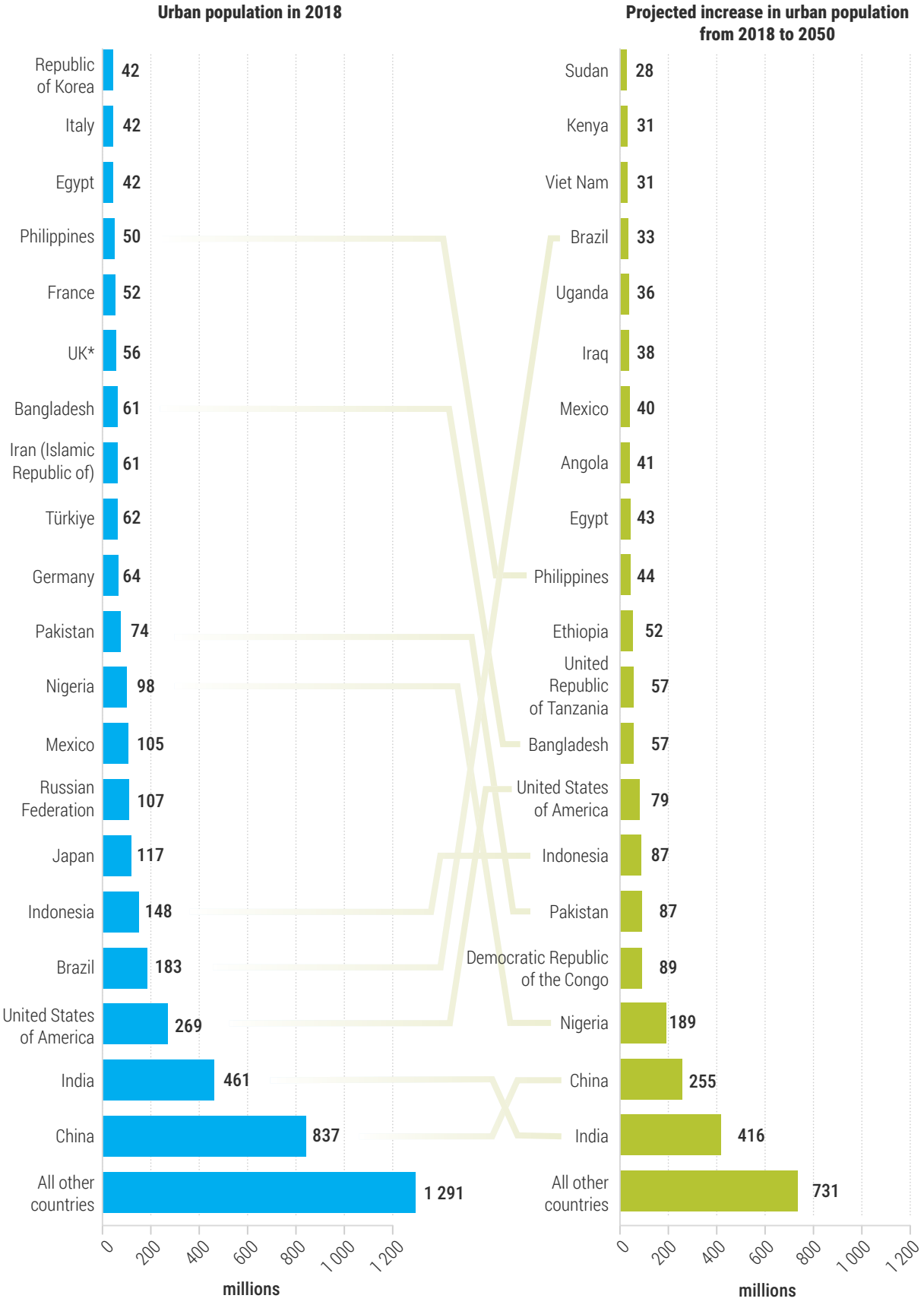
Social issues are equally vital. Housing affordability remains a serious crisis in both developed and developing countries (United Nations Human Settlements Programme [UN-Habitat] 2022). Rising housing costs often surpass the financial capacity of low-income groups, resulting in widespread housing insecurity (Glaeser et al. 2017; UN-Habitat 2022). Disparities in public services are also evident across urban areas. For example, limited access to green spaces disproportionately deprives low-income urban populations, with inequality nearly twice as severe in developing regions compared to developed countries (Chen et al. 2022).

Informal settlements and inadequate housing conditions continue to pose major challenges. Worldwide, about one billion people live in slums (UN-Habitat 2019). **Figure 2.13** illustrates that most of this population is concentrated in three main regions: South-East Asia, Sub-Saharan Africa, and Latin America and the Caribbean.

C. Environmental challenges

Environmental challenges in rapidly growing cities are complex and multi-layered. Waste management remains a major issue, particularly in sectors such as waste collection, landfills, and recycling. The rise of municipal solid waste and new waste types like plastics

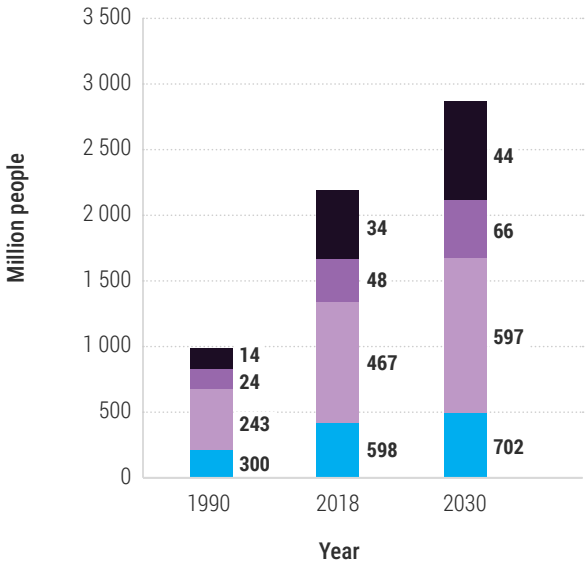
Figure 2.11: Urban population size in 2018 and increase in the projected urban population between 2018 and 2050 by countries



* The United Kingdom of Great Britain and Northern Ireland

Source: United Nations (2019)

Figure 2.12: Population and number of cities by size class of urban settlement in 1990, 2018 and 2030



Cities (500 000 to 1 million people)
Medium-sized cities (1 to 5 million people)
Large cities (5 to 10 million people)
Megacities (more than 10 million people)
XXX Number of cities by size

Note: Due to data unavailability, the figure does not include cities with populations below 500 000 people

Data source: World Urbanization Prospect (2018)

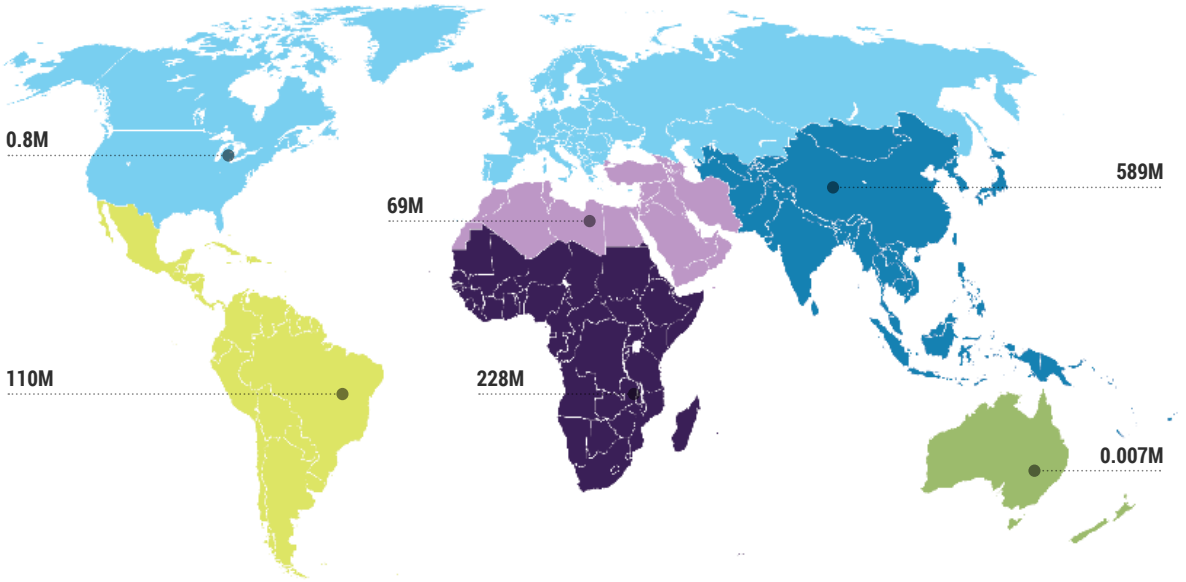
is happening quickly, but many cities lack enough landfill space and recycling facilities (Yang et al. 2017; Adebiyi-Abiola et al. 2019). Moreover, inadequate policies, weak regulations, and lack of enforcement worsen waste management problems. In low-income nations, 93 per cent of municipal waste is either burned or dumped in open landfills, posing serious environmental and health risks (Silpa et al. 2018).

Urbanization and human-driven emissions heighten the risk of heatwaves in cities. Additionally, continuous day-night heat waves – compound hot extremes – are more dangerous than isolated daytime or nighttime heat alone, especially for vulnerable groups like women and the elderly. Climate models project a two to fivefold rise in these events by the 2090s compared to the 2010s, increasing health risks for urban residents (Wang et al. 2021). Air pollution is also a major concern, as growing urban populations and industrial activities boost emissions from transportation, factories, and energy sectors. This worsens air quality, intensifying respiratory and cardiovascular illnesses, particularly in densely populated areas (Zhang et al. 2022).

2.2.5 Lifestyles and consumption

Lifestyles are leading drivers of the global environmental crises, as they are shaped by the everyday choices

Figure 2.13: Population per region living in slums and informal settlements



Latin America and the Caribbean
North America and Europe
Australia and New Zealand
Sub-Saharan Africa
North Africa and Western Asia
Central and Southern, Eastern and South-eastern Asia

Source: United Nations (2019)

individuals and societies make. How people decide to live, consume, and behave has profound repercussions on the health of our planet. Many modern lifestyles involve resource-intensive habits, overconsumption, and reliance on energy-demanding technologies. The rising worldwide demand for goods and services, fuelled by these lifestyle patterns, puts significant pressure on natural resources and ecosystems. Furthermore, lifestyle-related trends in urbanization, transportation, and food consumption contribute to greenhouse gas emissions and habitat loss.

The Global Resource Outlook (UNEP and IRP 2024) highlights the sharp increase in global material extraction over the past 50 years, rising from 30.9 billion tons in 1970 to 95.1 billion tons in 2020. By 2024, extraction is expected to reach 106.6 billion tons and is projected to grow at an average rate of over 2.3 per cent annually. Developed countries are projected to have the largest environmental footprint during this period (UNEP and IRP 2024). The anticipated growth in global demand is driven by a shift towards more resource-intensive lifestyles, influenced by rising per capita incomes, unsustainable consumption, and advancements in technology and infrastructure. Rapid population growth and resource consumption, without effective management of extraction, use, and disposal, will strain resource supply systems and cause unprecedented environmental pressures and impacts. Resource extraction, including biomass, fossil fuels, metal ores, and non-metallic materials, is projected to increase by 60 per cent between 2020 and 2060, from 100 to 160 billion tons (UNEP AND IRP 2024). Importantly, adopting demand-side strategies in key sectors such as buildings, transportation, and food could cut global greenhouse gas emissions by 40 to 70 per cent by 2050, offering a practical and urgent way to reduce environmental impact – highlighting the importance of sustainable lifestyles (Creutzig et al. 2022).

The causes of environmental issues are complex and deeply ingrained in society, requiring a comprehensive strategy to effectively tackle them. The future of land, freshwater, and ocean ecosystems depends on the widespread adoption of sustainable lifestyles. Addressing these issues calls for an integrated approach that highlights the importance of core values in motivating environmental action, leverages sociocultural influences to drive change, builds trust in institutions and individuals, and recognizes the significance of shaping social norms. By understanding and integrating these interconnected elements, we can work toward a sustainable future and mitigate the urgent environmental challenges we face.

Core values, especially altruistic and biospheric ones, greatly affect individuals' choices and commitment to environmental initiatives (Dietz 2014; Steg 2016). Customizing messages and appeals to reflect these values can boost the success of environmental campaigns (Bolderdijk et al. 2013; Boomsma and Steg 2014; Stephenson et al. 2015; Klaniecki et al. 2020). Moreover, awareness, personal norms, and self-efficacy are key factors in predicting readiness to engage in environmentally friendly behaviours (Schwartz 1977; Ajzen 1985; Stern 2000). Nonetheless, individuals need support and resources to overcome obstacles at the personal, institutional, and market levels (Young et al. 2010; Bray, Johns and Kilburn 2011; Carrington, Neville and Whitwell 2014).

Sociocultural factors, such as collective identity, cultural models, behaviours, and social structures, play a significant role in influencing how people respond to environmental challenges (Climact 2018; Thornton et al. 2020; Levis et al. 2024). When individuals feel a sense of connection to collective action, their efforts towards environmental solutions tend to be more effective and widespread. UNESCO (2019) highlights that culture serves as a crucial, renewable resource for addressing climate change and environmental issues, harnessing natural heritage, intangible heritage, and traditional knowledge to support initiatives from local to global, such as agroforestry in Sub-Saharan Africa and glacier management in South Asia (Morel et al. 2022). Concepts of citizenship and moderation, as core values, reinforce the idea of interconnectedness among individuals (Gill 2022). Social and cultural processes interact with individual, structural, institutional, and economic factors, shaping the decisions people make about environmental issues (Barr and Prillwitz 2014). Indigenous cultural values and practices that honour and care for nature provide lessons on how shared values can promote sustainability (Brondízio et al. 2021). Additionally, power relations and personal agency influence the development and prominence of environmental narratives (O'Neill and Smith 2014; Schneider-Mayerson et al. 2020).

Trust serves as a fundamental element influencing the adoption of sustainable practices and innovative solutions. Trust in organizations, suppliers, and

individuals is crucial for accepting new energy services, resource-efficient products, and community initiatives (Lutzenhiser 1993; Cherry et al. 2018; Li and Wang 2020). Developing trust in various stakeholders is seen as essential for fostering sustainable behaviours.

Changing social norms can be a defining factor in tackling environmental challenges and driving societal change (Nyborg et al. 2016; Otto et al. 2020). Providing feedback on individuals' actions in comparison to others, along with the effects of current trends, can motivate both adaptation and mitigation efforts (Abrahamse and Steg 2013; Delmas, Fischlein and Asensio 2013). Behavioural contagion, which involves the spread of ideas and behaviours similar to infectious diseases, plays a significant role in the climate crisis (Sunstein 2019), but it also offers opportunities to encourage positive change. Peer influence is crucial in shaping carbon-intensive consumption habits, highlighting that individual actions can influence others (Frank 1999). Understanding the influence of lifestyles, cultures and traditions on environmental problems is essential for promoting effective environmental action.

2.2.6 Governance

Kaufmann, Kraay, and Mastruzzi (2010) define governance as "the traditions and institutions through which authority is exercised." This encompasses all processes and practices involved in making and regulating decisions on issues of common concern, as well as designing and implementing effective public policies. It also includes public respect for the state and its institutions to promote economic performance and social well-being. Since governance involves the exercise of authority, it covers laws, such as decisions, regulations, and enforcement, institutions and decision-making processes that embody this authority (World Resources Institute [WRI] 2006). Different organizations interpret good governance in various ways, but it is generally characterized by openness, participation, accountability, efficiency and consistency (Bosselmann, Engel, and Taylor 2008).

Governance and environmental quality are closely connected, as failures in governance often cause environmental degradation. Comparing two different measures – the 2022 Environmental Performance Index and the 2022 World Governance Index – there is increasing evidence that good governance helps reduce pollution levels (Shandra, Shor, and London 2008; Clapp and Dauvergne 2005; Jorgenson and Clark 2012) and supports environmental improvement (Hassan 2020). Conversely, poor governance – stemming from inefficient regulatory frameworks, lack of transparency and accountability, and weak law enforcement – tends to lead to worse environmental outcomes.

Given the current global environmental crises, which involve complex multidimensional factors beyond traditional top-down governance, it is important to consider the role of multilevel governance. This concept describes the distribution of authority across various vertical levels and among multiple horizontal actors, encompassing both political structures and decision-making processes (Bache and Flinders 2004; Schäfer 2021).

The effectiveness of multilevel governance and its ability to facilitate coordination and collaboration across various levels of government, from local to global, as well as across different sectors and stakeholders, is essential for effectively addressing environmental challenges. Flexible and adaptive multilevel governance has also demonstrated success in tackling collective action problems related to common resources amid changing environmental conditions (Ostrom 1990; Ostrom 2017). Among the core governance principles that can help improve environmental outcomes, control of corruption, government effectiveness, transparency, and accountability may require further examination.

Control of corruption

Corruption is a widespread global issue, typically defined as the misuse of public authority for private gain (Rodriguez, Uhlenbruck and Eden 2005; Werlin 2016). It is a complex and multi-layered phenomenon that poses significant challenges to the economy. The World Bank estimates that corruption costs approximately US$1.5 trillion worldwide annually, accounting for about 2 per cent of global GDP. Additionally, corruption is viewed as one of the key obstacles to reaching sustainability goals, as it directly affects the environment and leads to negative consequences, such as increased pollution (Damania, Fredriksson and List 2003; Fredriksson, Vollebergh and Dijkgraaf 2004; Cole 2007; Leitão 2010; Biswas, Farzanegan and Thum 2012; Cepparulo, Eusepi and Giuriato 2019; Pei, Zhu and Wang 2021; Song, Xie and Shen 2021; Wu et al. 2021), as well as the inefficient use of natural resources (Yuan and Xiang

2018; Sinha et al. 2019; Zhou and Li 2021; Tawiah, Zakari and Alvarado 2024). It hampers green strategies and policies and limits access to public goods and services, thus disturbing the fragile balance between economic growth, social inclusion, and environmental sustainability.

Corruption often facilitates environmental crimes. Certain sectors, like forestry, fisheries, water management, extractive industries, and construction, are especially vulnerable to corruption. For instance, Böhmer (2019) notes that corruption and illegal deforestation frequently occur together, with the world's most forest-rich nations making little progress in combating corruption (Böhmer 2019). Countries in rainforest regions, home to significant biodiversity, local communities, including Indigenous Peoples, and vital environmental functions such as climate regulation, tend to perform poorly on the global Corruption Perception Index.

Government effectiveness

Several factors are preventing governments from realizing their environmental ambitions:

- The lack of policy coherence results in conflicting actions and funding across sectors such as the economy, industry, production, and consumption, as well as large-scale infrastructure, transport, food and agriculture, construction, taxation, and social benefits. Some of these policies even oppose environmental goals (Fischer 2018). Moreover, there is a shortage of ambitious policies that more effectively leverage public and private funding, as addressing environmental challenges demands investments far exceeding current levels (**Table 2.1**).

- Political polarization (Cole et al. 2023) and short-term cycles may discourage governments from tackling complex and long-term environmental issues (Povitkina 2018).

- Poor planning, inclusion, and coordination in designing and executing environmental strategies, along with a failure to recognize key synergies, interdependencies, and trade-offs between these strategies and other policy priorities such as energy, transport, industrial growth, and digitalization. Additionally, insufficient involvement of local, regional, Indigenous governments, and rights holders in the development of environmental policies impacts their implementation and risks undermining the intended results.

- Lack of adaptive and flexible approaches that can respond to changing circumstances, uncertainties, and risks associated with environmental challenges. This includes monitoring and evaluation of policies and actions, as well as learning from experiences to improve future responses (Folke et al. 2005).

- The lack of strong global leadership and cooperation among nations hampers efforts to address worldwide environmental issues, which require a coordinated global response. For instance, COP26 on Climate Change expressed "deep regret" that wealthy nations failed to meet their 2020 goal of contribution of US$100 billion annually to assist developing countries. This highlights the need for improved leadership and greater collaborative efforts to support the most affected and vulnerable nations facing environmental degradation.

Transparency and accountability

Transparency and accountability are crucial in the policymaking process and embody a citizens-centred approach to addressing environmental degradation. Since collaboration is vital, with every part of society having to contribute, actions are still required to promote transparency and effective governance by addressing:

- Limited access to credible and comprehensive information results in a weak basis for policy decisions. It also hinders civil society and citizens from monitoring policy implementation, reducing their ability to pressure the government to act. Furthermore, this issue negatively impacts the rights of the most marginalized and vulnerable groups.

- Lack of public awareness, acceptance and support of more participatory forms of public engagement hinder citizen involvement in problem-solving, environmental policies, and the fair distribution of costs and benefits associated with addressing environmental challenges.

- Insufficient education about environmental challenges contributes to resistance to lifestyle

Table 2.1: Investment needs: Summary

Theme (US$ trillion)	Power	Iron & Steel	Cement	Chemicals	Transport	Aviation	Shipping	Agriculture	Buildings	Total across sectors
Electrification & renewables	56.7	–	–	<0.1	35.1	2.8	–	–	–	94.6
Efficiency & circularity	–	0.7	0.4	0.2	4.0	0.2	0.7	0.6	5.3	12.1
Alternative technologies	2.5	1.6	1.1	2.0	2.0	2.1	1.7	1.3	0.8	15.0
Total investments	59.2	2.3	1.5	2.2	41.1	5.1	2.4	1.9	6.1	121.7
Region (US$ trillion)										
North America	9.6	0.1	0.1	0.5	8.1	0.9	0.3	0.2	1.3	21.1
Europe	9.1	0.1	0.1	0.6	7.4	1.1	0.7	0.3	1.3	20.7
Asia	34.3	1.3	1.0	0.9	21.7	2.8	1.2	0.8	2.5	66.4
Rest of the world	6.2	0.8	0.3	0.2	3.9	0.3	0.2	0.6	1.0	13.5
Total investments	59.2	2.3	1.5	2.2	41.1	5.1	2.4	1.9	6.1	121.7

Source: Boston Consulting Group and Global Financial Market Association 2020

changes and, in some countries, leads to strong opposition to environmental policies and practices.

- Lack of adequate sustainability disclosure and reporting in both public and private sectors.

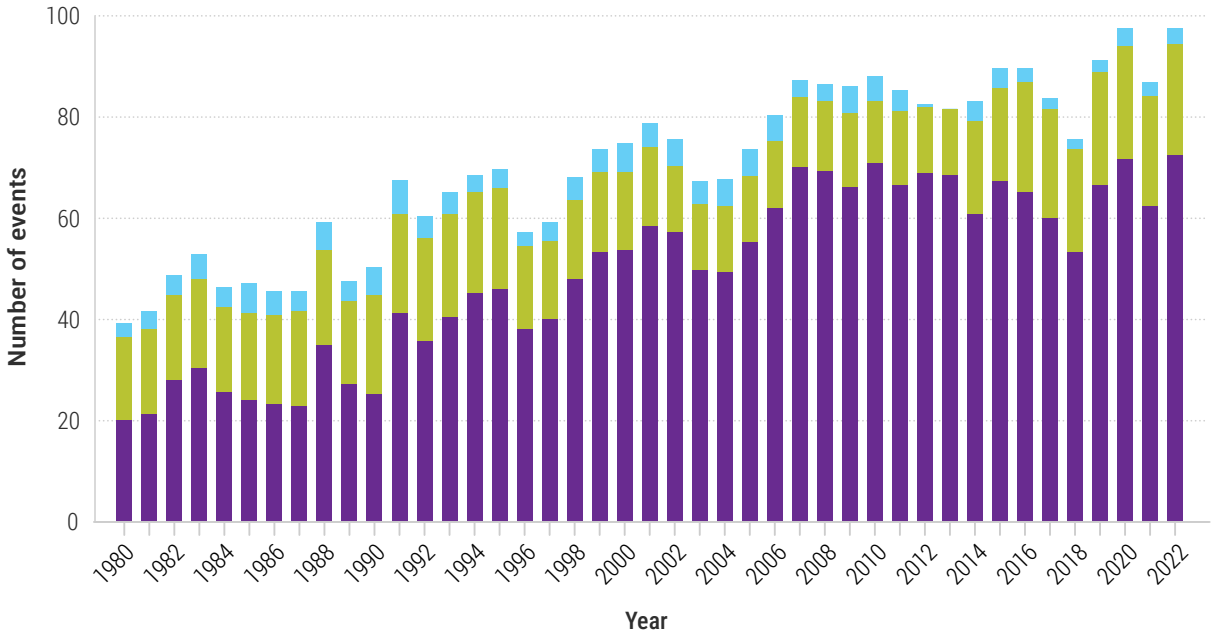
2.2.7 Shocks

A shock is defined as the occurrence of a largely unpredictable event, which can be natural or human-made. Unpredictability may stem from unknown aspects such as the event's intensity, timing, duration, or coverage. This definition covers a subset of hazard events listed in the UNDRR/ISC Hazard Information Profile (Murray et al. 2021), with the broader category including both predictable and less predictable hazards. Shocks can originate from natural processes that are geophysical, meteorological, hydrological, or biological. Examples include geophysical earthquakes or volcanic eruptions; hydrometeorological droughts, heatwaves, storms, and floods; and biological epidemics or pandemics. Human-made shocks can result from armed conflicts, extreme economic events like debt or financial crises, use of disease-causing agents, chemical weapons, or technological accidents, such as oil spills or industrial incidents.

Shocks can be cascading, interconnected, and multi-faceted. For example, an earthquake or landslide can generate a tsunami that destroys lives, livelihoods, and natural and built environments, cascading into an epidemic related to waterborne disease. Climate-related events such as droughts or biological events such as epidemics can be worsened by human activity and trigger a sovereign debt crisis, especially in low-income countries (International Monetary Fund [IMF] 2019; Cevik and Jalles 2022; United Nations Trade and Development [UNCTAD] 2022).

Shocks can become disasters when vulnerability combines with hazards (Blaikie et al. 2014; Taylor 2015; Gaillard 2021). Vulnerability refers to the susceptibility of people, societies, and ecosystems to harm. A high level of vulnerability to shocks is often linked to significant developmental challenges. Nearly half of low-income countries face risks from both debt and weather-related shocks, creating a cycle of ongoing vulnerabilities and economic stagnation (UNCTAD 2022). Understanding the human-made factors that

Figure 2.14: Trends in numbers of natural and human-caused shocks



Note: The armed conflicts considered in this figure are those between the military forces of two parties, at least one of which is the government of a state, and that have resulted in at least 25 battle-related deaths a year (Davies, Pettersson and Öberg 2023; Geditsch et al. 2002)

Source: Natural and technological shocks data from EM-DAT, CRED/UCLouvain, www.emdat.be; Armed conflict data from Upsala Conflict Data Programme, ucdp.uu.se; and sovereign debt default data of independent countries and regional/global financial crisis events from Reinhart and Rogoff (2011), Ams et al. (2019) and UNDP (2022).

contribute to vulnerability and shocks can help mitigate the adverse environmental impacts of shocks.

Trends in shocks over the past 40 years

The number of natural event-driven shocks threatening more than 10,000 people through death, injury, or homelessness has more than tripled over the past 40 years, as shown in **Figure 2.14**. The frequency and intensity of these events often increase due to human-induced climate change (IPCC 2022). In 2020, approximately 106 million people were affected by natural hazards such as earthquakes, tsunamis, floods, hurricanes, volcanoes, heatwaves, and wildfires – excluding biological events – with economic damages totalling US$161 billion (Ritchie, Roser, and Rosado 2022). Human-caused shocks, including armed conflicts and technological incidents, made up roughly half to a third of all shocks from 1980 to 2022.

Direct effects of shocks on environment

The effects of shocks on the environment, worsened by human-caused climate change, have led to widespread and sometimes irreversible repercussions across terrestrial, freshwater, cryospheric, atmospheric, and coastal and open-ocean ecosystems (IPBES 2019; IPCC 2022; Driscoll et al. 2024; Feehan et al. 2024; Ripple et al. 2024). Armed conflicts are inherently destructive and result in severe and lasting consequences for both land and marine environments. Major types of environmental damage caused by armed conflict include issues related to chemicals, fuels and associated infrastructure, waste and waste infrastructure, urban and critical infrastructure, agriculture and natural areas, environmental governance, and law enforcement (UNEP 2022). Armed conflicts can trigger complex, multi-faceted environmental crises with short- and long-term, often irreversible risks that create ripple effects beyond the conflict zones (UNEP 2007; Broomandi et

Credit: GreensandBlues/Envato

al. 2020; UNEP 2020; World Health Organization [WHO] 2021a; UNEP 2022).

Over the past 60 years, at least 40 per cent of intrastate conflicts have been linked to natural resource exploitation, including timber, diamonds, gold, oil, fertile land, and water. Studies show that conflicts over natural resources are twice as likely to reoccur within five years (UNEP 2022). Environmental impacts during armed conflicts, occupation, peacekeeping, and post-war rebuilding occur through various channels:

- Tactical strategies and unintended consequences (Gerges 1993; Biswas 2000; Organization for the Prohibition of Chemical Weapons 2022)
- Financing, especially when involving resource exploitation
- Breakdown of human security and development (Adger et al. 2014; Gates et al. 2012);
- Erosion or low prioritization of environmental governance (Bruch, Muffett, and Nichols 2016; Gaynor et al. 2016; Solomon et al. 2018; Bothe 2023); and
- Lack of recognition or enforcement of Indigenous and human rights (Tidwell and Zellen 2016).

Indirect and recursive impacts of shocks on environment

Shocks that impair food, water, and energy security, as well as socioeconomic outcomes (Bastos et al. 2020; UNEP 2022; Himaz 2022; Salmanidou et al. 2021; Syukriyah and Himaz 2024), can lead to or worsen resource conflicts. This often increases the vulnerability of affected populations, creating a cycle of worsening environmental conditions. For instance, mass displacement and survival strategies may cause deforestation, soil erosion, overuse of natural resources, and the rise of black markets for these resources (Black 1994; Jensen 2019).

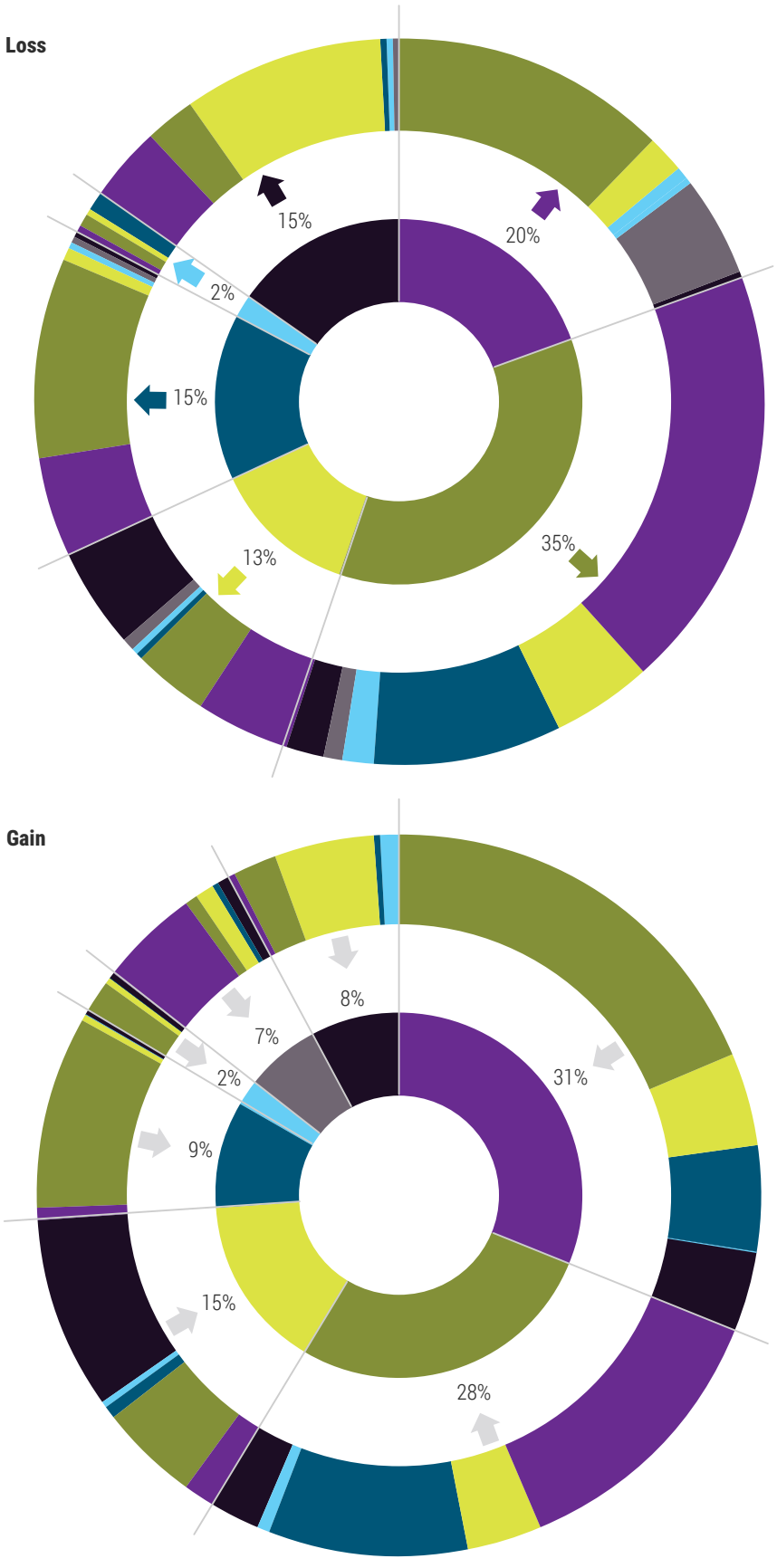
2.3 Pressures that affect the global environment

2.3.1 Land-use change

State and trends of global land-use transitions

Land-use change serves as a crucial indicator that reflects the significant influence of both human activities and natural processes on the Earth's surface (Anderson et al. 1976; Yu et al. 2022). Owing to the dedicated efforts of the European Space Agency (ESA), we have gained valuable insights into long-term land-use change patterns through the comprehensive 1992-2020 ESA Climate Change Initiative Land Cover (CCI LC) dataset (ESA 2017).

Figure 2.15: Proportions of land-use change gross loss and gross gain from 1992 to 2020



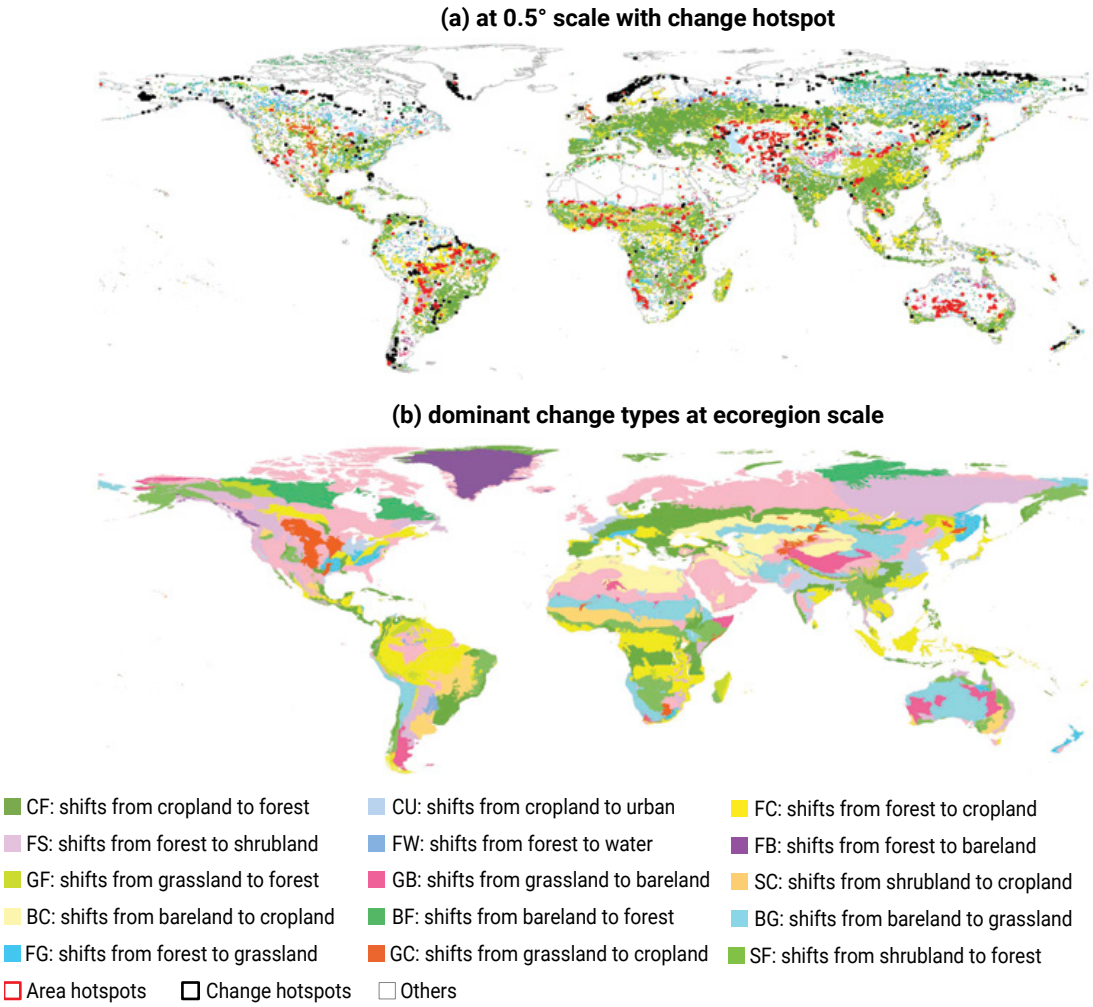
Source: Source: ESA (2017); Liu et al. (2018)

Analysing this dataset reveals that the most common land-use changes occur between cropland and forest (**Figure 2.15**). The ESA CCI-LC data shows that transitions labelled as "FC", forest to cropland, and "CF", cropland to forest, make up the largest areas of land-use change, with 129.89 and 85.70 million hectares respectively. These account for roughly 30 per cent of all land-use changes observed. Urban expansion also plays a major role in cropland loss. Around 30.61 million hectares of cropland were converted to urban areas, representing 67 per cent of urban-related land-use changes This expansion often pushes cropland into areas of natural vegetation. However, satellite data has been less effective at detecting land-use changes in other vital environments, such as grasslands and coastal marine areas, some of which have long histories of Indigenous stewardship (Chesnais et al. 2024).

The profound impact of urbanization on land-use change raises substantial concern due to the rapid pace of economic development and the surge in population density (Venter et al. 2016). Nevertheless, compared to other land-use changes, the overall global increase in urban areas remains relatively modest. From 1992 to 2020, the urban area expanded by 46.14 million hectares, representing 6 per cent of the total gross land-use changes. However, a critical concern related to urbanization is the loss of urban green spaces, which are essential for recreation and well-being.

The FC and CF types are common worldwide, as shown in **Figure 2.16**, including regions in Latin America, Eurasia, South Africa, Southeast Asia, and southern China. It is important to note that satellite data may not

Figure 2.16: Global land-use change map (a) at 0.5° scale with change hotspot, and (b) dominant change types at ecoregion scale



Note: (CF: shifts from cropland to forest; CU: shifts from cropland to urban; FC: shifts from forest to cropland; FG: shifts from forest to grassland; FS: shifts from forest to shrubland; FW: shifts from forest to water; FB: shifts from forest to bareland; GC: shifts from grassland to cropland; GF: shifts from grassland to forest; GB: shifts from grassland to bareland; SC: shifts from shrubland to cropland; SF: shifts from shrubland to forest; BC: shifts from bareland to cropland; BF: shifts from bareland to forest; BG: shifts from bareland to grassland).

Source: ESA (2017); Liu et al. (2018)

always accurately reflect land-use changes in certain areas. Among these regions, South America stands out as having notable hotspots related to the transition FC. Deforestation in South America is extensive, covering 75.70 million hectares, which accounts for 11 per cent of the total global land-use change area and a significant 63 per cent of the regional land-use change. This region has experienced the transformation of natural vegetation, especially forests, into croplands (Zabel et al. 2019). Furthermore, Asia and Africa show considerable hotspots of cropland expansion, with especially high concentrations in Central Asia (Potapov et al. 2022). While smallholder communities contribute to this change due to population growth and rising food demands, large-scale agribusinesses and corporations also play a key role, motivated by economic incentives such as global market demand. In Australia, hotspots of "BG" transitions, shifting from bareland to grassland, are visible in the south, highlighting the combined effects of climate change and human activities in grassland restoration (Gang et al. 2014).

Agricultural dynamics

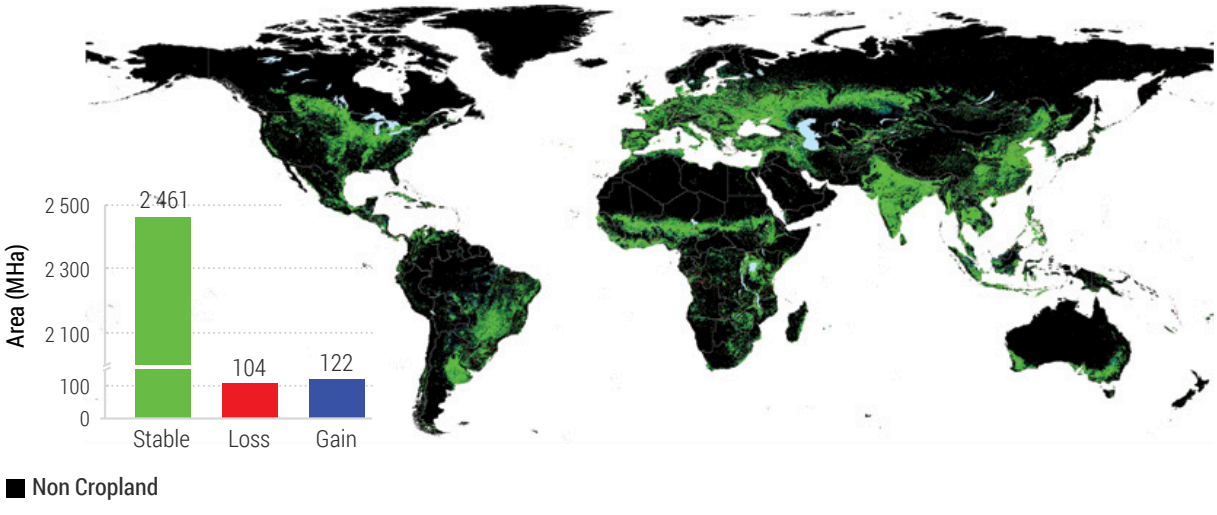
Cropland is vital for global food production and socioeconomic development (Brown 1981; Foley et al. 2011). From 2000 to 2020, most cropland remained stable, though a slight net increase of 17.28 million hectares indicated an overall growth trend (**Figure 2.17**). Notable variations in cropland were observed across specific regions. Sub-Saharan Africa, Southeast Asia, and parts of Latin America experienced significant cropland expansion due to factors such as population growth, agricultural intensification, and economic influences. In contrast, North America, Europe, and certain parts of Eastern Asia saw reductions in cropland due to urbanization, labour shortages, and land-use diversification (Yin et al. 2020; Crawford et al. 2024). Furthermore, the expansion of energy crops, including oil crops and solid energy crops, has also reduced cropland available for food production. This trend has been observed in various regions around the world, including the "corn belt" region in the Midwest of the United States of America (Wright, Thompson and Galloway 2013), and the proliferation of the oil/biodiesel production from rapeseed in Germany (Woźniak et al. 2019).

Delving into the analysis of three main staple crops—namely wheat, rice, and maize—revealed interesting trends. Despite fluctuations in their cultivated areas, their production has shown a steady increase since 2000. This growth has been driven by significant yield increases, ongoing population growth, and rising demand for feed and biofuel, which has stimulated expanded cultivation (Erenstein et al. 2022).

Forest dynamics

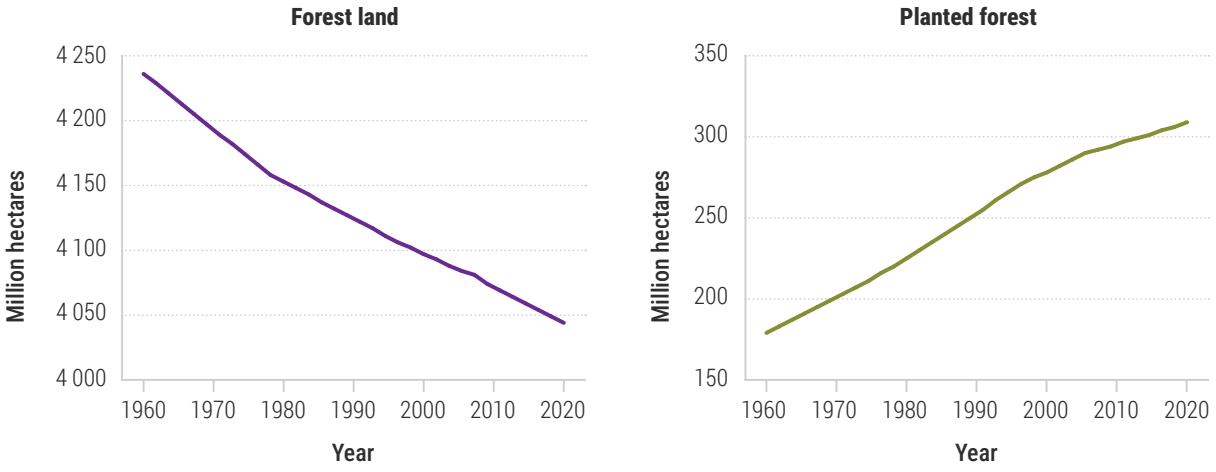
Despite the ongoing decrease in global forest area, efforts aimed at reducing deforestation have shown significant progress (**Figure 2.18**). According to FAOSTAT, from 1990 to 2000, there was an average annual forest loss of about 6.57 million hectares. After 2000, this rate decreased to 4.66 million hectares

Figure 2.17: Global cropland changes during 2000-2020



Source: ESA (2017)

Figure 2.18: Forest land and planted forest area, 1990-2020



Data source: FAO (2025)

per year and then further dropped to 4.31 million hectares per year since 2010. Meanwhile, the area of planted forests has been increasing, with rates of 3.68 million hectares per year during 1990-2000 and 4.62 million hectares per year during 2000-2010. Since 2010, the growth of planted forests has slowed, at a rate of 2.78 million hectares per year. Significant changes in forest cover have been observed across different regions (**Figure 2.19** and **2.20**).

Forest loss remains a significant issue in tropical regions like South America, Southeast Asia, and Central Africa (Hansen et al. 2013). Deforestation here is driven by agricultural expansion, logging, infrastructure development, such as the Bi-Oceanic Railway south of the Amazon, land grabbing, and illegal activities. In contrast, North America, Europe, and parts of Asia have made progress in forest conservation through initiatives like afforestation, reforestation, and sustainable management practices. Efforts such as China's Gain for Green and the African Great Green Wall have increased forest cover, but many reforested zones are monocultures with limited biodiversity benefits. Indigenous communities are also engaging in carbon forestry on their lands, though the prospects for sustainable development and safeguards of these schemes remain uncertain (van Kooten, Nijnik, and Bradford 2019).

Drivers and impacts of land-use change

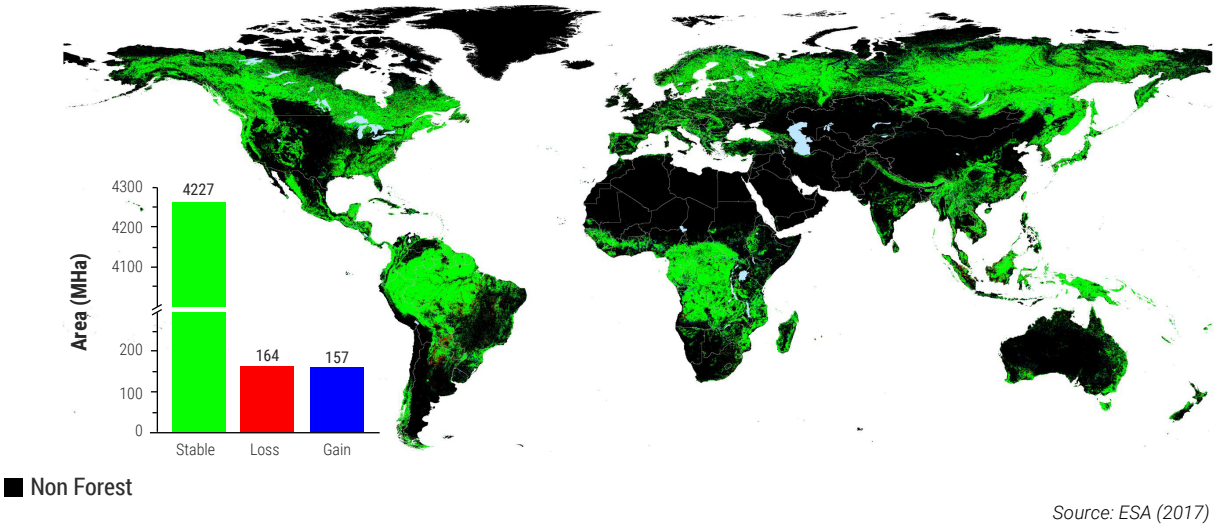
Many interconnected factors influence global land-use changes, affecting ecosystems and biodiversity. Population growth is a key driver, increasing food demand and prompting agricultural expansion. Simultaneously, issues like food waste, urbanization, climate change, and related factors intensify land-use pressures. Urbanization, stemming from population increase, threatens natural spaces by encroaching on habitats, destroying wildlife, and disrupting ecosystems (2.2.4). Environmental crises—such as pollution, climate change, drought, desertification, and soil degradation—are primary causes of environmental decline, while armed conflicts worsen these problems through deforestation, crop destruction, and loss of life and livestock (2.2.7). Additionally, the expansion of national parks and protected areas has contributed to regional land-use shifts.

Furthermore, resource exploitation, particularly in mining and timber industries, results in habitat destruction, pollution, and deforestation, aggravating geopolitical tensions and increasing habitat loss for various species (2.3.2). Additionally, invasive alien species, driven by global pressures such as climate change and land-use changes, disrupt native ecosystems and biodiversity (2.3.4). These pressures are closely linked and often interact in a complex way, making it harder to protect native biodiversity and natural resources (4.2). The regional growth of agriculture, driven by economic shocks, highlights the strong connection between human activities, land-use changes, and their effects on global biodiversity and natural resources, creating a cycle of growing environmental impact (2.4).

2.3.2 Resource use/exploitation

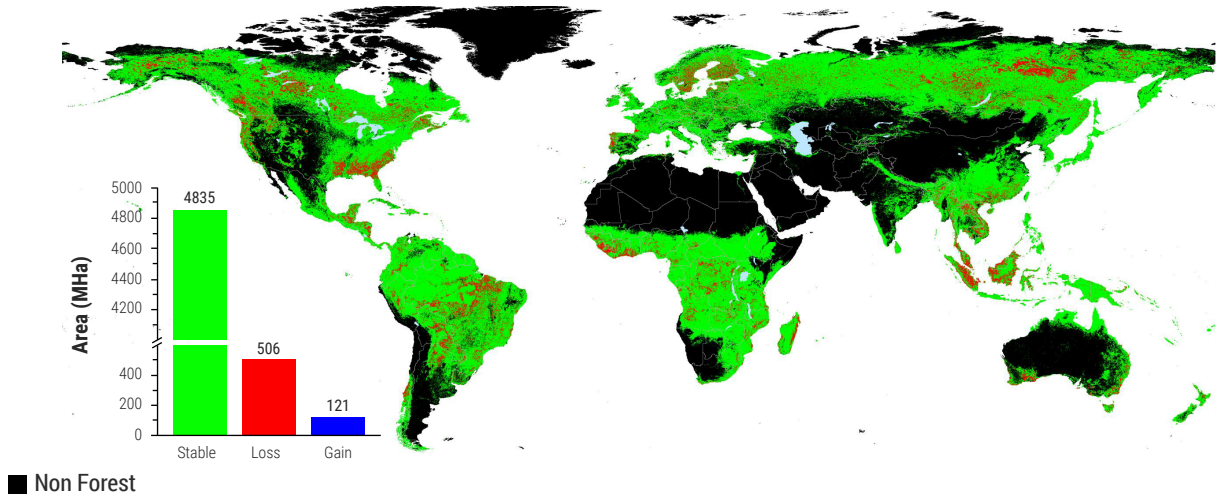
The rising demand for natural resources driven by a growing population, urbanization, economic progress, lifestyle choices, and natural disasters is putting a strain

Figure 2.19: Forest land and planted forest area (1990-2020)



Source: ESA (2017)

Figure 2.20: Global Forest changes during 2000-2020 at 30m



Source: Du et al. (2023); Hansen et al. (2013)

on the Earth's limited resources. The extraction of these resources has resulted in significant environmental pressures, as shown in **Figure 2.21**, which illustrates the annual average growth rate of consumption for various natural resources discussed below.

Fish and wildlife

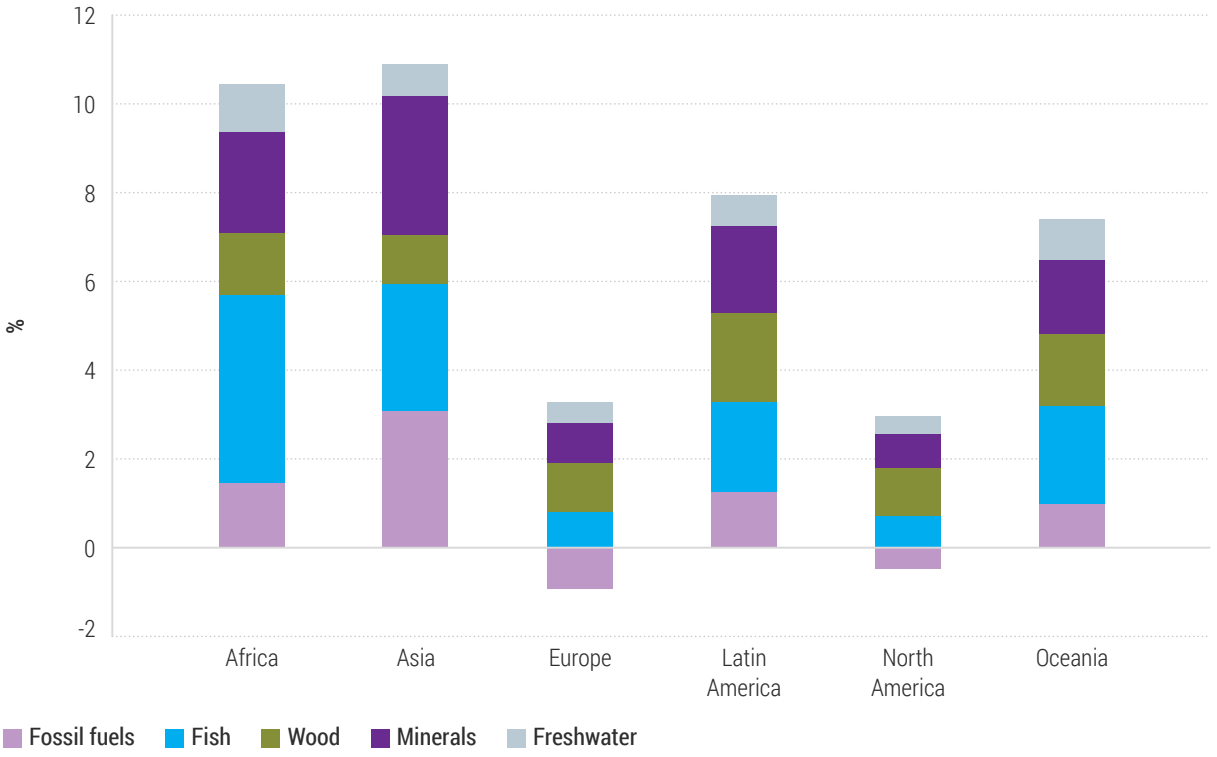
Global fish stocks are increasingly overexploited, with 37.7 per cent of fish stocks classified as unsustainably fished in 2021, up from 10 per cent in 1974, straining marine ecosystems (FAO 2024). Per capita fish consumption has also risen, doubling from 9.1 kg in 1961 to 20.7 kg in 2022 (FAO 2024).

Wildlife trafficking affects 4,000 species across 162 countries, contributing to biodiversity loss (United Nations 2024b). Since 1970, vertebrate populations have declined by 69 per cent due to exploitation and habitat destruction (World Wide Fund for Nature [WWF] 2022). Technological advancements like drones and satellite monitoring have enhanced conservation efforts but also pose risks of facilitating overexploitation (Ovando et al. 2021). Climate change worsens these problems, with rising ocean temperatures shrinking species' ranges and decreasing fish yields (IPCC 2022).

Energy

Fossil fuels – oil, natural gas, and coal – dominate global resource extraction, accounting for 80 per cent of primary energy consumption in 2023, mainly for transportation

Figure 2.21: Average annual growth rate (AAGR) in the use of key natural resources over two decades (2000 to 2023)



Source: UNdata (EDATA 2000–2021; ENV 2000–2021; ICS 2020–2021); Energy Institute (2022–2023); BP (2000–2022); FAOSTAT (2000–2021); FAO FRA (2022–2023); UN-Water (2022–2023)

and electricity (Energy Institute 2024). Their use emitted 36.8 billion metric tons of CO_2 in 2023, significantly contributing to climate change (Friedlingstein et al. 2025). Global per capita fossil fuel consumption remained stable at 1.9 tons of oil equivalent in 2023, ranging from 6.7 tons in North America to 0.6 tons in Africa (IEA 2024b). Reserves-to-production ratios in 2023 were 133 years for coal, 53 years for oil, and 52 years for natural gas (Energy Institute 2024). Industrialization and economic growth, especially in Asia, increased energy demand by 15 per cent from 2013 to 2023, though 40 per cent of this rise was met by clean energy, reducing fossil fuels' share from 82 to 80 per cent (IEA 2024b). Hydraulic fracturing has boosted shale gas production; while natural gas emits 50 per cent less CO_2 than coal, methane leaks threaten water resources and diminish climate mitigation gains. Urbanization and industry have increased fossil fuel use, but shifts like electric vehicles, or 18 per cent of 2023 car sales, are helping curb demand (IEA 2024b). The crisis caused by the 2022 onset of the war in Ukraine led to a six per cent increase in European coal use, disrupting supplies (IEA 2024b). Fossi fuel-related air pollution causes about 7 million premature deaths each year (WHO 2024).

Minerals and Rare-Earth Elements

The mining industry plays a crucial role in supporting global economic growth, providing essential resources for infrastructure, energy, and technology. Over the past 50 years, global material consumption has tripled and continues to grow by more than 2.3 per cent each year, fuelled by urbanization and industrialization (UNEP and IRP 2024). Advances in technology, including automated mining, satellite imaging, and advances in mining processes, have made it possible to extract minerals from remote areas (US Geological Survey 2021), boosting efficiency and lowering costs (United Nations 2025c). Despite these innovations, the industry faces difficulties in meeting rising global demand for minerals, expected to grow at 4 per cent annually due to the expansion of clean energy, infrastructure, and consumer products (United Nations 2025c).

The exploitation of rare earth elements has increased significantly, with demand for magnets that require them doubling from 2015 to 2023, reaching 93 kt in 2023 (IEA 2024c). The transition to green energy drives up the extraction of rare earth elements and

critical minerals, notably contributing to cobalt mining abuses and the proliferation of e-waste in Africa and Latin America (United Nations 2025c). Geopolitical conflicts and governance issues may further drive mineral extraction, potentially causing unrest (United Nations 2025c).

Wood and timber

Wood exploitation damages the environment by causing deforestation, biodiversity loss, soil degradation, and increased carbon emissions, disrupting ecosystems and intensifying climate change. Global wood product production peaked in 2018, marking the highest growth since 1947, with industrial roundwood production reaching 2.03 billion cubic metres (FAO 2019). The FAO's Global Forest Resources Assessment 2020 reported a net forest loss of 178 million hectares from 1990 to 2020, equivalent to the size of Libya (FAO 2020).

Roundwood consumption is projected to rise by 10 per cent to 2.2 billion cubic metres by 2030, mainly driven by Asia's economic growth and increasing demand for wood-based products (Lock et al. 2021). The wood products market is projected to grow at a compound annual growth rate (CAGR) of 7.1 per cent through 2025, with sustainable harvesting expected to meet demand through 2030 (Lock et al. 2021). Technological advancements, including enhanced plantation management, increased recycling, engineered wood composites, and biofuels, are expanding wood applications and improving industry sustainability.

Water

Excessive extraction of freshwater, pollution, and poor management are depleting water resources and damaging ecosystems. Mega-projects like dams disrupt natural flows, harming fish and communities. Overpumping groundwater for agriculture, industry, and domestic use often surpasses natural recharge rates, especially in urban areas with impermeable surfaces and shifting rainfall patterns, leading to unsustainable depletion. Additionally, demographic factors such as changes in population densities and movements can create further environmental pressures on water quality. This creates a vicious cycle, as securing clean water often involves exploiting other resources. Technological innovations can improve water availability, safety, efficiency, and treatment. Urbanization exacerbates freshwater stress, while lifestyle and dietary changes increase per capita water consumption. Extreme weather events exacerbate water scarcity and pollution.

2.3.3 Emissions: GHGs and other pollutants

GHGs and other pollutants adversely affect the environment across various spatial and temporal scales. This section analyzes sectoral and regional GHG emission contributions, while Chapter 3 on Air explores emission trends. Additionally, the major pollutants and their sources are also presented in this section. Chapters 3 to 6 on Air, Land, Oceans and Fresh Water provide detailed discussions on pollution in these specific resources.

2.3.3.1 Greenhouse gas emissions

Anthropogenic or human-induced emissions of carbon dioxide (CO_2) and other GHGs such as methane, nitrous oxide, sulphur hexafluoride, are primary drivers of climate change – representing one of the world's most urgent challenges. For the first time, the concentration of CO_2, methane, and nitrous oxide in the atmosphere has reached levels unseen in the last 800,000 years (IPCC 2023). During this period, atmospheric concentrations of CO_2 never surpassed 300 parts per million. However, with the industrial revolution and the burning of fossil fuels, there has been a rapid increase in emissions of CO_2, and consequently, global CO_2 levels have risen significantly in recent decades. For the first time in those 800,000 years, the CO_2 concentration is now well above 400 parts per million (IPCC 2023). What is staggering is the speed at which CO_2 concentrations have changed during this period. While historically CO_2 levels shifted over thousands of years, it has taken just a few decades to reach the current state.

Global GHG emissions grew by 1.9 per cent in 2023 (Crippa et al. 2024). Notably, energy-related CO_2 emissions rose by 0.9 per cent, or 321 million tons in 2022, despite pandemic-related fluctuations, reaching over 36.8 billion tons (IEA 2023a). However, this increase was below business-as-usual projections, due to growth in clean energy that offset approximately 550 million tons of emissions from increased coal and oil consumption (IEA 2023a). The 321 million tons rise in CO_2 emissions included contributions from:

- 60 million tons was from cooling and heating demands due to extreme weather conditions, and 55 million tons was due to the shutdown of nuclear power plants

- Emissions from industrial processes decreased by 102 million tons, especially in China and Europe, but emissions from combustion energy increased by 423 million tons

- CO_2 emissions from oil increased by 2.5 per cent – even more than from coal – largely from aviation

- Emission from fossil fuel increased further in 2022, relative to 2021 to 36.6 billion tons of CO_2/year

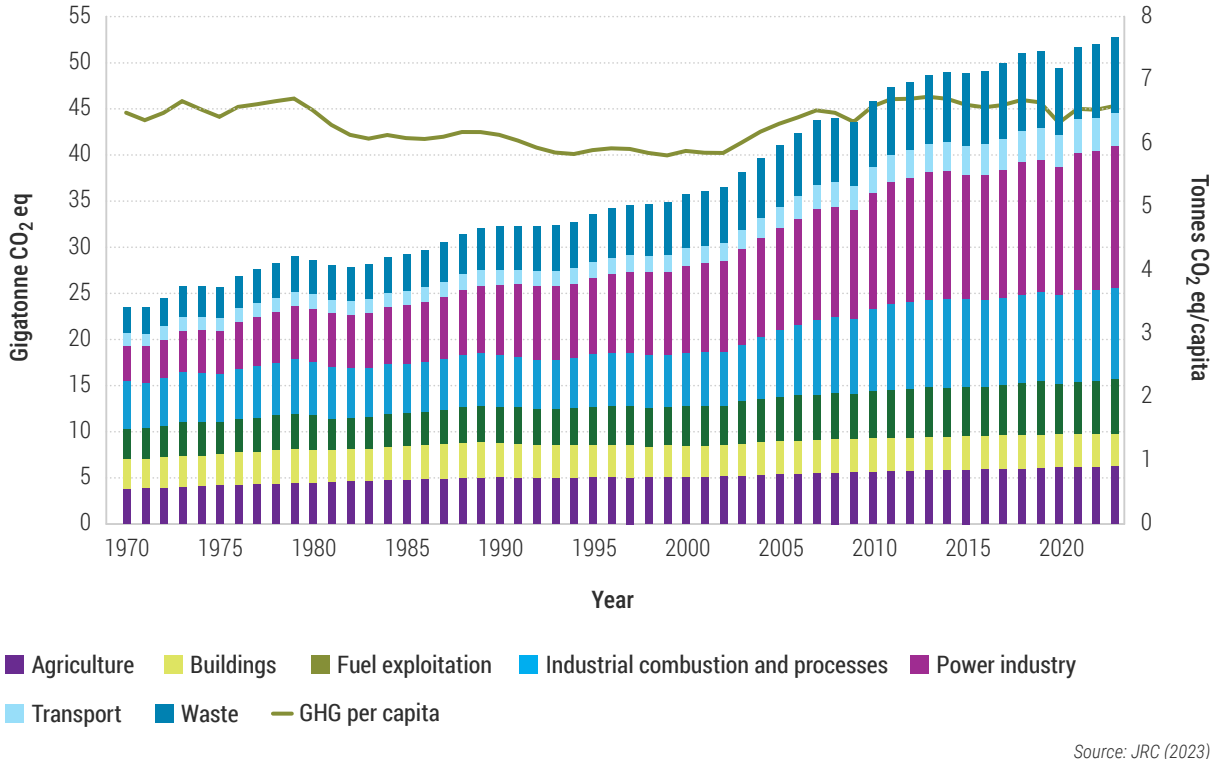
There were diverging trends across sectors and regions. CO_2 emissions grew in Asia, excluding China, and North America, surpassing the combined reductions in China and Europe. Among the various sectors, emissions from power and transport grew by 261 million tons and 254 million tons, respectively, more than offsetting reductions from industry and buildings (IEA 2023a).

Sectoral contributions

Global GHG emissions as estimated by the Emissions Database for Global Atmospheric Research (Crippa et al. 2024) for the period of 1970 to 2023 is presented in **Figure 2.22**. The total global GHG emissions in 2023 were 53 billion tons of CO_2 equivalent, about 1.9 per cent higher than the 2022 values. This represents an increase of nearly 1.5 per cent annually since 1990 – 61.8 per cent higher in 2023 compared to 1990.

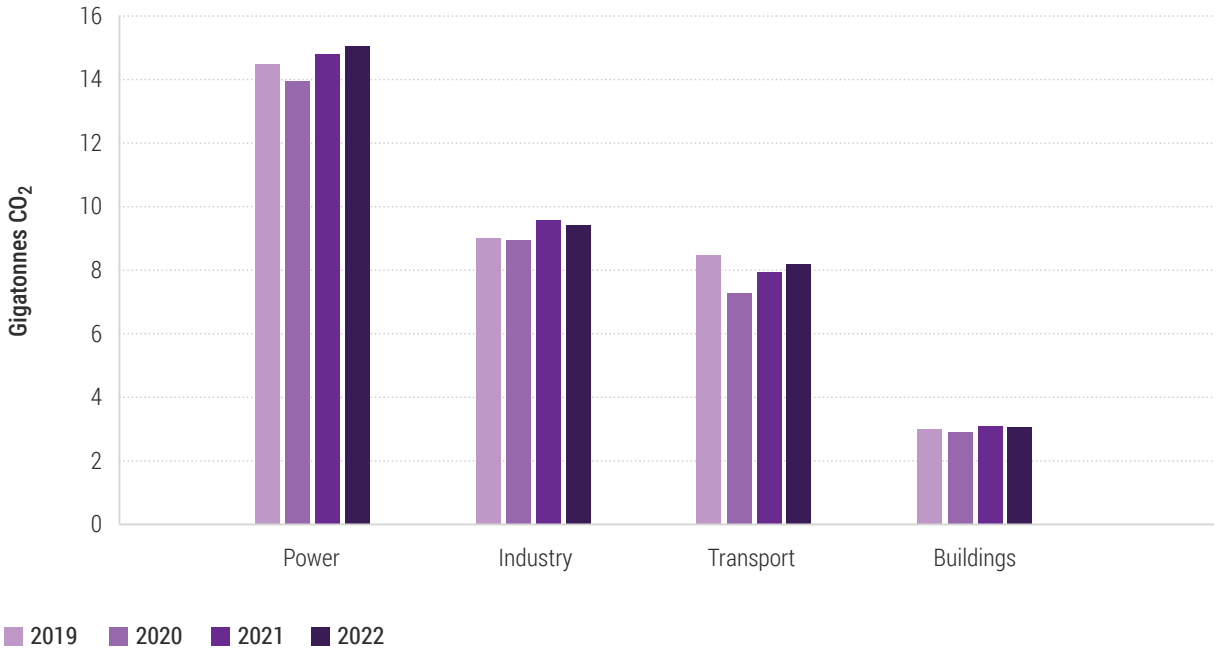
Emissions from five major global economic sectors – energy supply, industry, transport, direct energy use in buildings, and agriculture, forestry, and land-use change – are included in the global emissions inventory (**Figure 2.23**). Most growth in emissions has come from the energy supply (37 per cent, 20 billion tons of CO_2) industry (26 per cent, 14 billion tons of CO_2) and transport (14 per cent, 7.5 billion tons of CO_2) sectors since 1990 (Lamb et al. 2021; Dhakal et al. 2022). The agriculture, forestry, and land-use change sector and the building sector contributed to 9.5 billion tons of CO_2 or 18 per cent and 3.1 billion tons of CO_2 or 5.7 per cent, respectively. The use of coal was lower than expected, even though emissions from the electricity sector rose by 3.4 per cent. According to IEA (2023a), CO_2 emissions from energy combustion increased by about 1.3 per cent or 423 million tons in 2022, while CO_2 emissions from industrial processes decreased by 102 million tons.

Figure 2.22: Sectoral GHG emissions and emissions per capita from 1970 to 2023



Source: JRC (2023)

Figure 2.23: Global CO_2 emissions by sector from 2019 to 2022



Source: IEA (2023)

Regional contributions

In 2023, the GHG emissions from China, United States of America, India, the EU27, Russian Federation, and Brazil were the highest, collectively accounting for 64.2 per cent of fossil fuel consumption, and 62.7 per cent of total GHG emissions (Crippa et al. 2024). Compared to 2022, global GHG emissions increased by 1.9 per cent in 2023, reaching 53.0 billion tons of CO_2 equivalent (Crippa et al. 2024).

According to Crippa et al. (2024), among the 17 countries and regions contributing over one per cent to global GHG emissions, six experienced a decrease in emissions in 2023 compared to 2022. These include the United States of America -1.4 per cent, EU27 -7.5 per cent, Japan -6.0 per cent, Republic of Korea -2.2 per cent, Germany -10.5 per cent, and Pakistan -0.7 per cent. In contrast, all other major emitters saw an increase. India saw the highest rise at 6.1 per cent, followed by China at 5.2 per cent, and Indonesia at 4.1 per cent. Globally, per capita GHG emissions increased by 7.4 per cent, from 6.14 tons CO_2 equivalent in 1990 to 6.59 tons CO_2 equivalent in 2023.

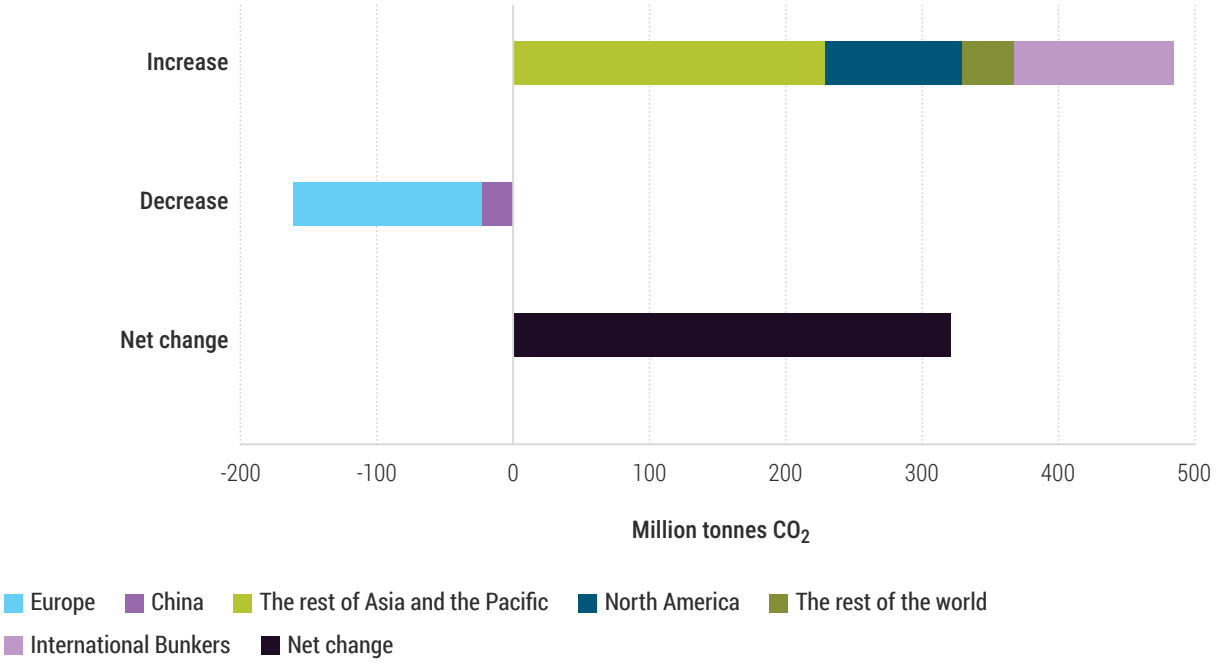
Meanwhile, afforestation and reforestation create a carbon sink of about 0.9 ± 0.3 billion tons of carbon/year, counterbalancing emissions from deforestation (IEA 2023a) (**Figure 2.24**). The largest contributors in this sector during this period are Brazil, Indonesia, and the Democratic Republic of Congo, which together account for over half of the world's total land-use emissions (IEA 2023a).

2.3.3.2 Other pollutants

Environmental pollution has become a worldwide threat to humans and ecosystems. The key differences from over 50 years ago are the scale of the issue and the complexity of involved pollutants (Naidu et al. 2021). Although our understanding of the sources, fate, behaviour, and effects of pollutants has improved, some problems remain. The constant addition of new chemicals and the discovery of their harmful impacts on living organisms, along with the release of increasingly complex wastes and synthetic chemicals like plastic polymers (UNEP 2023a), raise concerns. This has led to discussions about a Global Plastics Treaty to combat plastic pollution.

Additionally, recent issues such as antimicrobial resistance (Hanna, Tamhankar and Lundborg 2023; Van Bavel et al. 2024) are another cause for concern, particularly for aquatic ecosystems and related human health effects. With an estimated 70,000 to 350,000 chemicals registered for production and use (Bond and Garny 2019; Wang et al. 2020) and the limitations

Figure 2.24: Change in CO_2 emissions by region



Source: IEA (2023)

of premarket assessments in many countries, we are still making little progress towards creating "benign by design" chemicals and adopting a more comprehensive life cycle approach in their evaluation as pollutants (Kümmerer, Clark, and Zuin 2020).

Globally, the use of chemicals continues to increase and there are no signs this trend will change in the short term across sectors such as agriculture, textiles, building, and pharmaceutical industries (UNEP 2019).

A selected group of chemical pollutants that share certain properties, such as high persistence, bioaccumulation, and toxicity (Ashraf 2017), have been and continue to be of global concern. These include persistent organic pollutants (POPs) and mercury, and more recently, the so-called "forever chemicals," such as poly- and perfluorinated chemicals widely used in modern life. The Stockholm Convention for POPs, the Minamata Convention for Mercury, and the Basel and Rotterdam Conventions, which address both the transboundary transport of hazardous wastes and the prior informed consent of countries to receive hazardous chemicals, have been instrumental in controlling sources, emissions, and waste management for these pollutants. These agreements have also implemented effectiveness assessment tools, such as the global monitoring plan for POPs, aimed at demonstrating the decreasing spatial and temporal trends of POPs levels on a global scale (Stockholm Convention on Persistent Organic Pollutants 2023).

Recently, two initiatives have been launched to combat global chemical pollution, aiming to safeguard human health and ecosystems. The first is the UNEP Global Framework on Chemicals, introduced in 2023 as a continuation of the earlier Strategic Approach for International Chemicals Management. The second is the science-policy panel, established per UNEA Res. 5/8 (2022). The science-policy panel will enhance the connection between science and policy on global chemical pollution issues, similar to how the IPCC and IPBES operate for climate change and biodiversity loss. This will be vital for promoting informed, evidence-based decisions on chemicals and waste.

At a regional and local level, pollution sources differ in contaminant types and environmental impacts, especially in developing regions. Regional pollution from extractive activities like mining (Tang and Werner 2023) has been documented in Africa, Asia, and Latin America. While mining is essential for acquiring resources to combat climate change – offering global benefits – it also causes local environmental impacts, especially in areas where water and biodiversity are heavily affected. In recent decades, the rising demand

for critical minerals such as beryllium, lithium, copper, nickel, and zirconium has spurred increased mining activities worldwide to satisfy market needs.

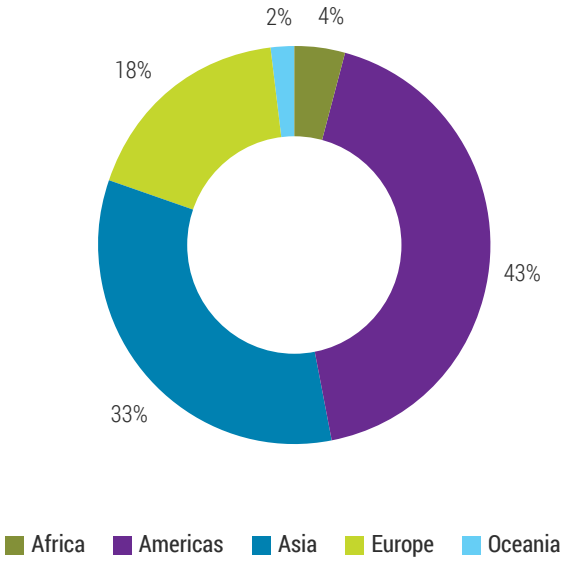
Critical minerals are essential elements required for developing and sustaining advanced technologies like smartphones, electric vehicles, and renewable energy systems (Hine, Gibson, and Mayes 2023). These minerals are crucial for manufacturing batteries that can reduce reliance on fossil fuels and help fight climate change. However, mining activities produce significant waste – up to 65 billion tons annually – posing serious environmental challenges related to storage and disposal (Kalisz et al. 2022).

Industrial agriculture continues to be a source of environmental pollution, considering that this activity relies on the continuous use of chemicals such as fertilizers, 136.5 kilogram per hectare in 2019 to 134.2 kilogram per hectare of arable land in 2022, the latest available data (World Bank 2023b), and pesticides increasing between 2019 and 2021 by almost 150,000 tons of active principles (FAO 2023) (**Figure 2.25**).While this ensures food security, it also causes environmental issues such as water eutrophication and pollution by pesticides.

Industrial chemicals of concern are present in many current-use articles and products, posing challenges for recycling and reuse. One example is the chemicals used in plastic materials as plasticizers or additives, whose complexity and effects have been described in the literature (Martínez-Pinna et al. 2023). Textiles also represent an emerging issue, as the global fashion market is expected to increase from US$1.5 trillion in 2020 to about US$2.25 trillion in 2025. There is growing concern regarding the chemicals used and the pollution that results when textiles become waste. Other problematic chemical classes include flame retardants with POPs properties and per- and polyfluorinated substances, widely used in many everyday products, which have gained public attention as the forever chemicals (Lim 2023).

Urbanization is increasingly a global trend, and if not managed properly, urban air pollution poses a serious threat to human health and ecosystems. Many benefits of reducing urban emissions, such as cutting greenhouse gases, also help lower urban air pollution. However, in many developing regions, levels of particulate matter remain a major challenge, and their reduction appears unfeasible under current consumption and production patterns (McDuffie et al. 2021). A global model estimates that, in 2022, 96 per cent, 82 per cent, and 53 per cent of Earth's populated areas experienced unhealthy air quality for at least one day, one week, and one month, respectively (Wei et al. 2023). The WHO, in 2022, reported that over 99 per cent of the world's population exceeded WHO air quality guidelines (WHO 2022). Urban sewage pollution and its sanitary consequences are another significant source of pollution (Howard 2021).

Figure 2.25: Pesticide use by region

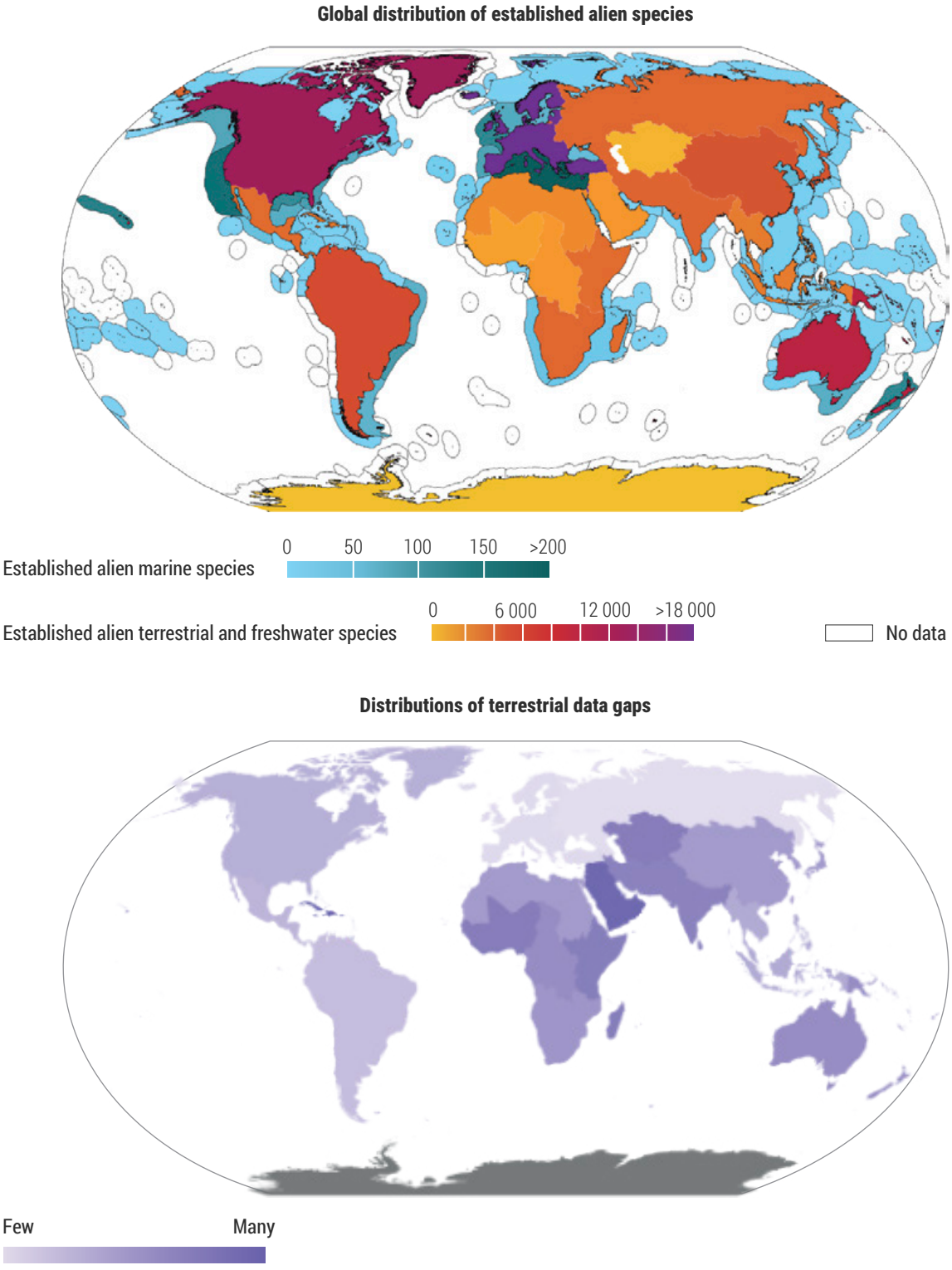


Source: FAOSTAT (2023)

2.3.4 Invasive Alien Species

Invasive alien species (IAS) are species introduced either intentionally or accidentally to areas outside their native range that have become successfully established and cause substantial impacts on the new environment (Convention on Biological Diversity 2002). Against a global backdrop of habitat loss and declines in the richness and abundance of many native species, some non-native species are increasing in number and spread, sometimes invasively. Over 3,500 invasive alien species with adverse effects have been recorded (IPBES 2023). Nearly one-fifth of the Earth's surface is estimated to be at risk of invasions (Purvis et al. 2019), with hotspots in developed countries across North America, Europe, Australasia, alongside many island systems. IPBES reported that the cumulative number of alien species was increasing at a rate of 13 per cent per decade and showed no signs of slowing down. Projections under current

Figure 2.26: Number of established alien species (terrestrial and freshwater) in the 18 IPBES subregions and marine ecoregions (marine)



Source: IPBES 2023

trends suggest that the number of established alien species could rise by 36 per cent by 2050 (Seebens et al. 2020; IPBES 2023). Indigenous Peoples as well as local communities may view IAS as part of their landscape and have rights of self-determination regarding their management and eradication. Some IAS provide benefits such as resources like wood or fibre, but most impacts are negative (IPBES 2023).

Invasive species can significantly disrupt ecosystems by altering their structure and function, often outcompeting native species for resources and pushing some towards extinction (Seebens et al. 2021). They can alter nutrient cycling, fire regimes, hydrological processes, and other ecosystem functions, resulting in cascading effects on ecosystem services (IPBES 2023). Species invasion can affect agricultural productivity, damage infrastructure, and disrupt industries such as fisheries and forestry. Previous global assessments (Millennium Ecosystem Assessment 2005; IPBES 2019; IPBES 2023) identify invasive species as a major driver of biodiversity decline, alongside climate change, pollution, land-use change, and direct exploitation. The economic costs of species invasion can be significant, both in terms of direct damage and management expenses. These costs have increased exponentially over time, with aquatic invasions alone costing the global economy at least US$23 billion in 2020 (Cuthbert et al. 2021), and across ecosystems exceeding US$423 billion annually in 2019, having quadrupled every decade since 1970 (IPBES 2019).

Invasive species currently threaten 14 per cent of critically endangered terrestrial vertebrates, with birds particularly affected, often due to introduced mammalian predators. The effects of invasive species on biodiversity are particularly severe on islands (Dueñas et al. 2021), where native species may have evolved without strong competition, predation, or pathogens. Birds on oceanic islands have been especially vulnerable to introduced predators, leading to declines in island avian diversity.

The introduction and spread of non-native plants can increase local floristic diversity (Sax and Gaines 2008); however, extinction can take time (Cronk 2016), and a temporary increase in species richness may mask longer-term declines. In addition, the spread of a few highly invasive species decreases compositional differences among floras, resulting in more homogeneous species assemblages (Daru et al. 2021). The increase in non-native species and homogenization of biotic diversity is a defining feature of the Anthropocene (Olden, Comte and Giam 2016; Daru et al. 2021). Invasive species can act as disease vectors (Hulme 2014), accelerating rates of pathogen spread and increasing risk of zoonotic spillover from wildlife reservoirs. The invasive Asian tiger mosquito (*Aedes albopictus*) has spread to every continent except Antarctica and is a major vector of several human viral diseases, including chikungunya, dengue, and West Nile (Rochlin et al. 2013). Invasive pathogens also present a direct threat to many species (Crowl et al. 2008). The invasive *Batrachochytrium dendrobatidis* fungal pathogen has led to dramatic declines in amphibian communities across the globe, although there is now some evidence of emerging host resistance (Voyles et al. 2018; Scheele et al. 2019). The chestnut blight fungus, *Cryphonectria parasitica*, native to Asia, has devastated temperate forests across the eastern United States of America (Anagnostakis 1987), and the *Xylella fastidiosa* bacterium threatens olive trees across Europe (White et al. 2020). The widespread and intensive planting of agricultural crops has facilitated the expansion of plant pests and pathogens beyond their native range as they follow their hosts (Crous et al. 2016).

Aichi Target 9 aimed to address the challenge of invasive species. The Target's aspirations are clear, "By 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment." Although there have been some notable successes in removing and controlling alien species, such as eradicating cats and rats from islands and using biological control to suppress weeds, efforts to achieve Aichi Target 9 have been insufficient (IPBES 2023).

The pressure from species invasions continues to increase (IPBES 2023), exacerbated through interactions with global pressures of climate change, land-use change, pollution, and other alien species – a process described as "invasional meltdown" (Pyšek et al. 2020).

2.4 Drivers, pressures, and the global environmental crises: Connecting the dots

The global environmental crises arise from the combined drivers (2.2) and pressures (2.3) placed on our planetary system (**Figure 2.1**). Different combinations of pressures compound each crisis, with some pressures being more influential than others, and their relative consequences varying across regions (Chapter 8) and scales. Building on **Figure 2.1**, we present a series of diagrams (**Figures 2.27** to **2.30**) to illustrate the relative strengths of the links between pressures and crises, highlighting the strength of confidence in the scientific evidence supporting them.

In each diagram, the height of the bar represents the relative contribution of different pressures to each crisis, with depth of shading indicating the confidence of the assessment. Assessments are qualitative, categorizing pressures as low, medium and high, based on expert opinion. Although quantitative evaluations are possible for some associations (Jaureguiberry et al. 2022), data are frequently lacking.

Climate change

Human-induced climate change has widespread impacts on ecosystems and is linked to shifts in precipitation, sea level rise, and the loss of glaciers and sea ice (IPCC 2023) (Global Environmental Crises Chapeau). It has led to severe adverse effects on the environment and people's well-being worldwide. Current global financial flows for adaptation are inadequate, resulting in an adaptation gap (IPCC 2023; UNEP 2023b).

Emissions from unsustainable resource use and energy practices – including lifestyles, production, consumption, and agriculture – have driven ongoing increases in GHG emissions (IPCC 2023; UNEP and IRP 2024). While CO_2 is the primary contributor to climate change, other GHGs and air pollutants such as methane, black carbon, and fine particulate matter ($PM_{2.5}$). also influence the climate (IPCC 2021). 55 per cent of CO_2 emissions come from resource extraction and use (UNEP and IRP 2024).

Demand for natural resources such as forest products, livestock grazing land, fish, crops, minerals, and fossil fuels has exceeded the Earth's capacity by more than 75 per cent (WWF 2022) – the consequences for climate change are mainly felt through increased GHG emissions generated during the creation, processing, and distribution of these resources. The adverse effects on the climate system will persist if current consumption patterns continue (FAO 2022).

Land-use changes driven by human consumption are a major factor in climate change, since land functions both as a carbon sink and source (IPCC 2019; Martin et al. 2022). From 2010 to 2019, land-use change and management accounted for roughly nine per cent of global GHG emissions, ranking as the second largest source (IPCC 2021).

Invasive alien species may pose an additional, though lower, pressure on the climate, for example, by increasing the frequency and intensity of wildfires, particularly in hotter and drier climates. Biomass-burning emissions can significantly impair atmospheric conditions with consequences for the wider climate system (Bacher et al. 2023; Dobracki et al. 2023).

Pollution

As demand for resources increases and the current linear model of take it, make it, dispose of it persists, the planet faces a pollution crisis. Resource exploitation is the main driver of pollution (IRP 2017). Pollution

Figure 2.27: Pressures leading to climate change

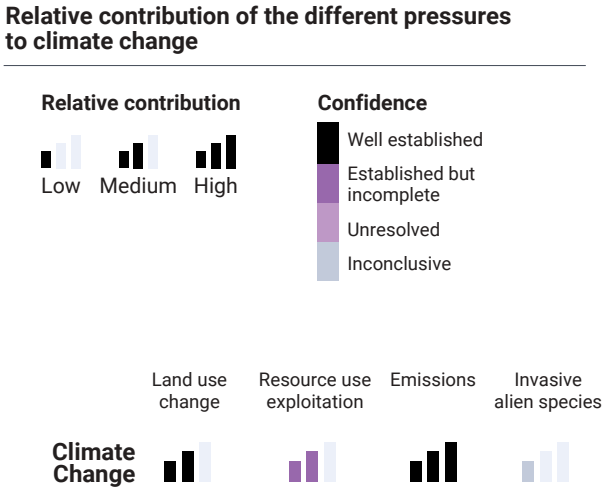
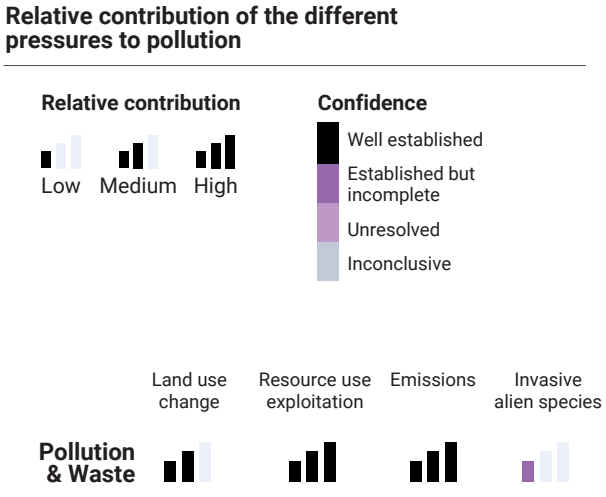


Figure 2.28: Pressures leading to pollution and waste



results from production and consumption patterns, aggravated by uneven distribution, overuse, and overpopulation (Wiedmann et al. 2020). Activities like deforestation, mining, and industrial agriculture lead to air, water, and soil pollution, degrading environmental quality and harming human health (Huo and Peng 2023). "Sacrifice zones," or pollution hotspots linked to significant health challenges, often accompany development. These zones frequently overlap with territories of Indigenous Peoples and other marginalized communities, raising serious environmental justice concerns (Maldonado 2018).

Emissions, including GHGs, are a category of pollutants that can have diffuse repercussions. While many regions have emissions regulations, reducing pollution is a societal challenge that requires behavioural change (Farage, Hansen and Uhl-Haedicke 2024). Technological advancements may assist in reducing pollution in some cases, such as in wastewater treatment or air emission controls (Jain 2024), but they have also historically been a source of new pollutants, like electronic waste. Technology can aid sustainability, yet there is limited empirical evidence on its role in driving transformative change to address the global environmental crises (IPBES 2024).

Land-use changes, particularly the conversion of natural habitats into agricultural land, are a major source of pollution due to the excessive use of fertilizer and pesticides. This leads to increased runoff and leaching of nutrients and pesticides into waterways and groundwater. Urbanization and higher population densities in cities contribute to air and water pollution from transport, heating, and waste. However, recent evidence shows that if properly planned, urbanization can reduce overall pollution levels (Sun et al. 2023) and diminish ecological footprints (Danish, Ulucak and Khan 2020).

Invasive species may contribute to transporting pollutants from one area to another, such as POPs carried by salmon (Montory et al. 2020). While invasive species are not usually considered a major pollutant, they have been recognized as a form of biological pollution (Elliott 2003).

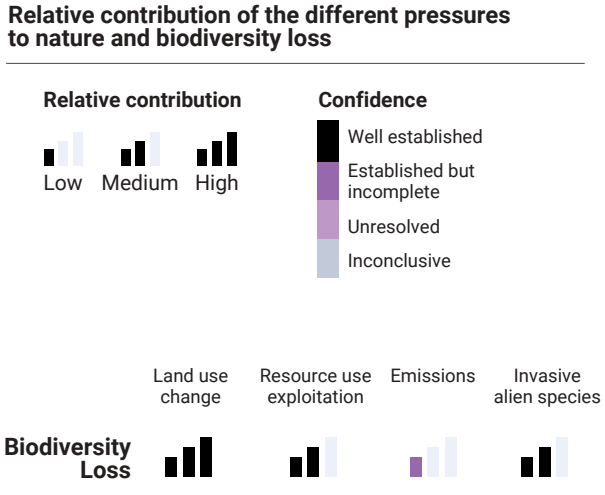
Biodiversity loss

Land-use change is the leading direct threat to biodiversity (Newbold et al. 2016; IPBES 2019). The expansion of agriculture to satisfy the growing demands of an increasingly resource-consuming human population is a key cause of habitat change. Rapid industrialization and urban growth contribute further to the destruction and fragmentation of natural habitats, with adverse outcomes for biodiversity (Kondratyeva et al. 2020; Laurance and Engert 2022; Simkin et al. 2022).

Resource use and overexploitation, whether for timber, minerals, or other natural products, can harm habitats and deplete vital ecosystem components (IRP 2017; Subramanian 2018; Huo and Peng 2023; Lu & Wang 2023). Direct exploitation of wildlife species can cause population collapses with cascading ecological consequences that are difficult to reverse (Daskalov et al. 2007; Myers et al. 2007; Huo and Peng 2023). Effective governance is essential for responsible resource management, while poor governance can result in uncontrolled exploitation and degradation of natural habitats (Springer, Campese and Nakangu 2021; IPBES 2024).

Invasive alien species are recognized as one of the five main drivers of biodiversity loss (IPBES 2023). Invasive species can displace native species through competition or predation and serve as vectors of disease, resulting in population declines and ecosystem imbalances (IPBES 2023). Increased movement of people and trade has raised the rates of alien species introductions, which show no signs of slowing (IPBES 2023).

Figure 2.29: Pressures leading to biodiversity loss



Emissions, including pollutants from industry, transport, and agriculture, can have both diffuse and localized impacts on biodiversity (IRP 2017; Villarrubia-Gomez et al. 2024). Bioaccumulation of pollutants can disproportionately effect species higher in the food chain and pose a risk to human health (Corsolini et al. 2005; Cordier et al. 2024; WHO 2021b). The effect of GHG emissions on biodiversity is largely indirect via their contribution to climate change. While the impacts of climate change on biodiversity are only beginning to be felt (Urban 2024), climate pressures are expected to accelerate rapidly over the next few decades (Pigot et al. 2023).

Land degradation

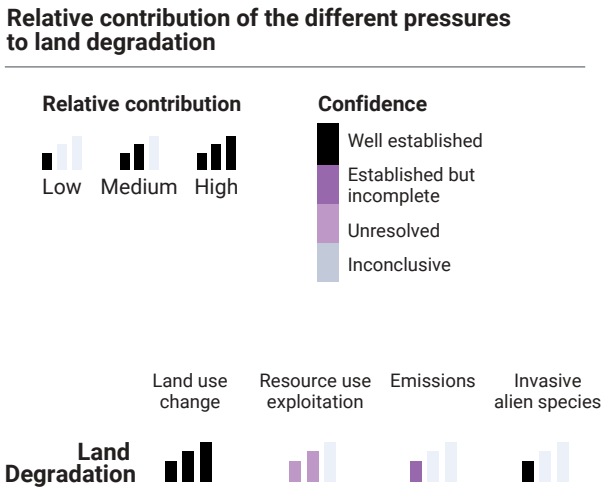
Population growth, conflict, urbanization, economic development, and associated high-consumption lifestyles can cause and worsen land degradation.

Land use change can directly cause land degradation. Agricultural expansion and intensive farming practices, which involve high pesticide and fertilizer use, are key contributors to land degradation and threaten agricultural productivity, ecosystems, and human health (Raj et al. 2023). An increase in contract farming, large-scale land acquisitions, and related processes can signify shifts in land governance towards value chain actors (Clapp 2021; Debonne et al. 2021). These shifts can lead to or intensify land degradation through land-use change and agricultural intensification (Debonne et al. 2021).

Natural resource use, such as wood and timber for bioenergy, increases competition for land, which directly affect food security and land degradation (Olsson et al. 2019; IPBES 2018). Biomass used as fuelwood and charcoal degrades forests and accounts for approximately two per cent of global GHG emissions (Olsson et al. 2019). Meanwhile, extraction of fossil fuels and minerals to meet growing demand for goods and energy is placing locally intense and growing burdens on land integrity.

Pollutants from industry and agriculture, such as industrial chemicals and fertilizers (2.3.3.1), can have both direct and indirect environmental impacts. While GHG emissions are not typically considered a direct cause of land degradation, degraded lands can increase GHG emissions, exacerbating climate change and further degrading ecosystems. In addition, the interaction between climate change and land degradation also affects food security by reducing crop yields (Rosenzweig et al. 2018; IPCC 2018; IPCC 2019), particularly in drylands – home to 2.3 billion people (Vicente-Serrano et al. 2024) – and in high mountain regions (IPCC 2019). Invasive alien species can exacerbate land degradation by disrupting native ecosystems, altering fire regimes and accelerating erosion. Various types of shocks (2.2.7), including armed conflict, can accelerate the rate and magnitude of land degradation processes and trigger new degradation patterns (Bowd et al. 2019; Olsson et al. 2019).

Figure 2.30: Pressures leading to land degradation



References

Abrahamse, W. and Steg, L. (2013). Social influence approaches to encourage resource conservation: A meta-analysis. Global Environmental Change 23(6), 1773-1785. https://doi.org/10.1016/j.gloenvcha.2013.07.029

Acemoglu, D. and Johnson, S. (2023). Power and Progress. Our 1000-Year Struggle Over Technology and Prosperity. https://shapingwork.mit.edu/power-and-progress/

Adebiyi-Abiola, B., Assefa, S., Sheikh, K. and García, J.M. (2019). Cleaning up plastic pollution in Africa. Science 365(6459), 1249-1251. https://doi.org/10.1126/science.aax3539

Adger, W.N., J.M. Pulhin, J. Barnett, G.D. Dabelko, G.K. Hovelsrud, M. Levy et al. Human security. In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir et al. (eds.). Cambridge: Cambridge University Press. chapter 12. https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap12_FINAL.pdf

AI Safety Summit (2023). AI Safety Summit 2023: Roundtable Chairs' Summaries, 1 November. AI Safety Summit. Bletchley Park, 1-2 November 2023. United Kingdom Government, https://www.gov.uk/government/publications/ai-safety-summit-1-november-roundtable-chairs-summaries/ai-safety-summit-2023-roundtable-chairs-summaries-1-november--2

Ajzen, I. (1985). From intentions to actions: A theory of planned behaviour. In Action Control: From Cognition to Behavior. Kuhl, J. and Beckmann, J. (eds.). Berlin, Heidelberg: Springer Berlin Heidelberg. 11-39. https://doi.org/10.1007/978-3-642-69746-3_2

Akinyemi, O., Efobi, U., Asongu, S. and Osabuohein, E. (2019). Renewable energy, trade performance and the conditional role of finance and institutional capacity in sub-Sahara African countries. Energy Policy 132, 490-498. https://doi.org/10.1016/j.enpol.2019.06.012

Ams, J., Baqir, R., Gelpern, A. and Trebesch, C. (2019). 275Sovereign Default. In Sovereign Debt: A Guide for Economists and Practitioners. Abbas, S.A., Pienkowski, A., Rogoff, K., Abbas, S.A., Pienkowski, A. and Rogoff, K. (eds.). Oxford University Press. https://doi.org/10.1093/oso/9780198850823.003.0008

Anagnostakis, S.L. (1987). Chestnut blight: The classical problem of an introduced pathogen. Mycologia 79(1), 23-37. https://doi.org/10.1080/00275514.1987.12025367

Anderson, J.T., Hardy, E.E., Roach, J.T. and Witmer, R.E. (1976). A Land Use and Land Cover Classification System for Use with Remote Sensor Data. https://pubs.usgs.gov/publication/pp964

Anser, M. (2023). Impact of technological advancements on international trade and finance. Modern Diplomacy. https://moderndiplomacy.eu/2023/03/23/impact-of-technological-advancements-on-international-trade-and-finance/. Accessed 15 May 2025

Ashraf, M.A. (2017). Persistent organic pollutants (POPs): a global issue, a global challenge. Environmental Science and Pollution Research 24(5), 4223-4227. https://doi.org/10.1007/s11356-015-5225-9

Bache, I. and Flinders, M. (2004). Multi-level Governance. Oxford University Press. https://doi.org/10.1093/0199259259.001.0001

Bacher, S., Galil, B.S., Nuñez, M.A., Ansong, M., Cassey, P., Dehnen-Schmutz, K. et al. (2023). Impacts of invasive alien species on nature, nature's contributions to people, and good quality of life. In Thematic Assessment Report on Invasive Alien Species and their Control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Roy, H.E., Pauchard, A., Stoett, P. and Renard Truong, T. (eds.). Bonn: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. chapter 4. https://doi.org/10.5281/zenodo.7430731

Barr, S. and Prillwitz, J. (2014). A smarter choice? Exploring the behaviour change agenda for environmentally sustainable mobility. Environment and Planning C: Government and Policy 32(1), 1-19. https://journals.sagepub.com/doi/abs/10.1068/c1201

Bastos, A., Ciais, P., Friedlingstein, P., Sitch, S., Pongratz, J., Fan, L. et al. (2020). Direct and seasonal legacy effects of the 2018 heat wave and drought on European ecosystem productivity. Science Advances 6(24), eaba2724. https://www.science.org/doi/abs/10.1126/sciadv.aba2724

Batty, M. (2018). Inventing Future Cities. MIT Press https://mitpress.mit.edu/9780262548656/inventing-future-cities/

Biswas, A.K. (2000). Scientific assessment of the long-term environmental consequences of war. In The Environmental Consequences of War: Legal, Economic, and Scientific Perspectives. Austin, J.E. and Bruch, C.E. (eds.). Cambridge: Cambridge University Press. 303-315. https://www.cambridge.org/core/product/9ED28778C3797F7E3DDBAE3FB1B90C1C

Biswas, A.K., Farzanegan, M.R. and Thum, M. (2012). Pollution, shadow economy and corruption: Theory and evidence. Ecological Economics 75, 114-125. https://doi.org/10.1016/j.ecolecon.2012.01.007

Black, R. (1994). Forced Migration and Environmental Change: the Impact of Refugees on Host Environments. Journal of Environmental Management 42(3), 261-277. https://doi.org/10.1006/jema.1994.1072

Blaikie, P., Cannon, T., Davis, I. and Wisner, B. (2004). At Risk: Natural Hazards, People's Vulnerability and Disasters. 2nd edn: Routledge. https://doi.org/10.4324/9780203714775

Böhmer, B. (2019). Corruption and illegal deforestation go hand in hand. Transparency International. https://www.transparency.org/en/blog/corruption-and-illegal-deforestation-go-hand-in-hand

Bolderdijk, J.W., Gorsira, M., Keizer, K. and Steg, L. (2013). Values determine the (in)effectiveness of informational interventions in promoting pro-environmental behaviour. PLOS ONE 8(12), e83911. https://doi.org/10.1371/journal.pone.0083911

Bond, G.G. and Garny, V. (2019). Inventory and evaluation of publicly available sources of information on hazards and risks of industrial chemicals. Toxicology and Industrial Health 35(11-12), 738-751. https://doi.org/10.1177/0748233719893198

Boomsma, C. and Steg, L. (2014). The effect of information and values on acceptability of reduced street lighting. Journal of Environmental Psychology 39, 22-31. https://doi.org/10.1016/j.jenvp.2013.11.004

Bosselmann, K., Engel, R. and Taylor, P. (2008). Governance for Sustainability: Issues, Challenges, Successes. Gland: International Union for Conservation of Nature. https://portals.iucn.org/library/sites/library/files/documents/EPLP-070.pdf

Boston Consulting Group and Global Financial Market Association (2020). Climate Finance Markets and the Real Economy: Sizing the Global Need and Defining the Market Structure to Mobilize Capital. https://www.sifma.org/wp-content/uploads/2020/12/Climate-Finance-Markets-and-the-Real-Economy.pdf

Bothe, M. (2023). Protection of the environment in relation to armed conflict—50 years of effort, and no end in sight. Environment and Security 1(1-2), 24-35. https://doi.org/10.1177/27538796231195601

Bowd, E.J., Banks, S.C., Strong, C.L. and Lindenmayer, D.B. (2019). Long-term impacts of wildfire and logging on forest soils. Nature Geoscience 12(2), 113-118. https://doi.org/10.1038/s41561-018-0294-2

BP (2024). BP Energy Outlook Edition. London. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2024.pdf

Bray, J., Johns, N. and Kilburn, D. (2011). An exploratory study into the factors impeding ethical consumption. Journal of Business Ethics 98(4), 597-608. https://doi.org/10.1007/s10551-010-0640-9

Brondízio, E.S., Aumeeruddy-Thomas, Y., Bates, P., Carino, J., Fernández-Llamazares, Á., Ferrari, M.F. et al. (2021). Locally Based, Regionally Manifested, and Globally Relevant: Indigenous and Local Knowledge, Values, and Practices for Nature. Annual Review of Environment and Resources 46(Volume 46, 2021), 481-509. https://doi.org/10.1146/annurev-environ-012220-012127

Broomandi, P., Guney, M., Kim, J.R. and Karaca, F. (2020). Soil contamination in areas impacted by military activities: A critical review. Sustainability 12(21), 9002. https://doi.org/10.3390/su12219002

Brown, L.R. (1981). World population growth, soil Erosion, and food security. Science 214(4524), 995-1002. https://doi.org/10.1126/science.7302578

Bruch, C., Muffett, C. and Nichols, S.S. (2016). Natural resources and post-conflict governance: Building a sustainable peace. In Governance, Natural Resources and Post-Conflict Peacebuilding. Routledge. https://www.taylorfrancis.com/chapters/edit/10.4324/9780203109793-1/natural-resources-post-conflict-governance-building-sustainable-peace-carl-bruch-carroll-muffett-sandra-nichols

Cafaro, P. (2021). Just population policies for an overpopulated world. The Ecological Citizen 5(1), 55–64. https://www.ecologicalcitizen.net/pdfs/epub-046.pdf

Cafaro, P., Hansson, P. and Götmark, F. (2022). Overpopulation is a major cause of biodiversity loss and smaller human populations are necessary to preserve what is left. Biological Conservation 272, 109646. https://doi.org/10.1016/j.biocon.2022.109646

Carrington, M.J., Neville, B.A. and Whitwell, G.J. (2014). Lost in translation: Exploring the ethical consumer intention–behaviour gap. Journal of Business Research 67(1), 2759-2767. https://doi.org/10.1016/j.jbusres.2012.09.022

Caulfield, M., Bouniol, J., Fonte, S.J. and Kessler, A. (2019). How rural out-migrations drive changes to farm and land management: A case study from the rural Andes. Land Use Policy 81, 594-603. https://doi.org/10.1016/j.landusepol.2018.11.030

Cepparulo, A., Eusepi, G. and Giuriato, L. (2019). Can constitutions bring about revolutions? How to enhance decarbonization success. Environmental Science & Policy 93, 200-207. https://doi.org/10.1016/j.envsci.2018.10.019

Cevik, S. and Jalles, J.T. (2022). An apocalypse foretold: Climate shocks and sovereign defaults. Open Economies Review 33(1), 89-108. https://doi.org/10.1007/s11079-021-09624-8

Chen, B., Wu, S., Song, Y., Webster, C., Xu, B. and Gong, P. (2022). Contrasting inequality in human exposure to greenspace between cities of Global North and Global South. Nature Communications 13(1), 4636. https://doi.org/10.1038/s41467-022-32258-4

Cherry, C., Scott, K., Barrett, J. and Pidgeon, N. (2018). Public acceptance of resource-efficiency strategies to mitigate climate change. Nature Climate Change 8(11), 1007-1012. https://doi.org/10.1038/s41558-018-0298-3

Chesnais, A., Brewer, J., Whyte, K., Saposhnik, R. and Johnson, M. (2024). Reform federal policies to enable Native American regenerative agriculture. Issues in Science and Technology 40, 50-54. http://dx.doi.org/10.58875/YQYW4711

Clapp, J. (2021). The problem with growing corporate concentration and power in the global food system. Nature Food 2(6), 404-408. https://doi.org/10.1038/s43016-021-00297-7

Clapp, J. and Dauvergne, P. (2011). Paths to a Green World: The Political Economy of the Global Environment. The MIT Press. http://www.jstor.org/stable/j.ctt5hhcr3

Climact (2018). Net Zero by 2050: From Whether to How. Louvain-la-Neuve. https://europeanclimate.org/wp-content/uploads/2018/09/NZ2050-from-whether-to-how.pdf

Cole, J.C., Gillis, A.J., van der Linden, S., Cohen, M.A. and Vandenbergh, M.P. (2023). Social psychological perspectives on political polarization: Insights and implications for climate change. Perspectives on Psychological Science 20(1), 115-141. https://doi.org/10.1177/17456916231186409

Cole, M.A. (2007). Corruption, income and the environment: An empirical analysis. Ecological Economics 62(3), 637-647. https://doi.org/10.1016/j.ecolecon.2006.08.003

Convention on Biological Diversity (2002). Alien species that threaten ecosystems, habitats or species. https://www.cbd.int/decision/cop/default.shtml?id=7197

Cordier, M., Uehara, T., Jorgensen, B. and Baztan, J. (2024). Reducing plastic production: Economic loss or environmental gain? Cambridge Prisms: Plastics 2, e2. https://www.cambridge.org/core/product/99BEE1E1A6C185B79CD2735B02C59AC6

Corsolini, S., Ademollo, N., Romeo, T., Greco, S. and Focardi, S. (2005). Persistent organic pollutants in edible fish: a human and environmental health problem. Microchemical Journal 79(1), 115-123. https://doi.org/10.1016/j.microc.2004.10.006

Cottingham, J., Germain, A. and Hunt, P. (2012). Use of human rights to meet the unmet need for family planning. The Lancet 380(9837), 172-180. https://doi.org/10.1016/S0140-6736(12)60732-6

Crawford, C.L., Wiebe, R.A., Yin, H., Radeloff, V.C. and Wilcove, D.S. (2024). Biodiversity consequences of cropland abandonment. Nature Sustainability 7(12), 1596-1607. https://doi.org/10.1038/s41893-024-01452-1

Creutzig, F., J. Roy, P. Devine-Wright, J. Díaz-José, F.W. Geels, A. Grubler et al. (2022). Demand, services and social aspects of mitigation. In IPCC 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum et al. (eds.). Cambridge: Cambridge University Press. chapter 5. https://www.ipcc.ch/report/ar6/wg3/chapter/chapter-5/

Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf, E. et al. (2024). GHG Emissions of all World Countries. Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC138862

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N. and Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food 2(3), 198-209. https://doi.org/10.1038/s43016-021-00225-9

Crist, E. (2019). Abundant Earth: Toward an Ecological Civilization. University of Chicago Press. https://doi.org/10.7208/chicago/9780226596945.001.0001

Cronk, Q. (2016). Plant extinctions take time. Science 353(6298), 446-447. https://doi.org/10.1126/science.aag1794

Crous, C.J., Burgess, T.I., Le Roux, J.J., Richardson, D.M., Slippers, B. and Wingfield, M.J. (2016). Ecological disequilibrium drives insect pest and pathogen accumulation in non-native trees. AoB Plants 9(1). https://doi.org/10.1093/aobpla/plw081

Crowl, T.A., Crist, T.O., Parmenter, R.R., Belovsky, G. and Lugo, A.E. (2008). The spread of invasive species and infectious disease as drivers of ecosystem change. Frontiers in Ecology and the Environment 6(5), 238-246. https://doi.org/10.1890/070151

Dadashpoor, H., Azizi, P. and Moghadasi, M. (2019). Land use change, urbanization, and change in landscape pattern in a metropolitan area. Science of The Total Environment 655, 707-719. https://doi.org/10.1016/j.scitotenv.2018.11.267

Damania, R., Fredriksson, P.G. and List, J.A. (2003). Trade liberalization, corruption, and environmental policy formation: Theory and evidence. Journal of Environmental Economics and Management 46(3), 490-512. https://doi.org/10.1016/S0095-0696(03)00025-1

Danish., Ulucak, R. and Khan, S.U.-D. (2020). Determinants of the ecological footprint: Role of renewable energy, natural resources, and urbanization. Sustainable Cities and Society 54, 101996. https://doi.org/10.1016/j.scs.2019.101996

Daru, B.H., Davies, T.J., Willis, C.G., Meineke, E.K., Ronk, A., Zobel, M. et al. (2021). Widespread homogenization of plant communities in

the Anthropocene. Nature Communications 12(1), 6983. https://doi.org/10.1038/s41467-021-27186-8

Dasgupta, P., Solow, R., Barrett, S., Maskin, E., Stiglitz, J., Dasgupta, A. et al. (2019). Time and the generations: Population ethics for a diminishing planet. Columbia University Press. http://www.jstor.org/stable/10.7312/dasg16012

Daskalov, G.M., Grishin, A.N., Rodionov, S. and Mihneva, V. (2007). Trophic cascades triggered by overfishing reveal possible mechanisms of ecosystem regime shifts. Proceedings of the National Academy of Sciences 104(25), 10518-10523. https://doi.org/10.1073/pnas.0701100104

Davies, S., Pettersson, T. and Öberg, M. (2023). Organized violence 1989–2022, and the return of conflict between states. Journal of Peace Research 60(4), 691-708. https://doi.org/10.1177/00223433231185169

Davis, S.J., Lewis, N.S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I.L. et al. (2018). Net-zero emissions energy systems. Science 360(6396), eaas9793. https://doi.org/10.1126/science.aas9793

de Haas, H., Castles, S. and Miller, M.J. (2019). The Age of Migration: International Population Movements in the Modern World. 6th edn: Bloomsbury Publishing. https://www.bloomsbury.com/uk/age-of-migration-9781352007121/

Debonne, N., van Vliet, J., Metternicht, G. and Verburg, P. (2021). Agency shifts in agricultural land governance and their implications for land degradation neutrality. Global Environmental Change 66, 102221. https://doi.org/10.1016/j.gloenvcha.2020.102221

Dellink, R., Chateau, J., Lanzi, E. and Magné, B. (2017). Long-term economic growth projections in the Shared Socioeconomic Pathways. Global Environmental Change 42, 200-214. https://doi.org/10.1016/j.gloenvcha.2015.06.004

Delmas, M.A., Fischlein, M. and Asensio, O.I. (2013). Information strategies and energy conservation behaviour: A meta-analysis of experimental studies from 1975 to 2012. Energy Policy 61, 729-739. https://doi.org/10.1016/j.enpol.2013.05.109

Delventhal, M.J., Fernández-Villaverde, J. and Guner, N. (2021). Demographic transitions across time and space. National Bureau of Economic Research Working Paper Series. Cambridge, MA: National Bureau of Economic Research. http://www.nber.org/papers/w29480.pdf

Deuster, C., Kajander, N., Muench, S., Natale, F., Nedee, A., Scapolo, F. et al. (2023). Demography and Climate Change: EU in the Global Context. Luxembourg: Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC133580

Dhakal, S., J.C. Minx, F.L. Toth, A. Abdel-Aziz, M.J. Figueroa Meza, K. Hubacek et al. (2022). 2022: Emissions trends and drivers. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. chapter 2. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter02.pdf

Dietz, T. (2014). Understanding environmentally significant consumption. Proceedings of the National Academy of Sciences 111(14), 5067-5068. https://doi.org/10.1073/pnas.1403169111

Dobracki, A., Zuidema, P., Howell, S.G., Saide, P., Freitag, S., Aiken, A.C. et al. (2023). An attribution of the low single-scattering albedo of biomass burning aerosol over the southeastern Atlantic. Atmos. Chem. Phys. 23(8), 4775-4799. https://acp.copernicus.org/articles/23/4775/2023/acp-23-4775-2023-discussion.html

Driscoll, D.A., Macdonald, K.J., Gibson, R.K., Doherty, T.S., Nimmo, D.G., Nolan, R.H. et al. (2024). Biodiversity impacts of the 2019–2020 Australian megafires. Nature 635(8040), 898-905. https://doi.org/10.1038/s41586-024-08174-6

Du, Z., Yu, L., Yang, J., Coomes, D., Kanniah, K., Fu, H. et al. (2023). Mapping annual global forest gain from 1983 to 2021 with landsat imagery. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 16, 4195-4204. https://doi.org/10.1109/JSTARS.2023.3267796

Dueñas, M.-A., Hemming, D.J., Roberts, A. and Diaz-Soltero, H. (2021). The threat of invasive species to IUCN-listed critically endangered species: A systematic review. Global Ecology and Conservation 26, e01476. https://doi.org/10.1016/j.gecco.2021.e01476

Efogo, F., Wonyra Kwami Ossadzifo. and Osabuohien, E. (2022). Foreign direct investment and participation of developing countries in global value chains: Lessons from the last decade. International Review of Applied Economics 36(2), 264-284. https://doi.org/10.1080/02692171.2021.1962255

Elliott, M. (2003). Biological pollutants and biological pollution––an increasing cause for concern. Marine Pollution Bulletin 46(3), 275-280. https://doi.org/10.1016/S0025-326X(02)00423-X

Engelman, R. and Johnson, D. (2019). Removing Barriers to Family Planning, Empowering Sustainable Environmental Conservation: A Background Paper and Call for Action. Margaret Pyke Trust, Population & Sustainability Network. https://margaretpyke.org/wp-content/uploads/2021/01/C1-Removing-Barriers.pdf

Erenstein, O., Jaleta, M., Sonder, K., Mottaleb, K. and Prasanna, B.M. (2022). Global maize production, consumption and trade: trends and R&D implications. Food Security 14(5), 1295-1319. https://doi.org/10.1007/s12571-022-01288-7

European Commission (2024). GHSL Data Package 2023. https://human-settlement.emergency.copernicus.eu/documents/GHSL_Data_Package_2023.pdf?t=1727170839

European Commission, International Labour Organization, Food and Agriculture Organization of the United Nations, Organization for Economic Co-operation and Development, United Nations Human Settlements Programme and World Bank (2020). A Recommendation on the Method to Delineate Cities, Urban and Rural Areas for International Statistical Comparisons. https://unhabitat.org/sites/default/files/2020/06/background_document_on_degree_of_urbanization.pdf

European Space Agency (2017). ESA: Land Cover CCI Product User Guide Version 2.0 http://maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf

Eyring, V., Gentine, P., Camps-Valls, G. et al. AI-empowered next-generation multiscale climate modelling for mitigation and adaptation. Nat. Geosci. 17, 963–971 (2024). https://doi.org/10.1038/s41561-024-01527-w

Farage, L., Hansen, N. and Uhl-Haedicke, I. (2024). "The change we seek should start with us": A qualitative analysis of perceptions and causes of littering in the Gambia. Current Research in Ecological and Social Psychology 6, 100177. https://doi.org/10.1016/j.cresp.2023.100177

Feehan, C.J., Filbee-Dexter, K., Thomsen, M.S., Wernberg, T. and Miles, T. (2024). Ecosystem damage by increasing tropical cyclones. Communications Earth & Environment 5(1), 674. https://doi.org/10.1038/s43247-024-01853-2

Filho, W.L., Balogun, A.-L., Olayide, O.E., Azeiteiro, U.M., Ayal, D.Y., Muñoz, P.D.C. et al. (2019). Assessing the impacts of climate change in cities and their adaptive capacity: Towards transformative approaches to climate change adaptation and poverty reduction in urban areas in a set of developing countries. Science of The Total Environment 692, 1175-1190. https://doi.org/10.1016/j.scitotenv.2019.07.227

Fischer, F. (2018). Environmental democracy: participation, deliberation and citizenship. In Environment and Society. Boström, M. and Davidson, D. (eds.). Cham: Palgrave Macmillan. 257-279. https://doi.org/10.1007/978-3-319-76415-3_12

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M. et al. (2011). Solutions for a cultivated planet. Nature 478(7369), 337-342. https://doi.org/10.1038/nature10452

Folke, C., Hahn, T., Olsson, P. and Norberg, J. (2005). Adaptive governance of social-ecological systems. Annual Review of Environment and Resources 30 (Volume 30, 2005), 441-473. https://doi.org/10.1146/annurev.energy.30.050504.144511

Food and Agriculture Organization of the United Nations (2019). Global production of wood products posts highest growth in 70 years. https://www.fao.org/newsroom/detail/Global-production-of-wood-products-posts-highest-growth-in-70-years/en. Accessed 20 May 2025

Food and Agriculture Organization of the United Nations (2020). Global Forest Resources Assessment 2020. Rome. https://doi.org/10.4060/ca9825en

Food and Agriculture Organization of the United Nations (2022). The Future of Food and Agriculture – Drivers and Triggers for Transformation.

Rome. https://openknowledge.fao.org/items/66a787f4-af91-4f6e-b436-560010ab72d4

Food and Agriculture Organization of the United Nations (2023). Pesticides use. Rome https://www.fao.org/faostat/en/#data/RP/visualize

Food and Agriculture Organization of the United Nations (2024). In Brief: The State of World Fisheries and Aquaculture 2024. Blue Transformation in Action. Rome. https://openknowledge.fao.org/handle/20.500.14283/cd0690en

Frank, R.H. (1999). Luxury Fever: Weighing the Cost of Excess. Princeton University Press. https://www.amazon.com/Luxury-Fever-Weighing-Cost-Excess/dp/0691146934

Fredriksson, P.G., Vollebergh, H.R.J. and Dijkgraaf, E. (2004). Corruption and energy efficiency in OECD countries: Theory and evidence. Journal of Environmental Economics and Management 47(2), 207-231. https://doi.org/10.1016/j.jeem.2003.08.001

Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Hauck, J., Landschützer, P. et al. (2025). Global Carbon Budget 2024. Earth System Science Data 17(3), 965-1039. https://doi.org/10.5194/essd-17-965-2025

Gaillard, J.C. (2022). The Invention of Disaster: Power and Knowledge in Discourses on Hazard and Vulnerability. Routledge. https://www.routledge.com/The-Invention-of-Disaster-Power-and-Knowledge-in-Discourses-on-Hazard-and-Vulnerability/Gaillard/p/book/9781032162720?srsltid=AfmBOooaQoz-XPb7Kaf_cvI3QJs3tPLrZ7xW3773Jg_NFVRra1BsMkyC

Gang, C., Zhou, W., Chen, Y., Wang, Z., Sun, Z., Li, J. et al. (2014). Quantitative assessment of the contributions of climate change and human activities on global grassland degradation. Environmental Earth Sciences 72(11), 4273-4282. https://doi.org/10.1007/s12665-014-3322-6

Gates, S., Hegre, H., Nygård, H.M. and Strand, H. (2012). Development consequences of armed conflict. World Development 40(9), 1713-1722. https://doi.org/10.1016/j.worlddev.2012.04.031

Gaynor, K.M., Fiorella, K.J., Gregory, G.H., Kurz, D.J., Seto, K.L., Withey, L.S. et al. (2016). War and wildlife: linking armed conflict to conservation. Frontiers in Ecology and the Environment 14(10), 533-542. https://doi.org/10.1002/fee.1433

Gerges, M.A. (1993). On the impacts of the 1991 Gulf War on the environment of the region: General observations. Marine Pollution Bulletin 27, 305-314. https://doi.org/10.1016/0025-326X(93)90038-L

Gill, C. (2022). Learning to Live Naturally: Stoic Ethics and its Modern Significance. Oxford University Press. https://global.oup.com/academic/product/learning-to-live-naturally-9780198866169?cc=ke&lang=en&#

Glaeser, E., Huang, W., Ma, Y. and Shleifer, A. (2017). A real estate boom with Chinese characteristics. Journal of Economic Perspectives 31(1), 93–116. https://www.aeaweb.org/articles?id=10.1257/jep.31.1.93

Gleditsch, N.P., Wallensteen, P., Eriksson, M., Sollenberg, M. and Strand, H. (2002). Armed Conflict 1946-2001: A New Dataset. Journal of Peace Research 39(5), 615-637. https://www.jstor.org/stable/1555346

Goldewijk, C.K. and Battjes, J.J. (1997). A Hundred Year (1890 - 1990) Database for Integrated Environmental Assessments (HYDE, version 1.1). National Institute of Public Health and the Environment (RIVM). https://www.pbl.nl/en/publications/a-hundred-year-1890-1990-database-for-integrated-environmental-assessments-hyde-version-11#authors

Guo, D., Jiang, K., Xu, C. and Yang, X. (2020). Clustering, growth and inequality in China. Journal of Economic Geography 20(5), 1207-1239. https://doi.org/10.1093/jeg/lbz038

Gupta, J., Scholtens, J., Perch, L., Dankelman, I., Seager, J., Sánder, F. et al. (2020). Re-imagining the driver–pressure–state–impact–response framework from an equity and inclusive development perspective. Sustainability Science 15(2), 503-520. https://doi.org/10.1007/s11625-019-00708-6

Hanna, N., Tamhankar, A.J. and Stålsby Lundborg, C. (2023). Antibiotic concentrations and antibiotic resistance in aquatic environments of the WHO Western Pacific and South-East Asia regions: A systematic review and probabilistic environmental hazard assessment. The Lancet Planetary Health 7(1), e45-e54. https://doi.org/10.1016/S2542-5196(22)00254-6

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A. et al. (2013). High-resolution global maps of 21st-century forest cover change. Science 342(6160), 850-853. https://doi.org/10.1126/science.1244693

Hassan, F.A. (2020). Effect of substituting lentil screening by-product for soybean meal on growth performance, nutrients digestibility and carcass parameters of growing rabbits. Egyptian Poultry Science Journal 40(2), 463-480. https://dx.doi.org/10.21608/epsj.2020.95968

High Level Panel of Experts on Food Security and Nutrition (2020). Food Security and Nutrition: Building a Global Narrative Towards 2030. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/8357b6eb-8010-4254-814a-1493faaf4a93/content

Himaz, R. (2022). Business recovery in Aceh and North Sumatra following the Indian Ocean Tsunami. International Journal of Disaster Risk Reduction 73, 102868. https://doi.org/10.1016/j.ijdrr.2022.102868

Hine, A., Gibson, C., and Mayes, R. (2023). Critical minerals: rethinking extractivism? Australian Geographer 54(3), 233-250. https://doi.org/10.1080/00049182.2023.2210733

Hornik, R. and McAnany, E. (2001). Mass media and fertility change. In Diffusion Processes and Fertility Transition: Selected Perspective. chapter 7. 208-239. https://www.ncbi.nlm.nih.gov/books/NBK223858/

Howard, G. (2021). The future of water and sanitation: Global challenges and the need for greater ambition. AQUA - Water Infrastructure, Ecosystems and Society 70(4), 438-448. https://doi.org/10.2166/aqua.2021.127

Hulme, P.E. (2014). Invasive species challenge the global response to emerging diseases. Trends in Parasitology 30(6), 267-270. https://doi.org/10.1016/j.pt.2014.03.005

Huo, J. and Peng, C. (2023). Depletion of natural resources and environmental quality: Prospects of energy use, energy imports, and economic growth hindrances. Resources Policy 86, 104049. https://doi.org/10.1016/j.resourpol.2023.104049

IK & LK Dialogues. (2025). Indigenous Knowledge and Local Knowledge Dialogues. Global Environment Outlook 7. Mexico City: CopIt-arXives. https://copitarxives.fisica.unam.mx/SC0011EN/SC0011EN.php

Intergovernmental Panel on Climate Change (2018). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla et al. (eds.). Cambridge: Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/sites/2/2022/06/SR15_Full_Report_HR.pdf

Intergovernmental Panel on Climate Change (2019). Summary for Policymakers. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. P.R. Shukla, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai et al. (eds.). https://www.ipcc.ch/srccl/chapter/summary-for-policymakers/

Intergovernmental Panel on Climate Change (2021). Climate Change 2021: The Physical Science Basis Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger et al. (eds.). Cambridge. https://www.ipcc.ch/report/ar6/wg1/

Intergovernmental Panel on Climate Change (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change P.R. Shukla, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak et al. (eds.). Cambridge. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf

Intergovernmental Panel on Climate Change (2023). Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. https://www.cambridge.org/core/books/climate-change-2021-the-physical-science-basis/415F29233B8BD19FB55F65E3DC67272B

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2018). The IPBES Assessment Report on Land Degradation and Restoration. Montanarella, L., Scholes, R. and Brainich, A. (eds.).

Bonn. https://files.ipbes.net/ipbes-web-prod-public-files/2018_ldr_full_report_book_v4_pages.pdf

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). Global Assessment Report on Biodiversity and Ecosystem Services. Bonn. https://www.ipbes.net/global-assessment

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2023). Summary for Policymakers of the Thematic Assessment Report on Invasive Alien Species and their Control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Roy, H.E., Pauchard, A., Stoett, P., Renard Truong, T., Bacher, S., Galil, B.S. et al. (eds.). Bonn. https://doi.org/10.5281/zenodo.7430692

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2024). Summary for Policymakers of the Thematic Assessment Report on the Underlying Causes of Biodiversity Loss and the Determinants of Transformative Change and Options for Achieving the 2050 Vision for Biodiversity of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. O'Brien, K., Garibaldi, L., Agrawal, A., Bennett, E., Biggs, O., Calderón Contreras, R. et al. (eds.). Bonn. https://doi.org/10.5281/zenodo.11382230

International Energy Agency (2020). Energy Technology Perspectives 2020. Paris. https://www.iea.org/reports/energy-technology-perspectives-2020

International Energy Agency (2023a). CO_2 Emissions in 2022. Paris. https://iea.blob.core.windows.net/assets/3c8fa115-35c4-4474-b237-1b00424c8844/CO_2Emissionsin2022.pdf

International Energy Agency (2023b). Global CO_2 emissions by sector, 2019-2022. Paris. https://www.iea.org/data-and-statistics/charts/global-co2-emissions-by-sector-2019-2022

International Energy Agency (2024a). Energy Technology Perspectives 2024. Paris. https://iea.blob.core.windows.net/assets/34511d5d-8dc8-42a2-8faf-b83606cffced/EnergyTechnologyPerspectives2024.pdf

International Energy Agency (2024b). World Energy Outlook 2024. Paris. https://iea.blob.core.windows.net/assets/140a0470-5b90-4922-a0e9-838b3ac6918c/WorldEnergyOutlook2024.pdf

International Energy Agency (2024c). Global Critical Minerals Outlook 2024. Paris. https://iea.blob.core.windows.net/assets/ee01701d-1d5c-4ba8-9df6-abeeac9de99a/GlobalCriticalMineralsOutlook2024.pdf

International Labour Organization (2019). Implementing the ILO Indigenous and Tribal Peoples Convention No. 169. Towards an Inclusive, Sustainable and Just Future. Geneva. https://www.ilo.org/sites/default/files/wcmsp5/groups/public/%40dgreports/%40dcomm/%40publ/documents/publication/wcms_735607.pdf

International Monetary Fund (2019). Building Resilience in Developing Countries Vulnerable to Large Natural Disasters. https://doi.org/10.5089/9781498321020.007

International Resource Panel (2017). Assessing Global Resource Use: A Systems Approach to Resource Efficiency and Pollution Reduction. Bringezu, S., Ramaswami, A., Schandl, H., O'Brien, M., Pelton, R., Acquatella, J. et al. (eds.). Nairobi: A Report by the International Resource Panel, United Nations Environment Programme. https://www.resourcepanel.org/file/904/download?token=Yvoil2o6

Jain, H. (2024). From pollution to progress: Groundbreaking advances in clean technology unveiled. Innovation and Green Development 3(2), 100143. https://doi.org/10.1016/j.igd.2024.100143

Jaureguiberry, P., Titeux, N., Wiemers, M., Bowler, D.E., Coscieme, L., Golden, A.S. et al. (2022). The direct drivers of recent global anthropogenic biodiversity loss. Science Advances 8(45), eabm9982. https://doi.org/10.1126/sciadv.abm9982

Jensen, S.K.G., Kumar, S., Xie, W., Tofail, F., Haque, R., Petri, W.A. et al. (2019). Neural correlates of early adversity among Bangladeshi infants. Scientific Reports 9(1), 3507. https://doi.org/10.1038/s41598-019-39242-x

Jorgenson, A.K. and Clark, B. (2012). Are the economy and the environment decoupling? A comparative international study, 1960-2005. American Journal of Sociology 118(1), 1-44. https://doi.org/10.1086/665990

Kalisz, S., Kibort, K., Mioduska, J., Lieder, M. and Małachowska, A. (2022). Waste management in the mining industry of metals ores, coal, oil and natural gas - A review. Journal of Environmental Management 304, 114239. https://doi.org/10.1016/j.jenvman.2021.114239

Kandt, J. and Batty, M. (2021). Smart cities, big data and urban policy: Towards urban analytics for the long run. Cities 109, 102992. https://doi.org/10.1016/j.cities.2020.102992

Kaufmann, D., Kraay, A. and Mastruzzi, M. (2010). The Worldwide Governance Indicators: Methodology and Analytical Issues. World Bank Policy Research Working Paper. World Bank. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1682130

Khan, S., Naushad, M., Lima, E.C., Zhang, S., Shaheen, S.M. and Rinklebe, J. (2021). Global soil pollution by toxic elements: Current status and future perspectives on the risk assessment and remediation strategies – A review. Journal of Hazardous Materials 417, 126039. https://doi.org/10.1016/j.jhazmat.2021.126039

Klaniecki, K., Duse, I.A., Lutz, L.M., Leventon, J. and Abson, D.J. (2020). Applying the energy cultures framework to understand energy systems in the context of rural sustainability transformation. Energy Policy 137, 111092. https://doi.org/10.1016/j.enpol.2019.111092

Kondratyeva, A., Knapp, S., Durka, W., Kühn, I., Vallet, J., Machon, N. et al. (2020). Urbanization Effects on Biodiversity Revealed by a Two-Scale Analysis of Species Functional Uniqueness vs. Redundancy. Frontiers in Ecology and Evolution Volume 8 - 2020. https://doi.org/10.3389/fevo.2020.00073

Koutroulis, A.G., Papadimitriou, L.V., Grillakis, M.G., Tsanis, I.K., Warren, R. and Betts, R.A. (2019). Global water availability under high-end climate change: A vulnerability-based assessment. Global and Planetary Change 175, 52-63. https://doi.org/10.1016/j.gloplacha.2019.01.013

Krieger, N. (2012). Who and What Is a "Population"? Historical Debates, Current Controversies, and Implications for Understanding "Population Health" and Rectifying Health Inequities. The Milbank Quarterly 90(4), 634-681. https://doi.org/10.1111/j.1468-0009.2012.00678.x

Kümmerer, K., Clark, J.H. and Zuin, V.G. (2020). Rethinking chemistry for a circular economy. Science 367(6476), 369-370. https://doi.org/10.1126/science.aba4979

La Ferrara, E., Chong, A. and Duryea, S. (2012). Soap operas and fertility: Evidence from Brazil. American Economic Journal: Applied Economics 4(4), 1–31. https://www.aeaweb.org/articles?id=10.1257/app.4.4.1

Lamb, W.F., Wiedmann, T., Pongratz, J., Andrew, R., Crippa, M., Olivier, J.G.J. et al. (2021). A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. Environmental Research Letters 16(7), 073005. https://iopscience.iop.org/article/10.1088/1748-9326/abee4e

Laurance, W.F. and Engert, J. (2022). Sprawling cities are rapidly encroaching on Earth's biodiversity. Proceedings of the National Academy of Sciences 119(16), e2202244119. https://doi.org/10.1073/pnas.2202244119

Leitão, A. (2010). Corruption and the environmental Kuznets Curve: Empirical evidence for sulfur. Ecological Economics 69(11), 2191-2201. https://doi.org/10.1016/j.ecolecon.2010.06.004

Levis, C., Flores, B.M., Campos-Silva, J.V., Peroni, N., Staal, A., Padgurschi, M.C.G. et al. (2024). Contributions of human cultures to biodiversity and ecosystem conservation. Nature Ecology & Evolution 8(5), 866-879. https://doi.org/10.1038/s41559-024-02356-1

Li, L. and Wang, W. (2020). The effects of online trust-building mechanisms on trust in the sharing economy: The perspective of providers. Sustainability 12(5), 1717. https://doi.org/10.3390/su12051717

Lianos, T.P. and Pseiridis, A. (2016). Sustainable welfare and optimum population size. Environment, Development and Sustainability 18(6), 1679-1699. https://doi.org/10.1007/s10668-015-9711-5

Lim, X. (2023). Could the world go PFAS-free? Proposal to ban 'forever chemicals' fuels debate. Nature 620(7972), 24-27. https://doi.org/10.1038/d41586-023-02444-5

Liu, X., Yu, L., Si, Y., Zhang, C., Lu, H., Yu, C. et al. (2018). Identifying patterns and hotspots of global land cover transitions using the ESA CCI Land Cover dataset. Remote Sensing Letters 9(10), 972-981. https://doi.org/10.1080/2150704X.2018.1500070

Lock, P., Legg, P., Whittle, L. and Black, S. (2021). Global Outlook for Wood Markets to 2030: Projections of Future Production, Consumption

and Trade Balance. Canberra: Australian Bureau of Agricultural and Resource Economics and Sciences. https://daff.ent.sirsidynix.net.au/client/en_AU/search/asset/1032821/1

López-Carr, D. and Burgdorfer, J. (2013). Deforestation drivers: Population, migration, and tropical land use. Environment: Science and Policy for Sustainable Development 55(1), 3-11. https://doi.org/10.1080/00139157.2013.748385

Lopez-Carr, D. and Ervin, D. (2017). Population-Health-Environment (PHE) synergies? Evidence from USAID-sponsored programmes in African and Asian core conservation areas. European Journal of Geography 8(3), 92-108. https://eurogeojournal.eu/index.php/egj/article/view/307

Lu, C. and Wang, K. (2023). Natural resource conservation outpaces and climate change: Roles of reforestation, mineral extraction, and natural resources depletion. Resources Policy 86, 104159. https://doi.org/10.1016/j.resourpol.2023.104159

Lutzenhiser, L. (1993). Social and behavioural aspects of energy use. Annual Review of Environment and Resources 18, 247-289. https://doi.org/10.1146/annurev.eg.18.110193.001335

Maldonado, J.K. (2018). Seeking Justice in an Energy Sacrifice Zone: Standing on Vanishing Land in Coastal Louisiana. 1st edn: Routledge. https://www.routledge.com/Seeking-Justice-in-an-Energy-Sacrifice-Zone-Standing-on-Vanishing-Land-in-Coasinado/p/book/9781629584010?srsltHLez_gxmGg0jbjIKMFgNRlV7s3zb9YxAQ

Marques, A., Martins, I.S., Kastner, T., Plutzar, C., Theurl, M.C., Eisenmenger, N. et al. (2019). Increasing impacts of land use on biodiversity and carbon sequestration driven by population and economic growth. Nature Ecology & Evolution 3(4), 628-637. https://doi.org/10.1038/s41559-019-0824-3

Martin, A., O'Farrell, P., Kumar, R., Eser, U., Faith, D.P., Gomez-Baggethun, E. et al. (2022). The role of diverse values of nature in visioning and transforming towards just and sustainable futures. In Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. chapter 5. https://doi.org/10.5281/zenodo.6522326

Martínez-Pinna, J., Sempere-Navarro, R., Medina-Gali, R.M., Fuentes, E., Quesada, I., Sargis, R.M. et al. (2023). Endocrine disruptors in plastics alter β-cell physiology and increase the risk of diabetes mellitus. American Journal of Physiology-Endocrinology and Metabolism 324(6), E488-e505. https://doi.org/10.1152/ajpendo.00068.2023

Matanle, P. (2017). Towards an Asia-Pacific 'Depopulation Dividend' in the 21st Century: Regional Growth and Shrinkage in Japan and New Zealand. The Asia-Pacific Journal: Japan Focus 15, 5. http://dx.doi.org/10.1017/S1557466017037706

McDuffie, E.E., Martin, R.V., Spadaro, J.V., Burnett, R., Smith, S.J., O'Rourke, P. et al. (2021). Source sector and fuel contributions to ambient PM2.5 and attributable mortality across multiple spatial scales. Nature Communications 12(1), 3594. https://doi.org/10.1038/s41467-021-23853-y

Meng, X. and Long, Y. (2022). Shrinking cities in China: Evidence from the latest two population censuses 2010–2020. Environment and Planning A: Economy and Space 54(3), 449-453. https://doi.org/10.1177/0308518X221076499

Millennium Ecosystem Assessment (2005). Ecosystems and Human Well-being: Synthesis. Washington DC.: World Resources Institute. https://www.millenniumassessment.org/documents/document.356.aspx.pdf

Montory, M., Habit, E., Fernandez, P., Grimalt, J.O., Kolok, A.S., Barra, R.O. et al. (2020). Biotransport of persistent organic pollutants in the southern Hemisphere by invasive Chinook salmon (Oncorhynchus tshawytscha) in the rivers of northern Chilean Patagonia, a UNESCO biosphere reserve. Environment International 142, 105803. https://doi.org/10.1016/j.envint.2020.105803

Morel H., Megarry W., Potts A., Hosagrahar J., Roberts D.C., Arikan Y. et al. (2022). Global Research and Action Agenda on Culture, Heritage, and Climate Change. International Co-sponsored Meeting on Culture, Heritage & Climate Change. https://openarchive.icomos.org/id/eprint/2716/1/ICSM%20CHC-Global%20Research%20and%20Action%20Agenda%20on%20Culture%2C%20Heritage%20and%20Climate%20Change.pdf

Murray, V., Abrahams, J., Abdallah, C., Ahmed, K., Angles, L., Benouar, D. et al. (2021). Hazard Information Profiles: Supplement to UNDRR-ISC Hazard Definition & Classification Review: Technical Report. Geneva: United Nations Office for Disaster Risk Reduction. https://www.undrr.org/media/73913/download?startDownload=20250521

Myers, R.A., Baum, J.K., Shepherd, T.D., Powers, S.P. and Peterson, C.H. (2007). Cascading Effects of the Loss of Apex Predatory Sharks from a Coastal Ocean. Science 315(5820), 1846-1850. https://doi.org/10.1126/science.1138657

Naidu, R., Biswas, B., Willett, I.R., Cribb, J., Kumar Singh, B., Paul Nathanail, C. et al. (2021). Chemical pollution: A growing peril and potential catastrophic risk to humanity. Environment International 156, 106616. https://doi.org/10.1016/j.envint.2021.106616

Newbold, T., Hudson, L.N., Arnell, A.P., Contu, S., De Palma, A., Ferrier, S. et al. (2016). Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. Science 353(6296), 288-291. https://doi.org/10.1126/science.aaf2201

Nyborg, K., Anderies, J.M., Dannenberg, A., Lindahl, T., Schill, C., Schlüter, M. et al. (2016). Social norms as solutions. Science 354(6308), 42-43. https://doi.org/10.1126/science.aaf8317

O'Neill, D.W., Fanning, A.L., Lamb, W.F. and Steinberger, J.K. (2018). A good life for all within planetary boundaries. Nature Sustainability 1(2), 88-95. https://doi.org/10.1038/s41893-018-0021-4

Olden, J.D., Comte, L. and Giam, X. (2016). Biotic Homogenization. In Encyclopedia of Life Sciences. 1-8. https://doi.org/10.1002/9780470015902.a0020471.pub2

Olsson, L., H. Barbosa, S. Bhadwal, A. Cowie, K. Delusca, D. Flores-Renteria et al. (2019). Land degradation. In Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts et al. (eds.). chapter 4. https://www.ipcc.ch/site/assets/uploads/sites/4/2019/11/07_Chapter-4.pdf

O'Neill, S.J. and Smith, N. (2014). Climate change and visual imagery. WIREs Climate Change 5(1), 73-87. https://doi.org/10.1002/wcc.249

Organization for Economic Co-operation and Development and European Commission (2020). Cities in the World: A New Perspective on Urbanization. OCED Urban Studies. Paris: Organization for Economic Co-operation and Development. https://doi.org/10.1787/d0efcbda-en

Organization for the Prohibition of Chemical Weapons (2022). Annex on Chemicals. https://www.opcw.org/chemical-weapons-convention/annexes/annex-chemicals/annex-chemicals. Accessed 31 August 2022.

Ostrom, E. (1990). Governing the Commons: The Evolution of Institutions for Collective Action. Political Economy of Institutions and Decisions. Cambridge: Cambridge University Press. https://www.cambridge.org/core/product/7AB7AE11BADA84409C34815CC288CD79

Ostrom, E. (2017). Polycentric systems for coping with collective action and global environmental change. In Global Justice. Routledge. 423-430. https://www.taylorfrancis.com/chapters/edit/10.4324/9781315254210-18/polycentric-systems-coping-collective-action-global-environmental-change-elinor-ostrom

Oswald, Y., Owen, A. and Steinberger, J.K. (2020). Large inequality in international and intranational energy footprints between income groups and across consumption categories. Nature Energy 5(3), 231-239. https://doi.org/10.1038/s41560-020-0579-8

Otto, I.M., Donges, J.F., Cremades, R., Bhowmik, A., Hewitt, R.J., Lucht, W. et al. (2020). Social tipping dynamics for stabilizing Earth's climate by 2050. Proceedings of the National Academy of Sciences 117(5), 2354-2365. https://doi.org/10.1073/pnas.1900577117

Ovando, D., Libecap, G.D., Millage, K.D. and Thomas, L. (2020). Coasean approaches to address overfishing: Bigeye Tuna conservation in the Western and Central Pacific Ocean. Marine Resource Economics 36(1), 91-109. https://doi.org/10.1086/711853

Pei, Y., Zhu, Y. and Wang, N. (2021). How do corruption and energy efficiency affect the carbon emission performance of China's industrial sectors? Environmental Science and Pollution Research 28(24), 31403-31420. https://doi.org/10.1007/s11356-021-13032-3

Pigot, A.L., Merow, C., Wilson, A. and Trisos, C.H. (2023). Abrupt expansion of climate change risks for species globally. Nature Ecology & Evolution 7(7), 1060-1071. https://doi.org/10.1038/s41559-023-02070-4

Potapov, P., Turubanova, S., Hansen, M.C., Tyukavina, A., Zalles, V., Khan, A. et al. (2022). Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. Nature Food 3(1), 19-28. https://doi.org/10.1038/s43016-021-00429-z

Povitkina, M. (2018). The limits of democracy in tackling climate change. Environmental Politics 27(3), 411-432. https://doi.org/10.1080/09644016.2018.1444723

Purvis, A., Molnár, Z., Obura, D., Ichii, K., Willis, K., Chettri, N. et al. (2019). Status and Trends – Nature. In Global assessment report of the Intergovernmental Science- Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondízio, J. Settele, S. Díaz and H. T. Ngo (eds.). https://doi.org/10.5281/ZENODO.3832006

Pyšek, P., Hulme, P.E., Simberloff, D., Bacher, S., Blackburn, T.M., Carlton, J.T. et al. (2020). Scientists' warning on Invasive Alien Species. Biological Reviews 95(6), 1511-1534. https://doi.org/10.1111/brv.12627

Radel, C., Jokisch, B.D., Schmook, B., Carte, L., Aguilar-Støen, M., Hermans, K. et al. (2019). Migration as a feature of land system transitions. Current Opinion in Environmental Sustainability 38, 103-110. https://doi.org/10.1016/j.cosust.2019.05.007

Raj, A., Dubey, A., Malla, M.A. and Kumar, A. (2023). Pesticide pestilence: Global scenario and recent advances in detection and degradation methods. Journal of Environmental Management 338, 117680. https://doi.org/10.1016/j.jenvman.2023.117680

Rees, W.E. (2020). Ecological economics for humanity's plague phase. Ecological Economics 169, 106519. https://doi.org/10.1016/j.ecolecon.2019.106519

Reinhart, C.M. and Rogoff, K.S. (2011). The forgotten history of domestic debt. The Economic Journal 121(552), 319-350. https://doi.org/10.1111/j.1468-0297.2011.02426.x

Ripple, W.J., Wolf, C., Gregg, J.W., Rockström, J., Mann, M.E., Oreskes, N. et al. (2024). The 2024 state of the climate report: Perilous times on planet Earth. BioScience 74(12), 812-824. https://doi.org/10.1093/biosci/biae087

Ritchie, H., Samborska, V. and Roser, M. (2018). Urbanization: The world population is moving to cities. Why is urbanization happening and what are the consequences? Our World in Data. https://ourworldindata.org/urbanization. Accessed 11 June 2025.

Ritchie, H., Rosado, P. and Roser, M. (2023). Energy. [OurWorldinData.org https://ourworldindata.org/energy

Rochlin, I., Ninivaggi, D.V., Hutchinson, M.L. and Farajollahi, A. (2013). Climate change and range expansion of the Asian tiger mosquito (Aedes albopictus) in Northeastern USA: Implications for public health practitioners. PLOS ONE 8(4), e60874. https://doi.org/10.1371/journal.pone.0060874

Rodriguez, P., Uhlenbruck, K. and Eden, L. (2005). Government corruption and the entry strategies of multinationals. Academy of Management Review 30(2), 383-396. https://doi.org/10.5465/amr.2005.16387894

Rosenzweig, C., Ruane, A.C., Antle, J., Elliott, J., Ashfaq, M., Chatta, A.A. et al. (2018). Coordinating AgMIP data and models across global and regional scales for 1.5°C and 2.0°C assessments. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 376(2119), 20160455. https://doi.org/10.1098/rsta.2016.0455

Rust, N. and Kehoe, L. (2017). A call for conservation scientists to empirically study the effects of human population policies on biodiversity loss. The Journal of Population and Sustainability 1(2), 53–65. https://doi.org/10.3197/jps.2017.1.2.53

Ryerson, W. (2012). How do we solve the population problem. In Life on the Brink: Environmentalists Confront Overpopulation. Cafaro, P. and Crist, E. (eds.). Athens, GA: University of Georgia Press. 240–254. https://ugapress.org/book/9780820343853/life-on-the-brink/

Salmanidou, D.M., Ehara, A., Himaz, R., Heidarzadeh, M. and Guillas, S. (2021). Impact of future tsunamis from the Java trench on household welfare: Merging geophysics and economics through catastrophe modelling. International Journal of Disaster Risk Reduction 61, 102291. https://doi.org/10.1016/j.ijdrr.2021.102291

Sax, D.F. and Gaines, S.D. (2008). Species invasions and extinction: The future of native biodiversity on islands. Proceedings of the National Academy of Sciences 105(supplement_1), 11490-11497. https://doi.org/10.1073/pnas.0802290105

Schäfer, A. (2021). Multilevel governance. In Dictionary of Political Science Vol. 1: AM. Theories, Methods, Concepts. Nohlen, D. and Schultze, R.-O. (eds.). München. 631-632. https://www.chbeck.de/nohlen-schultze-olaf-lexikon-politikwissenschaft-bd-1-a-m/product/27284333

Scheele, B.C., Pasmans, F., Skerratt, L.F., Berger, L., Martel, A., Beukema, W. et al. (2019). Amphibian fungal panzootic causes catastrophic and ongoing loss of biodiversity. Science 363(6434), 1459-1463. https://doi.org/10.1126/science.aav0379

Schneider-Mayerson, M., Gustafson Abel., Leiserowitz Anthony., Goldberg Matthew H., Rosenthal Seth A. and Ballew, M. (2023). Environmental Literature as Persuasion: An Experimental Test of the Effects of Reading Climate Fiction. Environmental Communication 17(1), 35-50. https://doi.org/10.1080/17524032.2020.1814377

Schwartz, S.H. (1977). Normative Influences on Altruism. Advances in Experimental Social Psychology 10, 221-279. https://doi.org/10.1016/S0065-2601(08)60358-5

Seebens, H., Bacher, S., Blackburn, T.M., Capinha, C., Dawson, W., Dullinger, S. et al. (2021). Projecting the continental accumulation of alien species through to 2050. Global Change Biology 27(5), 970-982. https://doi.org/10.1111/gcb.15333

Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A. et al. (2021). Weather and climate extreme events in a changing climate. In Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (eds.). Cambridge: Cambridge University Press. chapter 11. 1513-1766. https://www.cambridge.org/core/books/climate-change-2021-the-physical-science-basis/weather-and-climate-extreme-events-in-a-changing-climate/5BCB24C5699F1D42B2DE379BDD4E2119

Shandra, J.M., Shor, E. and London, B. (2008). Debt, structural adjustment, and organic water pollution: A cross-national analysis. Organization & Environment 21(1), 38-55. https://doi.org/10.1177/1086026608314759

Silpa, K., Yao, L.C., Perinaz, B.-T. and van Woerden, F. (2018). What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. https://openknowledge.worldbank.org/entities/publication/d3f9d45e-115f-559b-b14f-28552410e90a

Simkin, R.D., Seto, K.C., McDonald, R.I. and Jetz, W. (2022). Biodiversity impacts and conservation implications of urban land expansion projected to 2050. Proceedings of the National Academy of Sciences 119(12), e2117297119. https://doi.org/10.1073/pnas.2117297119

Sinha, A., Gupta, M., Shahbaz, M. and Sengupta, T. (2019). Impact of corruption in public sector on environmental quality: Implications for sustainability in BRICS and next 11 countries. Journal of Cleaner Production 232, 1379-1393. https://doi.org/10.1016/j.jclepro.2019.06.066

Sloggett, A. (2015). Measuring Fertility In Population Analysis for Policy and Programmes. [International Union for the Scientific Study of Population http://papp.iussp.org/sessions/papp101_s04/PAPP101_s04_010_010.html

Smith, P., J. Nkem, K. Calvin, D. Campbell, F. Cherubini, G. Grassi et al. (2019). Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Portner, D. C. Roberts et al. (eds.). Cambridge: Intergovernmental Panel on Climate Change. https://www.ipcc.ch/site/assets/uploads/2019/11/SRCCL-Full-Report-Compiled-191128.pdf

Solomon, N., Birhane, E., Gordon, C., Haile, M., Taheri, F., Azadi, H. et al. (2018). Environmental impacts and causes of conflict in the Horn of Africa: A review. Earth-Science Reviews 177, 284-290. https://doi.org/10.1016/j.earscirev.2017.11.016

Song, M., Xie, Q. and Shen, Z. (2021). Impact of green credit on high-efficiency utilization of energy in China considering environmental constraints. Energy Policy 153, 112267. https://doi.org/10.1016/j.enpol.2021.112267

Springer, J., Campese, J. and Nakangu, B. (2021). The Natural Resource Governance Framework. Improving Governance for Equitable and Effective Conservation. Gland: International Union for Conservation of Nature. https://portals.iucn.org/library/sites/library/files/documents/2021-031-En.pdf

Steg, L. (2016). Values, norms, and intrinsic motivation to act proenvironmentally. Annual Review of Environment and Resources 41, 277-292. https://doi.org/10.1146/annurev-environ-110615-085947

Stephenson, J., Barton, B., Carrington, G., Doering, A., Ford, R., Hopkins, D. et al. (2015). The energy cultures framework: Exploring the role of norms, practices and material culture in shaping energy behaviour in New Zealand. Energy Research & Social Science 7, 117-123. https://doi.org/10.1016/j.erss.2015.03.005

Stern, P.C. (2000). New environmental theories: Toward a coherent theory of environmentally significant behaviour. Journal of Social Issues 56(3), 407-424. https://doi.org/10.1111/0022-4537.00175

Stockholm Convention on Persistent Organic Pollutants (2023). Third Global Monitoring Report. https://chm.pops.int/Implementation/GlobalMonitoringPlan/MonitoringReports/tabid/525/Default.aspx

Su, C.-W., Dai, K., Ullah, S. and Andlib, Z. (2022). COVID-19 pandemic and unemployment dynamics in European economies. Economic Research-Ekonomska Istraživanja 35(1), 1752-1764. https://doi.org/10.1080/1331677X.2021.1912627

Subramanian, K. (2018). The crisis of consumption of natural resources. International Journal of Recent Innovations in Academic Research 2(4), 8-19. https://www.researchgate.net/publication/327384344_The_Crisis_of_Consumption_of_Natural_Resources

Sun, L., Chen, J., Li, Q. and Huang, D. (2020). Dramatic uneven urbanization of large cities throughout the world in recent decades. Nature Communications 11(1), 5366. https://doi.org/10.1038/s41467-020-19158-1

Sun, B., Fang, C., Liao, X., Guo, X. and Liu, Z. (2023). The relationship between urbanization and air pollution affected by intercity factor mobility: A case of the Yangtze River Delta region. Environmental Impact Assessment Review 100, 107092. https://doi.org/10.1016/j.eiar.2023.107092

Sunstein, C.R. (2019). Conformity. The Power of Social Influences. NYU Press. http://www.jstor.org/stable/j.ctv12fw6f0

Systems Change Lab (2025). Economics. World Resources Institute. https://systemschangelab.org/economics. Accessed 26 May 2025.

Syukriyah, D. and Himaz, R. (2024). Short and medium-run effects of the Indian Ocean tsunami on health costs in Indonesia. World Development 180, 106648. https://doi.org/10.1016/j.worlddev.2024.106648

Tamburino, L. and Bravo, G. (2021). Reconciling a positive ecological balance with human development: A quantitative assessment. Ecological Indicators 129, 107973. https://doi.org/10.1016/j.ecolind.2021.107973

Tan, J. (2021). Regional economic resilience of resource-based cities and influential factors during economic crises in China. In Economic Resilience in Regions and Organizations. Wink, R. (ed.). Wiesbaden: Springer Fachmedien Wiesbaden. 91-115. https://doi.org/10.1007/978-3-658-33079-8_4

Tang, L. and Werner, T.T. (2023). Global mining footprint mapped from high-resolution satellite imagery. Communications Earth & Environment 4(1), 134. https://doi.org/10.1038/s43247-023-00805-6

Tawiah, V., Zakari, A. and Alvarado, R. (2024). Effect of corruption on green growth. Environment, Development and Sustainability 26(4), 10429-10459. https://doi.org/10.1007/s10668-023-03152-w

Taylor, M. (2015). The Political Ecology of Climate Change Adaptation. Livelihoods, Agrarian Change and the Conflicts of Development. Routledge. https://www.routledge.com/The-Political-Ecology-of-Climate-Change-Adaptation-Livelihoods-agrarian-change-and-the-conflicts-of-developmentkSWGnutNeoixd7Acb

The Energy Institute (2024). Statistical Review of World Energy. The Energy Institute. https://www.energyinst.org/__data/assets/pdf_file/0006/1542714/684_EI_Stat_Review_V16_DIGITAL.pdf

Thornton, T.F., Mangalagiu, D., Ma, Y., Lan, J., Yazar, M., Saysel, A.K. et al. (2020). Cultural models of and for urban sustainability: assessing beliefs about Green-Win. Climatic Change 160(4), 521-537. https://doi.org/10.1007/s10584-019-02518-2

Tidwell, A.C. and Zellen, B.S. (eds.) (2016). Land, Indigenous Peoples and Conflict. 1st edn: Routledge. https://www.routledge.com/Land-Indigenous-Peoples-and-Conflict/Tidwell-Zellen/p/book/97811GCCDYEfzwhbmzEd1qQCp3bjlt

Tucker, C. (2019). A Planet of 3 billion: Mapping Humanity's Long History of Ecological Destruction and Finding Our Way to a Resilient Future. A Global Citizen's Guide to Saving the Planet. Atlas Observatory Press. https://www.amazon.com/Plaateway&sr=8-1

Turner, N. (2021). Influence of Religion and Religiosity on Fertility and Contraceptive Use in Continental Sub-Saharan Africa: A Comprehensive Review. Center for Open Science. https://ideas.repec.org/p/osf/thesis/sezdq.html

United Nations (2015). Population 2030: Demographic Challenges and Opportunities for Sustainable Development Planning. New York; NY. https://www.un.org/en/development/desa/population/publications/pdf/trends/Population2030.pdf

United Nations (2019a). World Urbanization Prospects. The 2018 Revision. https://population.un.org/wup/assets/WUP2018-Report.pdf

United Nations (2019b). World Population Prospects 2019. Highlights. https://population.un.org/wpp/assets/Files/WPP2019_Highlights.pdf

United Nations (2020). World Social Report 2020: Inequality in a Rapidly Changing World. https://social.desa.un.org/sites/default/files/publications/2023-03/World-Social-Report2020-FullReport.pdf

United Nations (2022). World Population Prospects 2022: Summary of Results. https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/wpp2022_summary_of_results.pdf

United Nations (2023a). GAR Special Report: Measuring Resilience for the Sustainable Development Goals. Geneva: United Nations Office for Disaster Risk Reduction. https://www.undrr.org/media/88718/download

United Nations (2023b). UNdata Environment Statistics Database. http://data.un.org/Explorer.aspx?d=ENV

United Nations (2024a). UNdata Fish, Seafood. https://data.un.org/Data

United Nations (2024b). World Wildlife Crime Report 2024. Vienna. https://www.unodc.org/cofrb/uploads/documents/ECOS/World_Wildlife_Crime_Report_2024.pdf

United Nations (2025a). UNdata Energy Statistics Database (2000–2021). http://data.un.org/Explorer.aspx?d=EDATA

United Nations (2025b). UNdata Commodity Trade Statistics Database. http://data.un.org/Explorer.aspx?d=EDATA

United Nations (2025c). Harnessing the potential of critical minerals for sustainable development. In World Economic Situation and Prospects 2025. Department of Economic and Social Affairs. chapter 2. https://www.un.org/development/desa/dpad/publication/world-economic-situation-and-prospects-2025/

United Nations Convention to Combat Desertification (2025). Great green wall initiatives. https://www.unccd.int/our-work/ggwi. Accessed March 2025

United Nations Development Programme (2022). The Sovereign Debt Crisis in Sri Lanka: Causes, Policy Response and Prospects. UNDP Regional Bureau for Asia and the Pacific. https://www.undp.org/sites/g/files/zskgke326/files/2022-11/UNDP-Sovereign-Debt-Crisis-in-Sri-Lanka-Report-2022.pdf

United Nations Development Programme (2024). Human Development Index (HDI). https://hdr.undp.org/data-center/human-development-index#/indicies/HDI Accessed 21 May 2025

United Nations Development Programme (2025). Human Development Report 2025. A Matter of Choice: People and Possibilities in the Age of AI. https://hdr.undp.org/system/files/documents/global-report-document/hdr2025reporten.pdf

United Nations Educational, Scientific and Cultural Organization (2019). UN World Water Development Report 2019 - Leaving No One Behind. https://unesdoc.unesco.org/ark:/48223/pf0000367306

United Nations Educational, Scientific and Cultural Organization (2021). Recommendation on the Ethics of Artificial Intelligence. Paris. https://unesdoc.unesco.org/ark:/48223/pf0000380455/PDF/380455eng.pdf.multi

United Nations Educational, Scientific and Cultural Organization (2023). UN World Water Development Report: Partnerships and cooperation for water. United Nations, https://unesdoc.unesco.org/ark:/48223/pf0000384655

United Nations Environment Programme (2007). Lebanon Post-Conflict Environmental Assessment. Nairobi. https://www.unep.org/resources/assessment/lebanon-post-conflict-environmental-assessment

United Nations Environment Programme (2019). Global Chemicals Outlook II – From Legacies to Innovative Solutions: Implementing the 2030 Agenda for Sustainable Development. Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/28113/GCOII.pdf?sequence=1&isAllowed=y

United Nations Environment Programme (2020). State of Environment and Outlook Report for the Occupied Palestinian Territory 2020. Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/32268/SEORP.pdf?sequence=1&isAllowed=y

United Nations Environment Programme (2022). The Environmental Impact of the Conflict in Ukraine: A Preliminary Review. Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/40746/environmental_impact_Ukraine_conflict.pdf?sequence=3&isAllowed=y

United Nations Environment Programme (2023a). Chemicals in Plastics - A Technical Report. Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/42366/Chemicals-in-Plastics.pdf?sequence=1&isAllowed=y

United Nations Environment Programme (2023b). Adaptation Gap Report 2023. Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/43796/adaptation_gap_report_2023.pdf?sequence=1&isAllowed=y

United Nations Environment Programme (2024). Emissions Gap Report 2024. Nairobi. https://wedocs.unep.org/handle/20.500.11822/46404

United Nations Environment Programme and International Resource Panel (2024). Global Resources Outlook 2024 - Bend the trend: Pathways to a Liveable Planet as Resource Use Spikes - Summary for Policymakers. Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/44902/GRO24_Summary_for_Policymakers.pdf?sequence=3&isAllowed=y

United Nations Human Settlements Programme (2019). The Urban SDG Monitoring Series. Monitoring SDG Indicator 11.1.1. Global Monitoring of Slums Remains a Key Concern for Achieving the Right to Adequate Housing Nairobi. https://unhabitat.org/sites/default/files/2020/06/the_urban_sdg_monitoring_series_monitoring_sdg_indicator_11.1.1.pdf

United Nations Population Fund (2022). As the world's population hits 8 billion people, UN calls for solidarity in advancing sustainable development for all 14 November 2022 https://www.unfpa.org/press/world%E2%80%99s-population-hits-8-billion-people-un-calls-solidarity-advancing-sustainable

United Nations Populations Fund (2019). PAPP101 - S01: Demography on the world stage. The demographic transition. Available: http://papp.iussp.org/sessions/papp101_s01/PAPP101_s01_090_010.html. Accessed: 15 August 2025

United Nations Trade and Development (2022). Tackling Debt and Climate Challenges in Tandem: A Policy Agenda. UNCTAD Policy Brief. Geneva. https://unctad.org/system/files/official-document/presspb2022d12_en.pdf

United States Geological Survey (2021). Mineral Commodity Summaries 2021. Mineral Commodity Summaries. Reston, VA. https://pubs.usgs.gov/periodicals/mcs2021/mcs2021.pdf

Urban, M.C. (2024). Climate change extinctions. Science 386(6726), 1123-1128. https://www.science.org/doi/abs/10.1126/science.adp4461

van Bavel, B., Berrang-Ford, L., Moon, K., Gudda, F., Thornton, A.J., Robinson, R.F.S. et al. (2024). Intersections between climate change and antimicrobial resistance: A systematic scoping review. Lancet Planet Health 8(12), e1118-e1128. https://doi.org/10.1016/s2542-5196(24)00273-0

van Kooten, G.C., Nijnik, M. and Bradford, K. (2019). Can carbon accounting promote economic development in forest-dependent, indigenous communities? Forest Policy and Economics 100, 68-74. https://doi.org/10.1016/j.forpol.2018.10.012

Vicente-Serrano, S.M., Pricope, N.G., Toreti, A., Morán-Tejeda, E., Spinoni, J., Ocampo-Melgar, A. et al. (2024). The Global Threat of Drying Lands: Regional and Global Aridity Trends and Future Projections. A Report of the Science-Policy Interface. United Nations Convention to Combat Desertification. https://www.unccd.int/sites/default/files/2024-12/aridity_report.pdf

Venter, O., Sanderson, E.W., Magrach, A., Allan, J.R., Beher, J., Jones, K.R. et al. (2016). Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. Nature Communications 7(1), 12558. https://doi.org/10.1038/ncomms12558

Villarrubia-Gómez, P., Carney Almroth, B., Eriksen, M., Ryberg, M. and Cornell, S.E. (2024). Plastics pollution exacerbates the impacts of all planetary boundaries. One Earth 7(12), 2119-2138. https://doi.org/10.1016/j.oneear.2024.10.017

Voyles, J., Woodhams, D.C., Saenz, V., Byrne, A.Q., Perez, R., Rios-Sotelo, G. et al. (2018). Shifts in disease dynamics in a tropical amphibian assemblage are not due to pathogen attenuation. Science 359(6383), 1517-1519. https://doi.org/10.1126/science.aao4806

Wang, J., Chen, Y., Liao, W., He, G., Tett, S.F.B., Yan, Z. et al. (2021). Anthropogenic emissions and urbanization increase risk of compound hot extremes in cities. Nature Climate Change 11(12), 1084-1089. https://doi.org/10.1038/s41558-021-01196-2

Wang, Q., Wang, X. and Li, R. (2022). Does urbanization redefine the environmental Kuznets curve? An empirical analysis of 134 Countries. Sustainable Cities and Society 76, 103382. https://doi.org/10.1016/j.scs.2021.103382

Wang, Z., Walker, G.W., Muir, D.C.G. and Nagatani-Yoshida, K. (2020). Toward a global understanding of chemical pollution: A first comprehensive analysis of national and regional chemical inventories. Environmental Science & Technology 54(5), 2575-2584. https://pubs.acs.org/doi/10.1021/acs.est.9b06379

Wei, J., Li, Z., Lyapustin, A., Wang, J., Dubovik, O., Schwartz, J. et al. (2023). First close insight into global daily gapless 1 km PM2.5 pollution, variability, and health impact. Nature Communications 14(1), 8349. https://doi.org/10.1038/s41467-023-43862-3

Werlin, H.H. (1994). Revisiting corruption: With a new definition. International Review of Administrative Sciences 60(4), 547-558. https://doi.org/10.1177/002085239406000401

White, S.M., Navas-Cortés, J.A., Bullock, J.M., Boscia, D. and Chapman, D.S. (2020). Estimating the epidemiology of emerging Xylella fastidiosa outbreaks in olives. Plant Pathology 69(8), 1403-1413. https://doi.org/10.1111/ppa.13238

Wiedmann, T., Lenzen, M., Keyßer, L.T. and Steinberger, J.K. (2020). Scientists' warning on affluence. Nature Communications 11(1), 3107. https://doi.org/10.1038/s41467-020-16941-y

Winkler, K., Fuchs, R., Rounsevell, M. and Herold, M. (2021). Global land use changes are four times greater than previously estimated. Nature Communications 12(1), 2501. https://doi.org/10.1038/s41467-021-22702-2

Wolff, M. and Wiechmann, T. (2017). Urban growth and decline: Europe's shrinking cities in a comparative perspective 1990–2010. European Urban and Regional Studies 25(2), 122-139. https://doi.org/10.1177/0969776417694680

World Bank (2023a). Global Economic Prospects, June 2023. https://openknowledge.worldbank.org/handle/10986/39846

World Bank (2023b). Fertilizer consumption (kilograms per hectare of arable land). World Development Indicators. https://data.worldbank.org/indicator/AG.CON.FERT.ZS

World Bank (2025). World Development Indicators. https://databank.worldbank.org/source/world-development-indicators

World Health Organization (2021a). WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10) Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. https://iris.who.int/bitstream/handle/10665/345329/9789240034228-eng.pdf?sequence=1

World Health Organization (2021b). Preventing Disease through Healthy Environments. Exposure to Mercury: A Major Public Health Concern. https://iris.who.int/bitstream/handle/10665/340715/9789240023567-eng.pdf?sequence=1#:~:text=Second%20edition,example%2C%20methylmercury%20and%20ethylmercury

World Health Organization (2022). Billions of people still breathe unhealthy air: New WHO data https://www.who.int/news/item/04-04-2022-billions-of-people-still-breathe-unhealthy-air-new-who-data#:~:text=Almost%20the%20entire%20global%20population,countries%20suffering%20the%20highest%20exposures

World Health Organization (2024). COP29 Special Report on Climate Change and Health: Health is the Argument for Climate Action. https://cdn.who.int/media/docs/default-source/environment-climate-change-and-health/58595-who-cop29-special-report_layout_9web.pdf

World Resources Institute (2006). WRI Annual Report 2005. Washington, DC. https://www.wri.org/webform/download_publication?source_entity_type=node&source_entity_id=39724

World Wide Fund for Nature (2022). Living Planet Report 2022 – Building a Nature Positive Society. Almond, R.E.A., Grooten, M., Juffe Bignoli and Petersen, T. (eds.). Gland. https://wwfint.awsassets.panda.org/downloads/embargo_13_10_2022_lpr_2022_full_report_single_page_1.pdf

Woźniak, E., Waszkowska, E., Zimny, T., Sowa, S. and Twardowski, T. (2019). The rapeseed potential in Poland and Germany in the context of production, legislation, and intellectual property rights. Frontiers in Plant Science 10. https://doi.org/10.3389/fpls.2019.01423

Wright, S.L., Thompson, R.C. and Galloway, T.S. (2013). The physical impacts of microplastics on marine organisms: A review. Environmental Pollution 178, 483-492. https://doi.org/10.1016/j.envpol.2013.02.031

Wu, H., Xia, Y., Yang, X., Hao, Y. and Ren, S. (2021). Does environmental pollution promote China's crime rate? A new perspective through government official corruption. Structural Change and Economic Dynamics 57, 292-307. https://doi.org/10.1016/j.strueco.2021.04.006

Wyman, R. and Yao, G. (2017). Population. In Routledge Handbook of Religion and Ecology. Jenkins, W., Tucker, M.E. and Grim, J. (eds.). chapter 32. https://www.routledge.com/Routledge-Handbook-of-Religion-and-Ecology/Jenkins-Tucker-Grim/p/book/9781138315938?srsltid=AfmBOoos_pYy7ShlIntud0_7VofCUPgnyehJz3-Gly5TxTumhsm1_hWD

Yang, H., Xia, J., Thompson, J.R. and Flower, R.J. (2017). Urban construction and demolition waste and landfill failure in Shenzhen, China. Waste Management 63, 393-396. https://doi.org/10.1016/j.wasman.2017.01.026

Yin, H., Brandão, A., Buchner, J., Helmers, D., Iuliano, B.G., Kimambo, N.E. et al. (2020). Monitoring cropland abandonment with Landsat time series. Remote Sensing of Environment 246, 111873. https://doi.org/10.1016/j.rse.2020.111873

Young, W., Hwang, K., McDonald, S. and Oates, C.J. (2010). Sustainable consumption: Green consumer behaviour when purchasing products. Sustainable Development 18(1), 20-31. https://doi.org/10.1002/sd.394

Yu, L., Du, Z., Dong, R., Zheng, J., Tu, Y., Chen, X. et al. (2022). FROM-GLC Plus: toward near real-time and multi-resolution land cover mapping. GIScience & Remote Sensing 59(1), 1026-1047. https://doi.org/10.1080/15481603.2022.2096184

Yuan, B. and Xiang, Q. (2018). Environmental regulation, industrial innovation and green development of Chinese manufacturing: Based on an extended CDM model. Journal of Cleaner Production 176, 895-908. https://doi.org/10.1016/j.jclepro.2017.12.034

Zabel, F., Delzeit, R., Schneider, J.M., Seppelt, R., Mauser, W. and Václavík, T. (2019). Global impacts of future cropland expansion and intensification on agricultural markets and biodiversity. Nature Communications 10(1), 2844. https://doi.org/10.1038/s41467-019-10775-z

Zhang, Z., Zhang, Q., Wang, T., Xu, N., Lu, T., Hong, W. et al. (2022). Assessment of global health risk of antibiotic resistance genes. Nature Communications 13(1), 1553. https://doi.org/10.1038/s41467-022-29283-8

Zhou, A. and Li, J. (2021). Impact of anti-corruption and environmental regulation on the green development of China's manufacturing industry. Sustainable Production and Consumption 27, 1944-1960. https://doi.org/10.1016/j.spc.2021.04.031

Credit: NASA Visible Earth

PART B

State and Trends of the Environment

Global Environmental Crises Chapeau

Indigenous Knowledge and Local Knowledge Chapeau B

Chapter 3
Air

Chapter 4
Land and Soils

Chapter 5
Oceans and Coasts

Chapter 6
Freshwater

Chapter 7
Implications of Environmental Crises on the Socioeconomic Dimensions of the Sustainable Development Goals

Chapter 8
Interlinkages Across Environmental Changes, Scales and Geographic Regions and Subregions

Coordinating Lead Authors: Jonathan Davies (University of British Columbia)

Lead Authors: Ricardo O. Barra (University of Concepcion), Stephan Harrison (University of Exeter), Mulako Kabisa (University of the Witwatersrand), Indu K Murthy (Center for Study of Science, Technology and Policy), Ravendra Naidu (University of Newcastle), Dulce Flores-Renteria (SECIHTI-Center for Research and Advanced Studies of the National Polytechnic Institute), Elias Symeonakis (Manchester Metropolitan University), Fiffy Hanisdah Binti Saikim (Universiti Malaysia Sabah), Maria-Cristina Tirado-von der Pahlen (University of California), Natalia Tarasova (D. Mendeleev University of Chemical Technology of Russia), Le Yu (Tsinghua University)

Fellows: Christina Karakizi (National Technical University of Athens, Hellenic Space Center) Eleni Sofikiti (National Technical University of Athens)

Credit: travellersnep/Envato

Global Environmental Crises Chapeau

C.1 A planet in crisis

In March 2024, the United Nations Environment Assembly called for urgent collaborative action to address the global environmental crises defined as the crisis of climate change, the crisis of biodiversity loss, land degradation and desertification, and the crisis of pollution and waste (UNEP/EA.6/HLS.1). These environmental crises risk catastrophic consequences for human well-being and may therefore also be regarded as social, economic, safety and security crises. More than 40 per cent of the global population lives in areas that have experienced significant biodiversity decline (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES] 2024a), while 71 per cent of the working population – 2.4 billion people – are exposed to excessive heat at work (International Labour Organization [ILO] 2019), seven million deaths annually are attributed to pollution (Fuller et al. 2022), and land degradation is increasing by 100 million hectares every year (United Nations Convention to Combat Desertification [UNCCD] n.d.; Tomalka et al. 2024). Rapid and irreversible environmental shifts, exacerbated by interactions and feedback between and among the crises that may precipitate environmental tipping points, are of increasing concern (10.5). For example, rising temperatures have the potential to accelerate land degradation and ecosystem disruption, both of which may feed back to exacerbate the climate and biodiversity crises (Pörtner et al. 2021).

C.1.1 Climate change

Climate change, unequivocally driven by greenhouse gas (GHG) emissions from human activities such as burning fossil fuels and deforestation, has warmed the Earth's surface by an average of at least 1.3°C (Intergovernmental Panel on Climate Change [IPCC] 2023a; World Meteorological Organization [WMO] 2024a; Obada et al. 2024). The last two years – 2023 and 2024 – were the warmest on record, with the 2024 global temperature averaging 1.55°C warmer than the period before widespread industrialization (Copernicus 2024; WMO 2024b). This indicates a rapid acceleration towards or beyond the 1.5°C threshold of the Paris Agreement (Lamboll et al. 2023). At 1.5°C warming, increasing extreme weather patterns, sea-level rise, loss of coral reefs, a reduction in rainforest biomass and a decline of mangrove forests can be expected. The Arctic Ocean may become ice-free in summer by the mid-2050s, a sea-level rise of more than 1.5 metres is possible due to Antarctic and Greenland ice-sheet melt, and a 70–90 per cent decline in coral reefs is likely (IPCC 2021a; IPCC 2022; Kim et al. 2023; Buis 2024; Jahn et al. 2024). The impacts of these changes are experienced differently across regions, communities and populations and are exacerbated by existing differences and vulnerabilities (WMO 2024c).

The economic, environmental, social and health costs of climate change are substantial and projected to escalate steeply, with significant cost disparities across regions and socioeconomic contexts (IPCC 2022). Women, particularly in developing countries, are more vulnerable to climate change effects due to their roles in agriculture and water collection (Fruttero et al. 2023). The global cost of climate-induced extreme weather events in the past 20 years is estimated at US$143 billion per year, with the United States incurring a cost of US$27 billion in 2024 (Newman and Noy 2023; National Centers for Environmental Information2025). Costs have increased exponentially over the last five years, and cumulative costs from 2014–2023 are estimated at US$2 trillion, affecting 1.6 billion people (Oxera 2024). Climate-related costs are compounded by the indirect risks associated with rising temperatures, especially health issues such as heat-related illnesses and deaths, and food and water security (United Nations Office for Disaster Risk Reduction 2023).

Modelled pathways show with high confidence that the projected warming by 2040 can only be avoided if rapid and deep emissions cuts are made in all sectors in this decade (IPCC 2023b). To achieve the Paris target of 1.5° C would require cuts in emissions of 42 per cent by 2030 and 57 per cent by 2035, whereas emissions in 2030 would be comparable to today even with full implementation of current nationally determined contributions (UNEP, 2024).

C.1.2 Biodiversity loss

An estimated one million species are currently at risk of extinction (IPBES 2019) and current extinction rates are calculated to be several orders of magnitude greater than background rates estimated from the fossil record (De Vos et al. 2015). The world is accumulating a large extinction debt – the number of species committed to extinction – as a consequence of humanity's past actions (Spalding and Hull 2021) (Wang et al. 2025). Many iconic species are at imminent risk of extinction, including the California Condor, Black Rhino, and the Bornean Orangutan (IUCN 2025). Genetic diversity loss since the Industrial Revolution, conservatively estimated at 5-10 per cent globally and at over 25 per cent on islands (Leigh et al. 2019; Exposito-Alonso et al. 2022), poses a threat to evolutionary potential and adaptation to future global change. In agricultural systems, the erosion of crop genetic diversity undermines productivity and resilience to climate change (Khoury et al. 2021). Almost 60 per cent of the world's land surface is now subject to moderate or intense human pressure (Williams et al. 2000U). Human activities are increasingly altering the marine environment, with marine species adversely affected across 57 per cent of their range on average (O'Hara, Frazier and Halpern 2021).

Several ecosystems are already considered ecologically collapsed, including the Rapa Nui subtropical broadleaf forests on Easter Island, and the Aral Sea between Kazakhstan and Uzbekistan (Bland et al. 2018). Rates of future collapse may be more rapid than previously anticipated (Willcock et al. 2023). Coral reefs, which are critical to marine biodiversity and the livelihoods of millions, are at risk from rising sea temperatures and ocean acidification, with mass bleaching events now occurring every six years on average. This threatens the economic backbone of coastal communities and the entire reef ecosystem (Mies et al. 2020). The Amazon rainforest, a vital global carbon store, is being ravaged by deforestation and

Credit: JuiceFlair/Envato

forest fires, transitioning from a carbon sink to a carbon source, with profound implications for global climate regulation (Butt et al. 2023). Regional warming might push the Amazon rainforest towards a tipping point where significant amounts of carbon could be released into the atmosphere, exacerbating feedbacks to the climate system (Artaxo 2023).

Biodiversity of plants, animals, fungi and microbes underlies healthy ecosystems and supports essential ecosystem services, including clean air and water, food, feed, fibre and bioenergy. It regulates disease and climate, provides protection against erosion and extreme weather events, encourages soil formation and biogeochemical cycling, and is a source of innumerable cultural benefits to all peoples (IPBES 2019). Over 75 per cent of agricultural crops are dependent at least in part on insect pollinators (Klein et al. 2007), while over 2.4 billion people may benefit from the coastal protection provided by mangrove forests (United Nations Environment Programme [UNEP] 2023). However, over 70 per cent of the global population inhabits environmentally compromised areas, where ecosystem services are being lost or degraded, and many ecosystems have already exceeded safe limits for biodiversity (Newbold et al. 2016). Globally, the degradation of ecosystems will lead to a loss of services worth between US$10 trillion and US$44 trillion annually (Mies et al. 2020; World Economic Forum 2020). Developing a stronger bioeconomy could help support sustainable development and the conservation of both biological and cultural diversity (Huddart et al. 2022).

C.1.3 Land degradation and desertification

Land degradation is the result of anthropogenic actions that exploit the land, causing a decline in the utility, fertility, biodiversity, and overall health of the environment. Land degradation adversely affects 24–40 per cent of the global land area (IPCC 2019; Edrisi et al. 2022; UNCCD 2022) and over 3.2 billion people (IPBES 2018a). From 2015 to 2019, at least 100 million hectares of fertile and productive land

were lost annually worldwide, an area equivalent to twice the size of Greenland (UNCCD 2023). Ocean degradation negatively affects approximately 66 per cent of the global oceans (IPBES 2019; IPCC 2021b), impinging on the livelihoods and food security of over 3 billion people who depend on marine resources. Overfishing, coastal destruction and pollution continue to degrade vital marine habitats, including coral reefs, mangroves and seagrass meadows (Food and Agriculture Organization [FAO] 2022). In drylands, which encompass one-third of global land area, land degradation through the expansion of croplands and unsustainable management practices, exacerbated by climate change, can lead to desertification and a loss of primary productivity (Kimmell, Fagan and Havrilla 2023). Land degradation weakens the role of forests as carbon sinks, significantly reducing their capacity to provide key ecosystem services such as carbon storage, water and nutrient cycling and support of biodiversity (IPCC 2019; Ekka et al. 2023; Winkler et al. 2023). Land degradation, in synergy with climate change, may force 50 million to 700 million people to migrate by 2050 (IPBES 2018a). In the Global South, approximately 143 million people could be displaced due to the effects of climate change on land by 2050 (Almulhim et al. 2024).

Globally, the estimated annual costs of land degradation are large, but uncertain, and range between US$18 billion and US$20 trillion (UNCCD 2019a). Projections to 2050 predict further losses of 36 gigatons of carbon from soils, and gross emissions due to forest degradation are projected to reach 10.2 gigatons of CO_2 (UNCCD 2019b; Assis et al. 2022). Water-induced soil erosion, a leading process of land degradation, is estimated to impose cumulative global GDP losses ranging from US$216 billion to US$625 billion between 2015 and 2070, which translates to an annual loss of approximately US$4 billion to US$11 billion (Sartori et al. 2024). The effect on global food production is a key concern, with a potential reduction of up to 33.7 million tons (Sartori et al. 2019) and a corresponding 30 per cent increase in world food prices by 2040 (ELD Initiative 2015a). Reversing land degradation would restore soil health and fertility, combat desertification and prevent further degradation, allowing for sustainable food production and livelihoods (Pandit et al. 2020). The estimated cost of fulfilling current global restoration commitments ranges from US$311 billion to US$2,146 billion over a 10-year period (Verhoeven et al. 2024); however, adopting sustainable land management globally could generate US$75.6 trillion in annual economic benefits (ELD Initiative 2015b). Indigenous cultural values and nature-respecting practices offer valuable insights into how collective behaviours can holistically support land sustainability (Shrivastava and Zsolnai 2022).

C.1.4 Pollution and waste

Environmental pollution is the world's largest risk factor for disease and premature death, with nine million human deaths annually attributable to some form of pollution (Fuller et al. 2022). More than 90 per cent of pollution-related deaths occur in low and middle-income countries (Fuller et al. 2022). Pollution affects women's health differently, particularly in terms of reproductive health and exposure to household pollutants. The adverse health effects of pollution on the elderly may also be disproportionate (Simoni et al. 2015; Fan et al. 2022).

Pollutants in the environment encompass a wide range of contaminants, including noise, light and radioactive pollution, as well as contaminated water, soil and land contamination, atmospheric pollution, industrial waste and plastic litter. Collectively, these pollutants threaten biodiversity, contaminate food sources, and can lead to long-term health consequences for wildlife and human populations (Lee et al. 2024). Hazardous waste, including solid waste and medical waste (Windfeld & Brooks 2015), can have both direct and indirect effects on the environment and human health (Zhang et al. 2022). Waste management practices can also be a major source of GHG emissions (Friedrich & Trois, 2011). Toxic metals, such as lead, mercury, and cadmium, are of particular concern due to their persistence in the environment and their ability to accumulate in biological systems (Lee et al. 2024). Fine particulate matter (PM2.5) pollution has been linked to cardiac and respiratory disease (Hayes et al. 2020). Chemical pollutants include pesticides in food, nutrient run-off in the sea, rivers and lakes, and endocrine-disrupting chemicals in drinking water and personal-care products (Naidu et al. 2021). In recent years, a major concern has been the emergence of new pollutants, including pharmaceuticals and microplastics that may be ingested or absorbed by plants and animals (Lim 2021; Vethaak and Legler 2021), antibiotic resistance genes and nanoparticles, as well as forever chemicals such as per- and poly-fluorochemicals (Cousins et al. 2022). These emerging

contaminants present unique challenges due to their widespread occurrence and the complexity of their effects on health and the environment.

Anthropogenic pollutants are now ubiquitous, from the highest mountain peak (Napper et al. 2020) to the abyssal sea floor (Nakajima et al. 2021), and ecosystem degradation due to pollution is observed throughout the world (Dar et al. 2025). Over recent years, there has been increased awareness of plastic pollution in the oceans: the global abundance of floating plastic particles is estimated to weigh between 1.1 million and 4.9 million tons (Eriksen et al. 2023). Dispersed pollutants may become concentrated through catchment drainage and bioaccumulation, with toxic effects at different levels of biological organization, as documented for some endocrine-disrupting chemicals (Luo et al. 2024). Chemical pollution will continue to adversely affect human health and ecosystems, given the current trends in chemical production, use and disposal (UNEP 2019).

C.1.5 Interacting global crises

The global environmental crises are intricately interconnected but are frequently addressed individually by researchers and policymakers. This overlooks the potential for understanding their interactions and the opportunity to identify solution pathways that may provide multiple co-benefits or result in trade-offs and unintended consequences. For example, a narrow focus on mitigating GHG emissions from fossil fuels by promoting biofuels or tree planting in natural grasslands can result in biodiversity loss (Bond et al. 2019; Tudge, Purvis and De Palma 2021). However, managing land through sustainable and regenerative agriculture, livestock and forestry practices can enhance soil health, carbon storage, reduce GHG emissions and promote biodiversity (Kopitkke 2019; Pörtner et al. 2021). Land restoration, including afforestation, and reduced land degradation could provide more than one-third of the cost-effective GHG mitigation activities needed by 2030 (IPBES 2018a), and allow the attainment of net zero earlier (IPCC 2023b).

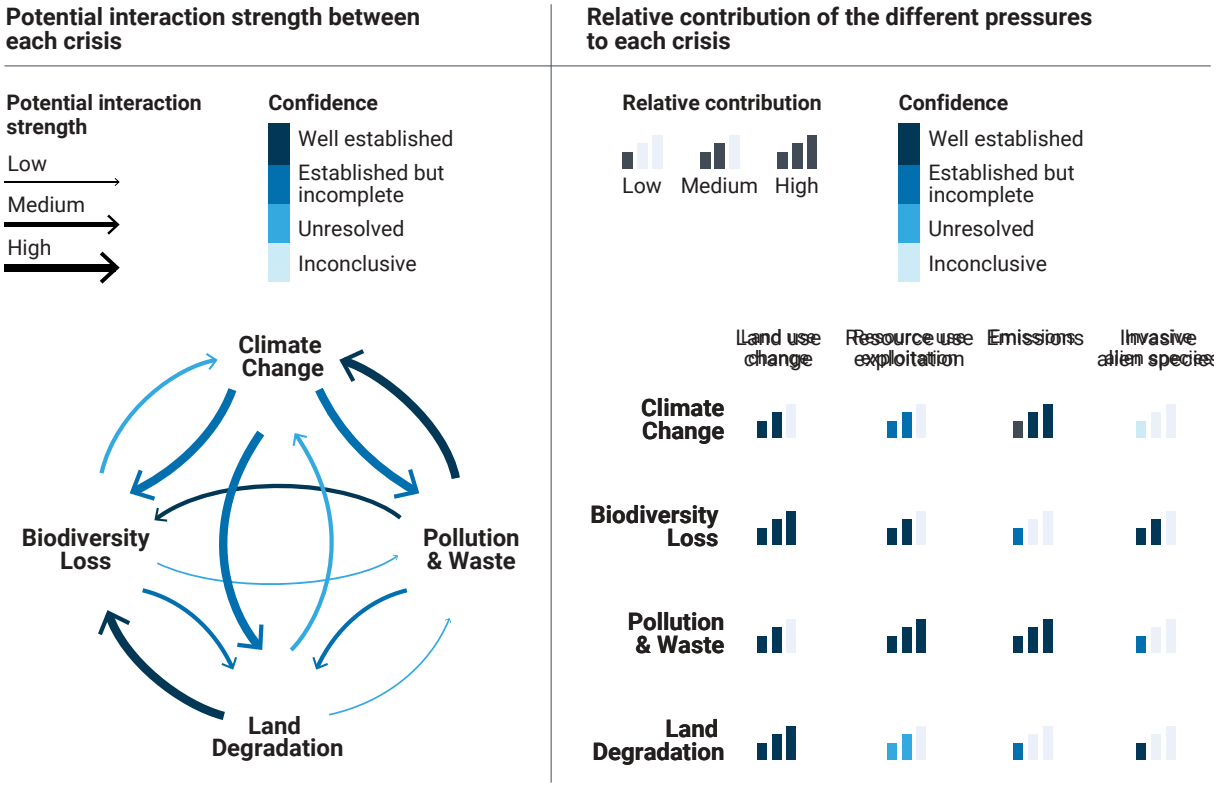
Figure C.1 illustrates the potential for interactions between crises, recognizing their asymmetrical bidirectionality. For instance, the effect of climate change on biodiversity loss is likely stronger than the effect of biodiversity loss on climate change. As an example, some models suggest climate change could lead to the complete disappearance of warm-water coral reefs by 2050 (IPCC 2023b), while the degradation of coral ecosystems may only indirectly influence the climate by altering water flow that favours sea grasses (James et al. 2023). However, the strength of interactions will also vary across temporal and spatial scales, and between regions and ecosystems. Some of this important variation can be observed through examining the different priority issues among regions (8.1). The potential pairwise interactions between crises is illustrated by overlaying maps of their pressures (Table C.1–C.6), demonstrating how each crisis is also multifaceted and can thus be described along many possible axes. In some cases, knowledge of the effects of interactions between crises may be data-limited (IPBES 2024a), or full effects may only become apparent in the future due to gradual or non-linear responses (10.5). New research approaches are needed to address these challenges (Pfenning-Butterworth et al. 2024) (Chapter 10), that also allow for integration of Indigenous Knowledge.

Considering only the pairwise relationships between crises fails to represent the complex interactions, feedbacks and interdependencies among them; they are all interconnected spatially, temporally and causally. The pairwise connections between crises can also form longer chains of interactions that may include non-linearities that challenge simple extrapolations (Pfenning-Butterworth et al. 2024). While no single representation can fully capture these complexities, they should be considered when identifying solution pathways (FAO et al. 2022; IPBES 2024a).

Each environmental crisis can be defined along multiple axes, and is subject to, and emerges from, various pressures (2.2;2.3). Pressures are as defined in Chapter 2:

- Land-use change represents the conversion from one land-use type to another, with the most prevalent land-use transitions occurring between forest and cropland. Land-use change does not necessarily indicate a change in biodiversity.
- Resource use and exploitation consider multiple resources, including exploitation of fish and wildlife, fossil fuels, minerals and rare elements, wood and timber, and water extraction.

Figure C.1: Interconnectedness of the global environmental crises of climate change, biodiversity loss, land degradation and desertification, and pollution and waste



- Emissions encompass greenhouse gases and other pollutants, including short-lived climate pollutants, such as black carbon, and chemical pollutants from industry and agriculture.
- Invasive alien species are defined as species introduced to areas outside their native range that have become successfully established and cause substantial negative effects on the new environment.

Interactions shown as arrows between some crises are stronger than others, with arrow width indicative of potential interaction strengths (part a). Bars (part b) represent the relative contribution of the different pressures to each crisis as low, medium and high. Depth of shading reflects qualitative assessment of confidence – well established, established but incomplete, unresolved, and inconclusive – in the assigned contribution weights.

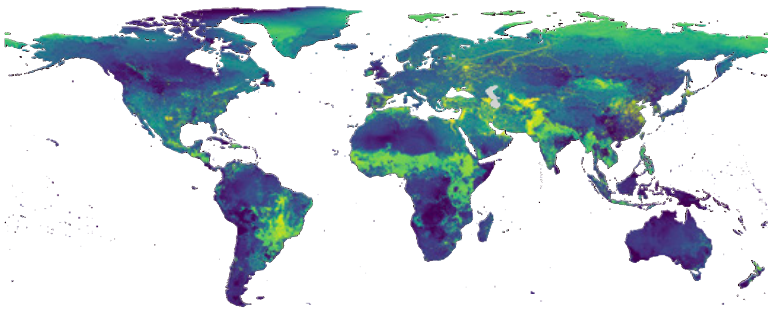
Table C.1:Potential for interactions between climate change and pollution

Heatmaps overlaying pressures illustrate the potential for interactions between the environmental crises. All pressures are standardized to a uniform scale, assuming equal weights. High pressure intensity areas, assuming additive interactions, are indicated in yellow and low intensity areas in blue. Areas of no data are shown in grey. Regions where overlapping pressures are both high might be indicative of an elevated risk of compounding pressures and could be informative for directing mitigation measures or adaptive responses. However, considerable uncertainty over the strength of interactions remains.

Heatmaps were created using the best available data, harmonizing spatial resolution and normalizing values between 0 and 1. Existing annual products or computed annual means from products of higher temporal resolution – for example, daily or monthly – were used, and multi-year trends were created by computing linear trendlines based on the annual time-series.

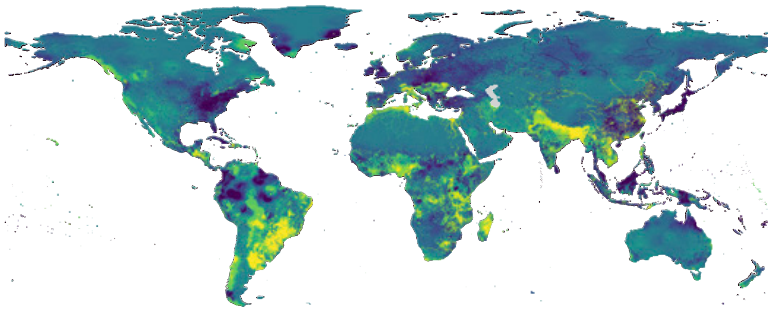
Table C.1: Potential for interactions between climate change and pollution (cont.)

Temperature and CH_4 trends (1982–2022)



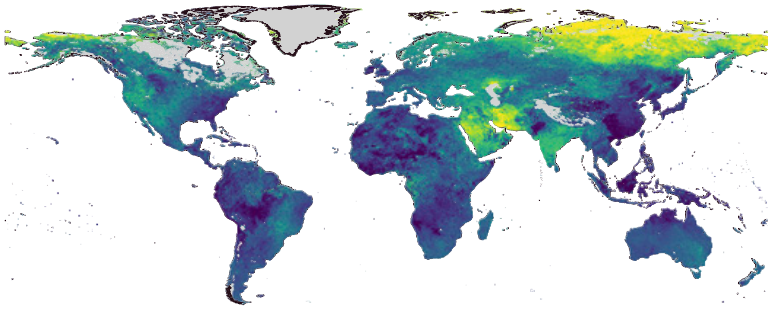
Source: Temperature data University of East Anglia Climatic Research Unit et al. (2024) and Methane (CH_4) data European Commission (2024a).

Precipitation and primary particulates trends (1982–2022)



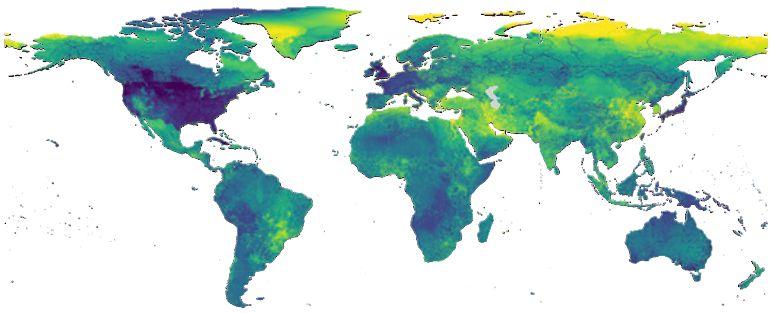
Source: Precipitation data University of East Anglia Climatic Research Unit et al. (2024) and primary particulates data European Commission (2024b). Precipitation is presented through its inverse component (1-precipitation) in this combined map.

Aerosols (2000-2022) and temperature (1982-2022) trends



Source: Aerosol data National Aeronautics and Space Administration (2024) and Temperature data University of East Anglia Climatic Research Unit et al. (2024)

NO_X and temperature trends (1982-2022)



Source: Nitrogen oxides (NO_x) data European Commission (2024b) and Temperature data University of East Anglia Climatic Research Unit et al. (2024)

Effects of climate change → on pollution

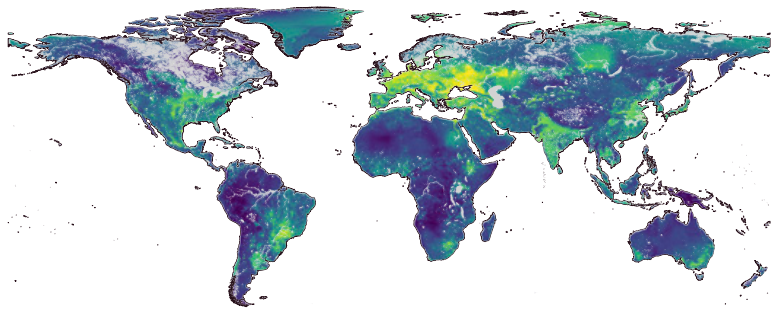
While the mechanistic relationships between pollutant behaviour, fate, and effects is still not fully understood (Noyes and Lema 2015; Hatje et al. 2022), extreme weather events release chemicals and other pollutants into the environment, and warming temperatures can aggravate methane emission from wetlands (Feron et al. 2024). Changes in temperature and precipitation patterns can also increase fine particulate matter pollution from wildfires and drought (Xie et al. 2022).

Effects of pollution → on climate change

Atmospheric pollution has both regional and global effects on climate. Tropospheric ozone is a component of air pollution and mediates the longevity of methane, a potent GHG (Griffiths et al. 2021). Atmospheric particulate and aerosol pollutants include black carbon, and their climate effects are seen mainly at high latitudes, including the Antarctic (not shown). Here, they alter the albedo of snow and ice, contributing to high melt rates of glaciers, sea ice and ice sheets (Gul et al. 2021).

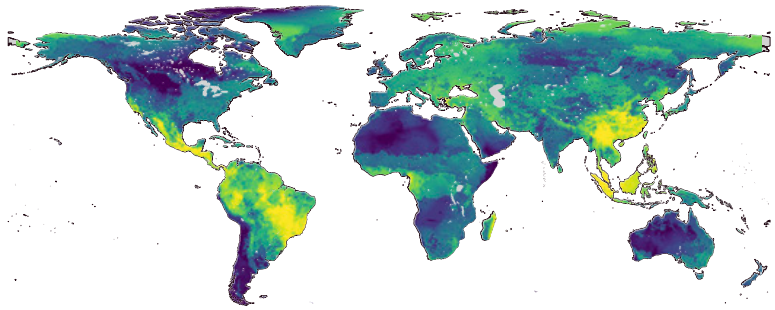
Table C.2: Potential for interactions between climate change and biodiversity

Maximum temperature trend (1982–2020) and biodiversity intactness index (2020)



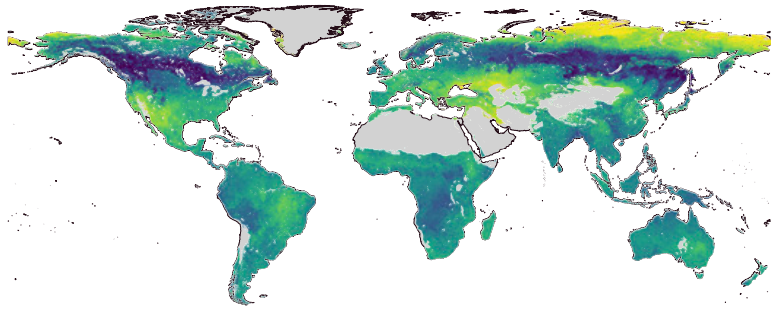
Source: Temperature data (University of East Anglia Climatic Research Unit et al. (2024) and Bio Intactness Index data Samapriya et al. (2024). Biodiversity Intactness Index (BII) is presented through its inverse component (1-BII) in this combined map.

Temperature trend (1982–2019) and species extinction risk (2019)



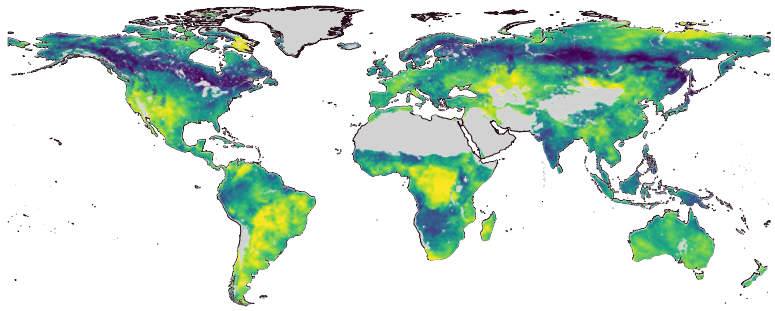
Source: Temperature data University of East Anglia Climatic Research Unit et al. (2024) and species extinction risk data UNEP-WCMC (2020).

NDVI and temperature trends (1982-2022)



Source: NDVI (Normalized difference vegetation index) data Li et al. (2023) and Temperature data University of East Anglia Climatic Research Unit et al. (2024). NDVI is presented through its inverse component (1-NDVI) in this combined map.

NDVI and drought severity index trends (1982–2022)



Source: NDVI data Li et al. (2023) and Palmer Drought Severity Index (PDSI) data Abatzoglou et al. (2018). NDVI is presented through its inverse component (1-NDVI) in this combined map.

Effects of climate change → on biodiversity

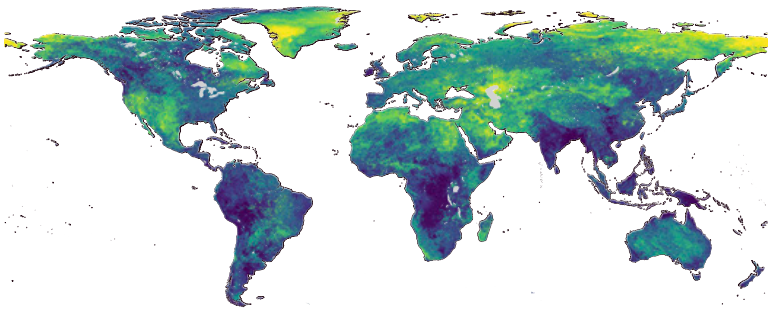
Projections suggest that one in three species may be threatened by climate change under high-emissions scenarios (Urban 2024), and climate change may become the dominant extinction driver by the end of the century (IPBES 2024b). Coral reefs have been disproportionately affected by warming seas and ocean acidification (Hoegh-Guldberg et al. 2017). More extreme and more frequent weather-driven events, such as wildfires, directly threaten wildlife populations, although mortality rates are uncertain (Jolly et al. 2022). Many species are shifting their distributions to cooler climates, moving polewards or upwards in elevation (Chen et al. 2011). Climate-induced changes in the timing of life history events risk generating trophic asynchronies, for instance, a mismatch between flowering times and pollinator availability (Fuentes, Hamann and Limpus 2010; Thackeray et al. 2010). Differences in species' ability to acclimatize and adapt may also exacerbate disease outbreaks (Cohen et al. 2019).

Effect of changes in biodiversity → on climate change

Changes in biodiversity can affect climate at regional and local scales (IPCC 2023b). At high latitudes, climate warming has led to the revegetation of tundra, resulting in a feedback cycle as increased vegetation furthers warming as albedo decreases. At mid-latitudes, the replacement of forests by grasslands can increase albedo (Hasler et al. 2024); however, this can also reduce carbon storage capacity (Gibbs et al. 2007). At local scales, forest loss can lead to shifts in atmospheric water vapour concentrations, altering cloud cover and evapotranspiration rates.

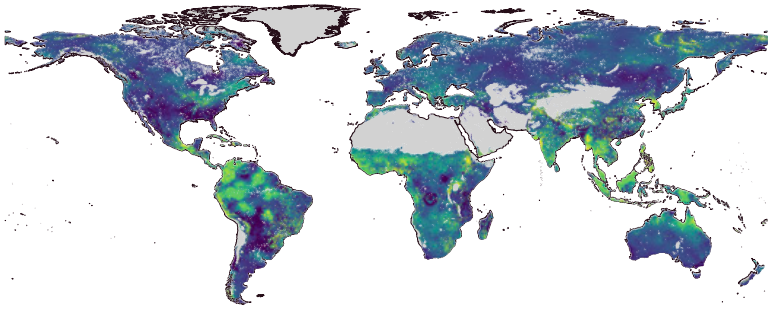
Table C.3: Potential for interactions between climate change and land degradation

Temperature trend (1982–2022) and land productivity trend (2007–2022)



Source: Temperature data University of East Anglia Climatic Research Unit et al. (2024) and land productivity data Ivits and Cherlet (2013). Land productivity is presented through its inverse component (1- land productivity) in this combined map.

Precipitation trend (1982–2012) and soil erosion (2012)

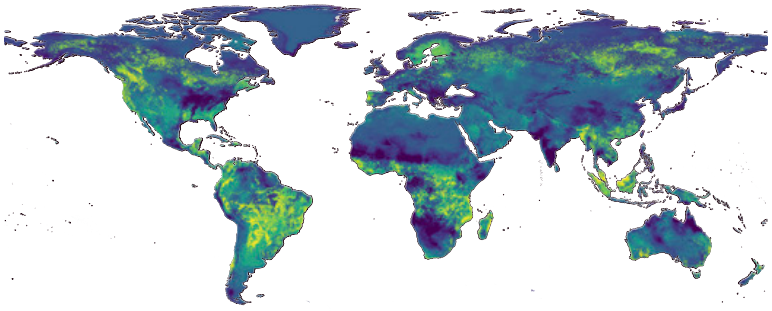


Source: Precipitation data University of East Anglia Climatic Research Unit et al. (2024) and soil erosion data European Commission (2017).

Effects of climate change → on land degradation

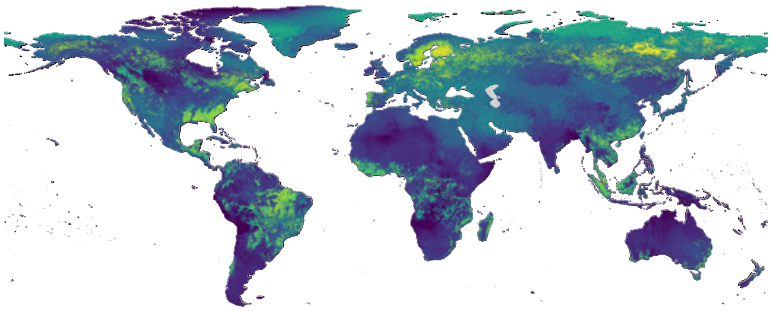
The effects of climate change on land degradation occur at multiple scales. One primary process is the reduction of soil organic matter pools directly triggered by the effects of rising temperatures (Crowther et al. 2016). The Middle East has been particularly affected, with elevated dust levels damaging people's health (Mousavi, Moshir and Kalantari 2024). Climate change-induced extreme weather events such as hurricanes, wildfires, droughts, floods and landslides can additionally increase land degradation (Bandh et al. 2021; Talukder et al. 2021). Precipitation shifts that enhance plant growth and land productivity, can reduce land degradation (Abbasi et al. 2020). However, higher precipitation intensities, especially following prolonged drought, can lead to increased erosion and flooding, exacerbating land degradation (Olsson et al. 2019)..

Forest loss (total for 2000-2022) and evapotranspiration trend (1982-2022)



Source: Forest loss data Hansen et al. (2013) and Evapotranspiration (ET) data (Abatzoglou et al. (2021). ET is presented through its inverse component (1-ET) in this combined map.

Forest loss (total for 2000-2022) and temperature trend (1982-2022)



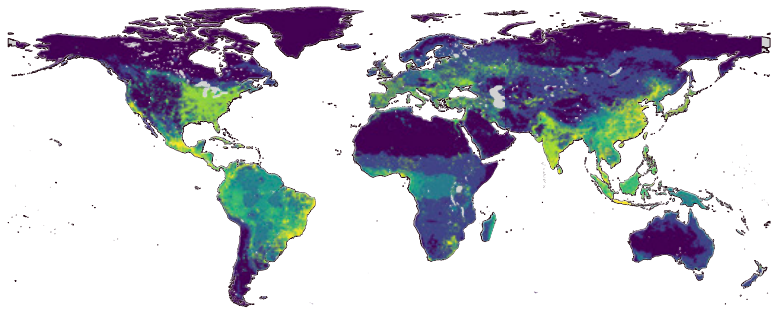
Source: Forest loss data Hansen et al. (2013) and temperature data University of East Anglia Climatic Research Unit et al. (2024)

Effects of land degradation → on climate change

Deforestation and habitat conversion for agriculture and other land uses release stored carbon, increasing GHG emissions (Houghton 2020). Forest degradation and land clearing can also alter surface albedo, further aggravating warming trends (Olsson et al. 2019) (Worlanyo and Jiangfeng 2021). Degraded land, especially through deforestation and soil erosion, reduces carbon sequestration, depleting vital carbon sinks (Lal 2019; Olsson et al. 2019). Loss of soil fertility in agricultural systems prompts increased inorganic fertilizer use that releases nitrous oxide, a potent GHG (IPBES 2018b; IPCC 2019), initiating a feedback loop.

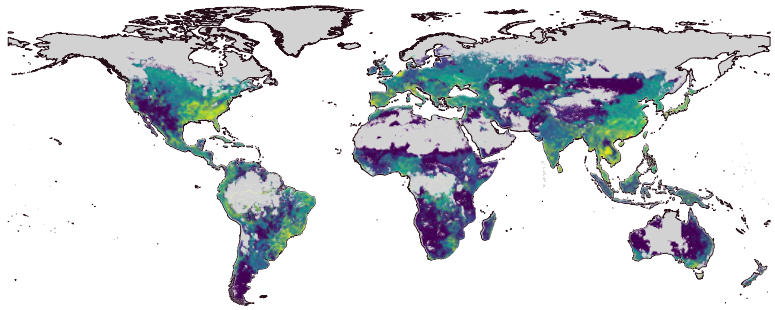
Table C.4: Potential for interactions between pollution and biodiversity loss

Untreated sewage (2015) and species extinction risk (2019)



Source: Untreated sewage data Jones et al. (2020) and species extinction risk data UNEP-WCMC (2020)

Pesticide pollution (2015) and global extinction probabilities for freshwater fish species (2021)

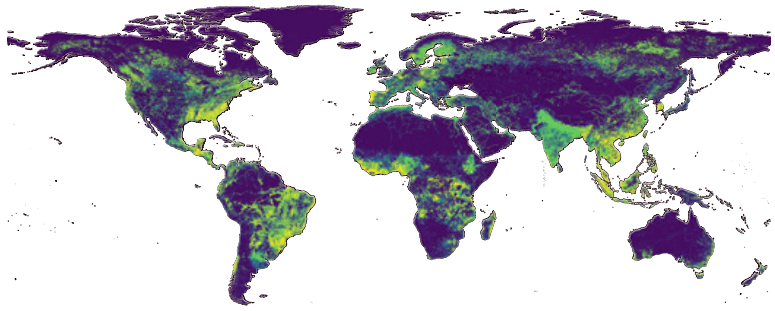


Source: Pesticide pollution data Tang et al. (2021) and global extinction probabilities for freshwater fish species data from data Verones et al. (2022)

Effects of pollution → on biodiversity loss

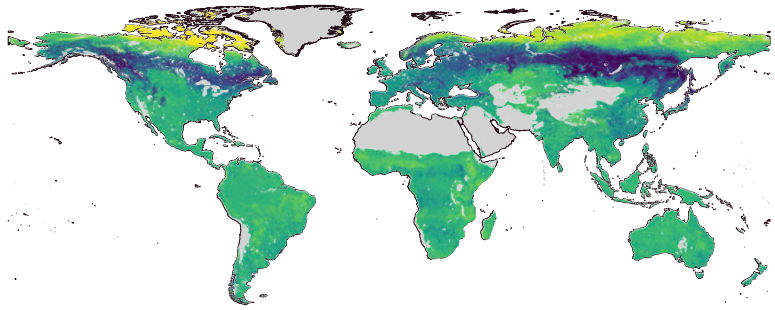
Environmental pollution by hazardous chemicals can have significant adverse effects on terrestrial and aquatic life (Jaureguiberry et al. 2022; Sigmund et al. 2023). Examples include the decline in pollinators linked to pesticide use (Goulson et al. 2015), sediment, sewage and fertilizer pollution in freshwater systems, and a vast number of manufactured chemicals that pollute the marine, freshwater and terrestrial environments (Sigmund et al. 2023). Air pollution, including ground level ozone, has effects on ecosystems and human health (Nowak et al. 2015). Pollutants of new or increasing concern include micro- and nanoplastics (Sharma and Chatterjee 2017), persistent organic pollutants that can accumulate in the food chain, endocrine-disrupting chemicals (Encarnação et al. 2019), and microorganisms (Paruch et al. 2019).

Forest loss (total for 2000-2022) and CO_2 trend (1982-2022)



Source: Forest loss data Hansen et al. (2013) and carbon dioxide (CO_2) data European Commission (2024a)

NDVI trend (1982–2021) and tropospheric ozone trend (2005–2021)



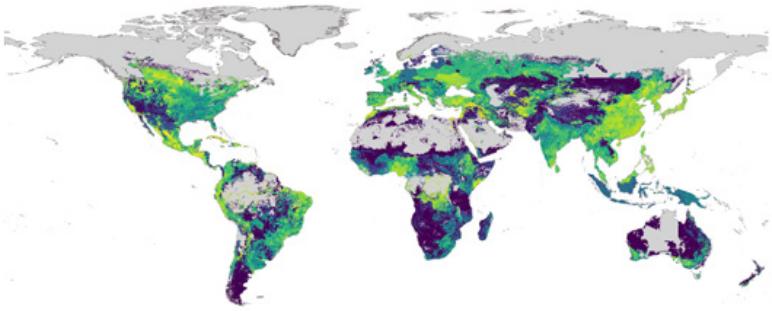
Source: NDVI data Li et al. (2023) and tropospheric ozone data Miyazaki (2024). NDVI is presented through its inverse component (1-NDVI) in this combined map..

Effect of changes in biodiversity → on pollution

Biodiversity loss affects pollution in several ways, including via the reduction of vegetation cover, especially in forests, which play a role in reducing air pollution from ozone, nitrous oxide, and particulate matter (Nowak et al. 2018), in addition to sequestering CO_2. Wildfires can adversely affect biodiversity and simultaneously lead to increases in atmospheric pollution (Yue and Unger 2018). The reduced resilience of ecosystems to pollutants in stressed ecosystems is well documented (Vallero 2019; Horton and Barnes 2020; Zaghloul et al. 2020).

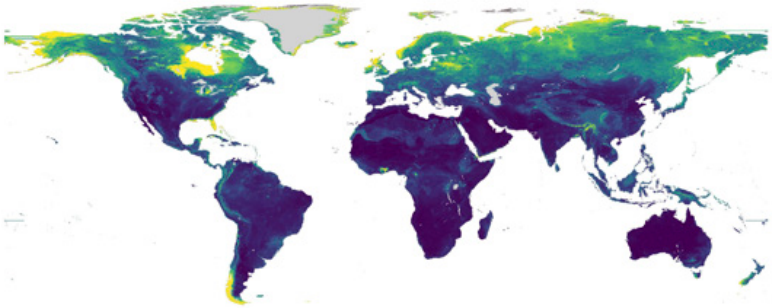
Table C.5: Potential for interactions between pollution and land degradation

Pesticide pollution (2015) and salinization (2016)



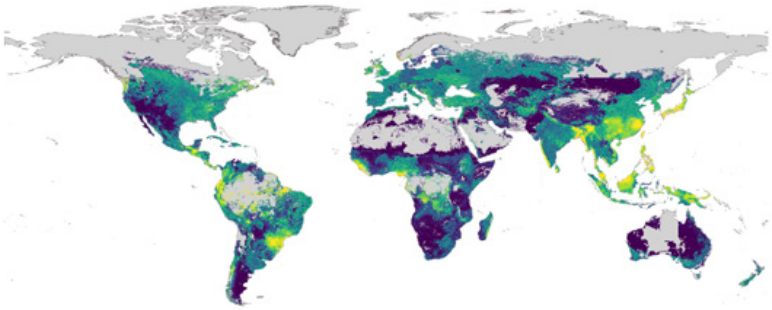
Source: Pesticide pollution data Tang et al. (2021) and salinization data Ivushkin (2019)

Soil total nitrogen (2020)



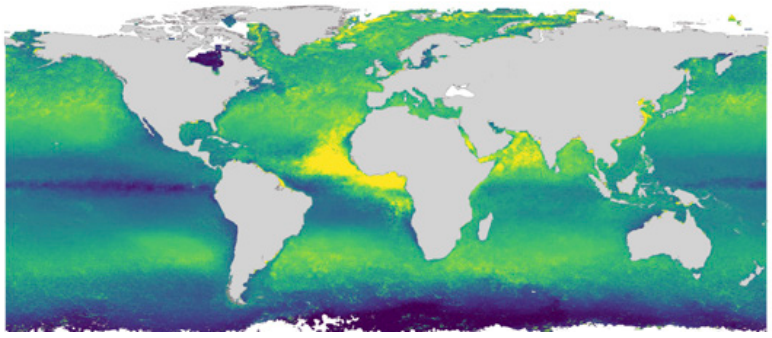
Source: Soil total nitrogen data Poggio et al. (2021)

Run-off and pesticide pollution (2015)



Source: Run-off data Abatzoglou et al. (2021) and pesticide pollution data Tang et al. (2021)

Seawater total suspended matter and plastic pollution in the oceans (2020)



Source: Seawater total suspended matter data from https://resourcewatch.org/data/explore/ocn011-Total-Suspended-Matter and seawater plastic pollution data derived from the predicted concentrations of plastic items on the ocean surface Kaandorp et al. (2023).

Effects of pollution → on land degradation

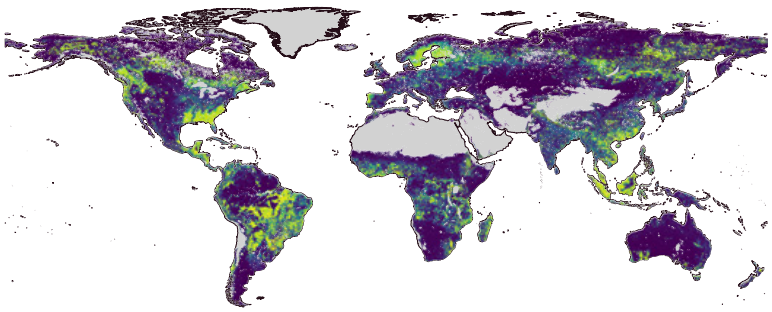
The use of pesticides and fertilizers in agriculture has increased over time (Food and Agriculture Organization [FAO], 2023), leading to land degradation. Overextraction of groundwater and irrigation practices can alter soil salinity, leading to changes in soil structure, pH, oxidation-reduction potential, and the ability to support plant growth (Rengasamy 2016). Chemical pollution of the soil with pesticides and particulate material, including micro- and nanoplastics, produces shifts in soil microbial and mesofauna, altering soil functions (Grantz, Garner and Johnson 2003; Majumder et al. 2021). Nitrogen deposition results in a fertilizer effect, accelerating plant growth. It also stimulates soil carbon loss from the acceleration of microbial metabolism, causing soil acidification (Chen et al. 2016; Xiao et al. 2020). Sulphur emissions from fossil fuels further contribute to acid deposition and reduced soil fertility (UK Centre of Ecology and Hydrology 2016).

Effects of land degradation → on pollution

Deforestation, along with other forms of land clearing, such as clearing for agriculture, infrastructure development, and mining, indirectly affects the quality of land and water by increasing the rates of soil erosion and sediment transport, and accelerating the loss of nutrient-rich soil surface (Artiola et al. 2019). Land degradation resulting in soil erosion can also lead to increased pollution and sedimentation in streams and rivers (Phuong, Shrestha and Chuong 2017). Mining activities are linked to deforestation, soil erosion, and contamination of water bodies with heavy metals (Pandey et al. 2022). Surface run-off is also a major source of plastic pollution in the oceans (Lebreton et al. 2017).

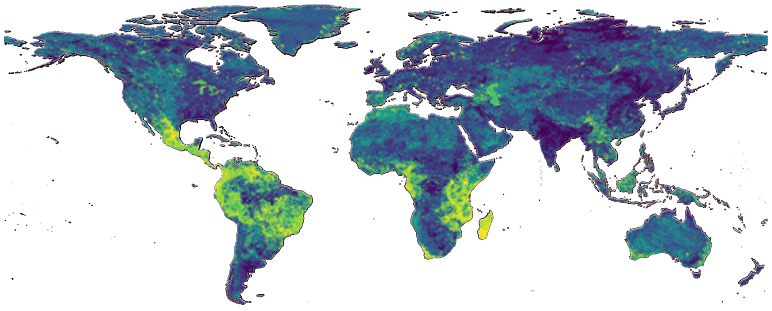
Table C.6: Potential for interactions between biodiversity and land degradation

Forest loss (total for 2000–2012) and soil erosion (2012)



Source: Forest loss data Hansen et al. (2013) and soil erosion data European Commission (2017)

Plant extinction risk (1950–2022) and land productivity trend (2007–2022)

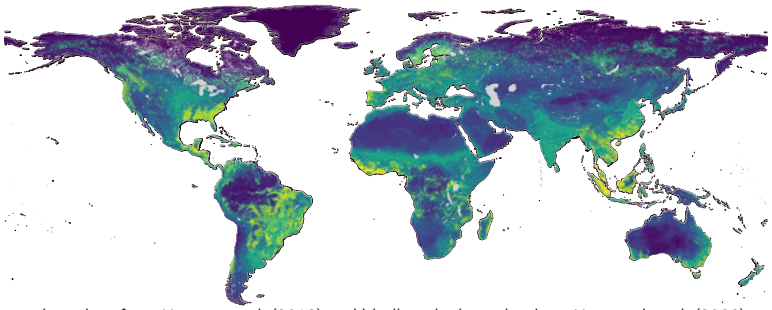


Plant extinction risk derived from data of plants listed by IUCN (https://www.iucnredlist.org/) as either Critically Endangered (CR), Endangered (EN), or Vulnerable (VU) and land productivity data (Ivits and Cherlet 2013). Land productivity is presented through its inverse component (1- land productivity) in this combined map.

Effect of changes in biodiversity → on land degradation

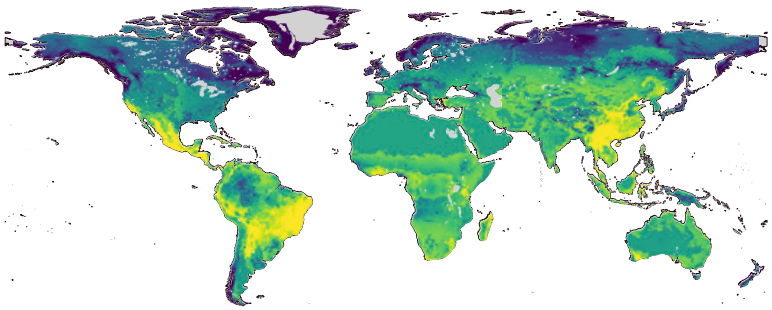
Biodiversity loss has a direct effect on land degradation. Forest loss or thinning reduces biodiversity, causing a decline in forest productivity and carbon stocks (IPBES 2018). Forest loss also reduces the amount of plant residues and organic matter in the soil and removes the protective layer that controls run-off and soil erosion (Orgiazzi and Panagos 2018; Mayer et al. 2020). The local extinction of large herbivores, carnivores and primates has led to what has been termed Empty Forest Syndrome (Pires and Galetti 2023). This biotic impoverishment has cascading ecological consequences, altering plant species composition, nutrient cycling, and forest regeneration (Pires and Galetti 2023).

Forest loss (total for 2000–2020) and biodiversity habitat integrity (2020)



Forest loss data from Hansen et al. (2013) and biodiversity integrity data Harwood et al. (2022). Biodiversity integrity is presented through its inverse component (1-biodiversity integrity) in this combined map.

Aridity index (average of 1982–2019) and species extinction risk (2019)



Aridity index calculated as the ratio of precipitation to evapotranspiration data (Abatzoglou et al. 2021) and species extinction risk data (UNEP-WCMC 2020). Aridity index is presented through its inverse component (1- aridity index) in this combined map.

Effects of land degradation → on biodiversity loss

Land degradation significantly contributes to biodiversity loss primarily by altering or destroying natural habitats. Desertification reduces ecosystem productivity and the biotic-carrying capacity of the environment. Declines in soil quality and vegetation cover can additionally disrupt ecosystem integrity and increase habitat fragmentation (Banks-Leite et al. 2020), while degraded ecosystems can facilitate invasion by non-native species (Heringer et al. 2020) that are major drivers of biodiversity decline (IPBES 2019).

C.2 The crisis in human–nature relationships

The global environmental crises can be considered together as a single crisis: the crisis in human–nature relationships. Changes in sociocultural values and worldviews, that is, natural resources and land as commodities, as well as rapid urbanization and deforestation, are key drivers of the disconnection of humans from nature, leading to the devaluation of nature, thereby facilitating and legitimizing destructive practices (Barragan-Jason et al. 2022; Barragan-Jason et al.2023).

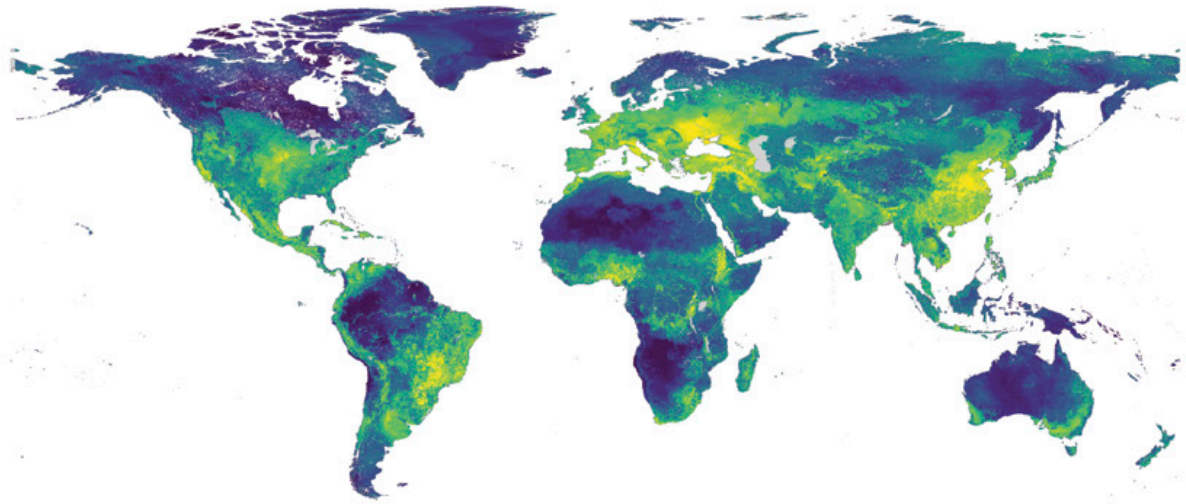
Climate change, biodiversity loss and land degradation and pollution and waste are mostly driven by socioeconomic systems that run on unsustainable resource extraction and consumption patterns. They also have major socioecological effects, including resource-driven disputes, human conflict, and the proliferation of environmental refugees (Beery et al. 2023; World Economic Forum 2023; SDG16). The scale, pace and intensity of anthropogenic environmental change have increased inequality and inequity, threatening stability, resilience and sustainability (McPhearson et al. 2021). Armed conflicts lead to compounded, multidimensional environmental crises with both short and long-lasting, frequently irreversible effects (UNEP 2022; UNEP 2024; Krampe Kreutz and Ide 2025).

The literature suggests that humans are now living beyond planetary limits (e.g. IPCC 2021; IPBES 2019; Brondizio et al. 2021; Díaz, et al. 2019; McPhearson et al. 2021;), with adverse effects on quality of life (Díaz et al. 2019) and ecosystem health (Persson et al. 2022). Exceeding the Earth's capacity (Chapter 10) will affect or displace millions of people (Caesar et al. 2024), with coastal communities, small islands and peoples in drylands and the Arctic at disproportionate risk (IPCC 2023b). Indigenous Peoples and displaced populations and refugees are particularly vulnerable to the global environmental crises, and the homelands and territories of traditional communities that depend on the lands and ecosystems are often exposed to overlapping adverse effects (IPCC 2023a; IPCC 2023b) (**Figure C.2**).

C.2.1 Indigenous Peoples' perspectives and the values crisis in the human–nature relationship

A reconnection with nature is key to human and planetary health, and to valuing the shift towards sustainability. The Intergovernmental Panel on Climate Change and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services provided evidence of the need for transformative change in human–nature interactions to achieve sustainable targets, including a better valuation of nature (IPBES 2019; Pörtner et al. 2021). The extent to which people

Figure C.2: Geographical variation in intensity of overlapping pressures associated with the global environmental crises



Note: summation of change in global temperature (1982–2022) (University of East Anglia Climatic Research Unit et al. 2024), soil erosion (2012) (European Commission 2017), pesticide pollution (2015) (Tang et al. 2021), change in drought severity (Drought Severity Index 1982–2022) (Abatzoglou et al. 2021), and an index representing biodiversity habitat integrity (2020) (Harwood et al. 2022). All variables were normalized between zero and one. Yellow shading indicates regions of high-pressure intensity across the crises, blue shading indicates regions of low pressure-intensity. Regions where pressures overlap might represent locations with high potential for interactions between crises (Tables C.1–C.6).

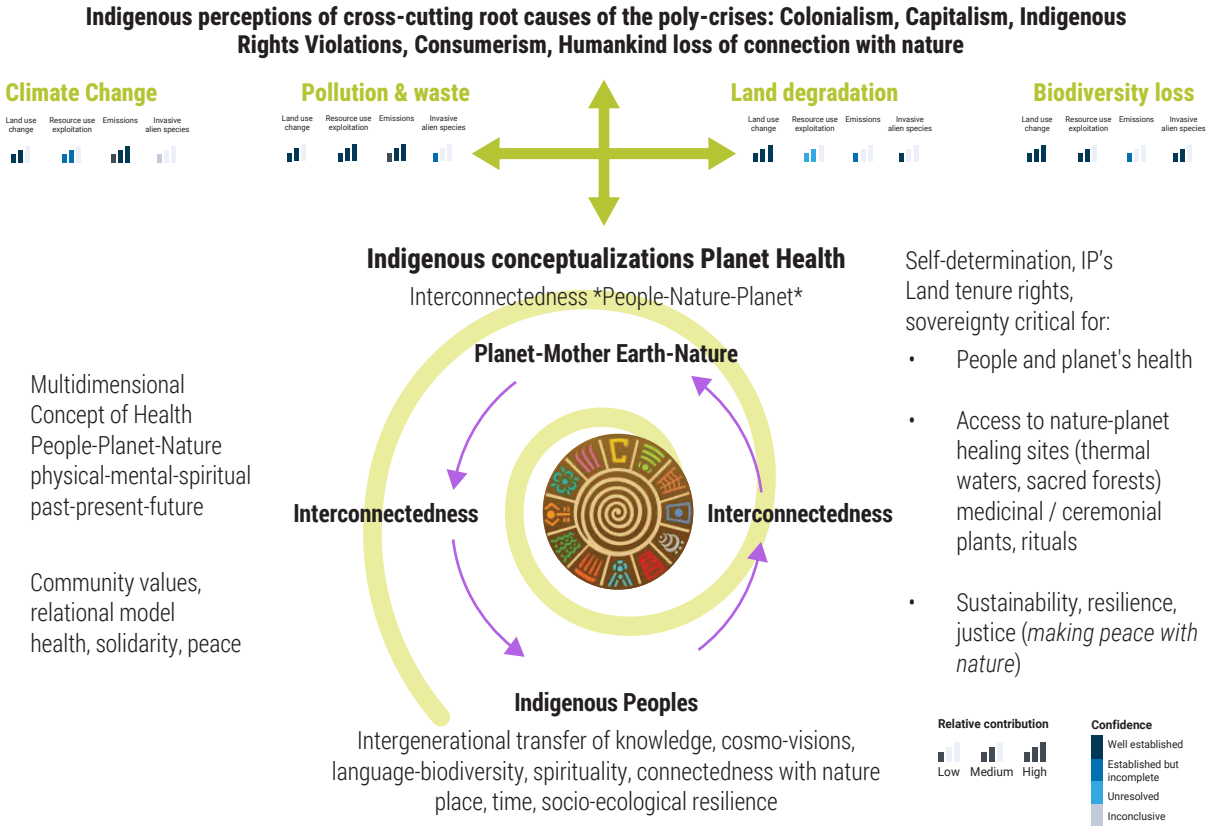
recognize themselves as part of nature, referred to as human-nature connectedness, is a societal trait that facilitates achieving sustainability. This requires a transformative change, including an awareness of connectivity among the environmental crises and new norms for human-nature interactions (Barragan-Jason et al. 2022; Barragan-Jason et al. 2023).

Indigenous conceptualizations of planetary health provide crucial intergenerational perspectives on addressing the drivers of the global environmental crises. The holistic views on people, nature and the planet as Mother Earth found in many Indigenous Knowledge systems and sciences, and rooted in Indigenous languages, also compels the view of the global environmental crises as interconnected or as different aspects of a single crisis – the crisis in human-nature relationships. Embracing more holistic worldviews (**Figure C.3** and **Figure 1. IK & LK Chapeau B**) may provide both a better perspective on the roots – pressures and drivers – of the environmental crises and a deeper understanding of their effects on local communities and Indigenous Peoples who live on, own and manage over a quarter of the world's land area (IPBES 2022).

Nature and customary laws govern Indigenous Peoples' lifeways, considering future generations. Indigenous community-centred values related to lands, peoples and cultures offer opportunities to learn how collective values and behaviours can support sustainability for the next seven generations (Brondízio et al. 2021). This requires self-determination, land tenure rights, sovereignty, agency and inclusive governance.

Indigenous Knowledge and Local Knowledge can offer alternative options to address the complex adverse effects of the environmental crises. More holistic solutions may be found through considering different knowledge systems, sovereignty, ethics of co-existence, ancestral connections to the landscapes and nature, and socioecological approaches to resilience, focusing on human–nature interactions. Indigenous women play a crucial role in biodiversity conservation and climate resilience, leveraging traditional knowledge and sustainable practices; yet women are disproportionally excluded from decision-making (Akalibey et al. 2024; Lima and Cunha 2024). However, Indigenous Knowledge and Local Knowledge is currently at risk from multiple pressures (Fernández-Llamazares

Figure C.3: Interconnected worldview of the global environmental crises recognizing that the crises can be considered together as a single crisis – the crisis in human–nature relationships



Credit: © Brent Stirton/Getty Images for FAO, CIRAD, CIFOR, WCS

et al. 2021) – another facet of the crisis in human-nature relationships.

The geographic variations in the intensity of the crises and their influences on Earth's systems differ among socioeconomic groups and countries. To remain within Earth's limits and to achieve a just and sustainable future will require unprecedented, radical, and coordinated systems transformations (McPhearson et al. 2021) across the human-dominated systems of economy, energy, circularity and food (Chapters 14–17).

References

Abatzoglou, J.T., S.Z. Dobrowski, S.A. Parks, K.C. Hegewisch, 2018, Terraclimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958-2015, Scientific Data 5:170191, doi:10.1038/sdata.2017.191

Abbasi, A.O., Salazar, A., Oh, Y., Reinsch, S., del Rosario Uribe, M., Li, J. et al. (2020). Reviews and syntheses: Soil responses to manipulated precipitation changes – an assessment of meta-analyses. Biogeosciences 17(14), 3859-3873. https://doi.org/10.5194/bg-17-3859-2020

Akalibey, S., Hlavackova, P., Schneider, J., Fialova, J., Darkwah, S. and Ahenkan, A. (2024). Integrating indigenous knowledge and culture in sustainable forest management via global environmental policies. Journal of Forest Science 70(6), 265-280. https://doi.org/10.17221/20/2024-JFS

Almulhim, A.I., Alverio, G.N., Sharifi, A., Shaw, R., Huq, S., Mahmud, M.J. et al. (2024). Climate-induced migration in the Global South: An in depth analysis. npj Climate Action 3(1), 47. https://doi.org/10.1038/s44168-024-00133-1

Artaxo, P. (2023). Amazon deforestation implications in local/regional climate change. Proceedings of the National Academy of Sciences of the United States of America 120(50), e2317456120. https://doi.org/10.1073/pnas.2317456120

Artiola, J.F., Walworth, J.L., Musil, S.A. and Crimmins, M.A. (2019). Chapter 14 - Soil and Land Pollution. In Environmental and Pollution Science (Third Edition). Brusseau, M.L., Pepper, I.L. and Gerba, C.P. (eds.). Academic Press. 219-235. https://www.sciencedirect.com/science/article/pii/B9780128147191000148

Assis, T.O., Aguiar, A.P.D., von Randow, C. and Nobre, C.A. (2022). Projections of future forest degradation and CO_2 emissions for the Brazilian Amazon. Science Advances 8(24), eabj3309. https://doi.org/10.1126/sciadv.abj3309

Bandh, S.A., Shafi, S., Peerzada, M., Rehman, T., Bashir, S., Wani, S.A. et al. (2021). Multidimensional analysis of global climate change: A review. Environmental Science and Pollution Research 28(20), 24872-24888. https://doi.org/10.1007/s11356-021-13139-7

Banks-Leite, C., Ewers, R.M., Folkard-Tapp, H. and Fraser, A. (2020). Countering the effects of habitat loss, fragmentation, and degradation through habitat restoration. One Earth 3(6), 672-676. https://doi.org/10.1016/j.oneear.2020.11.016

Barragan-Jason, G., de Mazancourt, C., Parmesan, C., Singer, M.C. and Loreau, M. (2022). Human–nature connectedness as a pathway to sustainability: A global meta-analysis. Conservation Letters 15(1), e12852. https://doi.org/10.1111/conl.12852

Barragan-Jason, G., Loreau, M., de Mazancourt, C., Singer, M.C. and Parmesan, C. (2023). Psychological and physical connections with nature improve both human well-being and nature conservation: A systematic review of meta-analyses. Biological Conservation 277, 109842. https://doi.org/10.1016/j.biocon.2022.109842

Beery, T., Stahl Olafsson, A., Gentin, S., Maurer, M., Stålhammar, S., Albert, C. et al. (2023). Disconnection from nature: Expanding our understanding of human–nature relations. People and Nature 5(2), 470-488. https://doi.org/10.1002/pan3.10451

Bland, L.M., Rowland, J.A., Regan, T.J., Keith, D.A., Murray, N.J., Lester, R.E. et al. (2018). Developing a standardized definition of ecosystem collapse for risk assessment. Frontiers in Ecology and the Environment 16(1), 29-36. https://doi.org/10.1002/fee.1747

Bond, W.J., Stevens, N., Midgley, G.F. and Lehmann, C.E.R. (2019). The trouble with trees: Afforestation plans for Africa. Trends in Ecology & Evolution 34(11), 963-965. https://doi.org/10.1016/j.tree.2019.08.003

Brondízio, E.S., Aumeeruddy-Thomas, Y., Bates, P., Carino, J., Fernández-Llamazares, Á., Ferrari, M.F. et al. (2021). Locally Based, Regionally Manifested, and Globally Relevant: Indigenous and Local Knowledge, Values, and Practices for Nature. Annual Review of Environment and Resources 46, 481-509. https://doi.org/10.1146/annurev-environ-012220-012127

Buis, A. (2024). A Degree of Concern: Why Global Temperatures Matter. [National Aeronautics and Space Administration https://climate.nasa.gov/news/2865/a-degree-of-concern-why-global-temperatures-matter/

Butt, E.W., Baker, J.C.A., Bezerra, F.G.S., von Randow, C., Aguiar, A.P.D. and Spracklen, D.V. (2023). Amazon deforestation causes strong regional warming. Proceedings of the National Academy of Sciences of the United States of America 120(45), e2309123120. https://doi.org/10.1073/pnas.2309123120

Caesar, L., Sakschewski, B., Andersen, L.S., Beringer, T., Braun, J., Dennis, D. et al. Planetary Health Check Report 2024. Potsdam: Potsdam Institute for Climate Impact Research. https://www.planetaryhealthcheck.org/storyblok-cdn/f/301438/x/a4efc3f6d5/planetaryhealthcheck2024_report.pdf

Chen, D., Li, J., Lan, Z., Hu, S. and Bai, Y. (2016). Soil acidification exerts a greater control on soil respiration than soil nitrogen availability in grasslands subjected to long-term nitrogen enrichment. Functional Ecology 30(4), 658-669. https://doi.org/10.1111/1365-2435.12525

Chen, I.-C., Hill, J.K., Ohlemüller, R., Roy, D.B. and Thomas, C.D. (2011). Rapid Range Shifts of Species Associated with High Levels of Climate Warming. Science 333(6045), 1024-1026. https://doi.org/10.1126/science.1206432

Cohen, J.M., Civitello, D.J., Venesky, M.D., McMahon, T.A. and Rohr, J.R. (2019). An interaction between climate change and infectious disease drove widespread amphibian declines. Global Change Biology 25(3), 927-937. https://doi.org/10.1111/gcb.14489

Copernicus (2024). The year 2024 set to end up as the warmest on record. https://climate.copernicus.eu/year-2024-set-end-warmest-record Accessed: 16 April 2025

Cousins, I.T., Johansson, J.H., Salter, M.E., Sha, B. and Scheringer, M. (2022). Outside the safe operating space of a new planetary boundary for Per- and Polyfluoroalkyl Substances (PFAS). Environmental Science & Technology 56(16), 11172-11179. https://doi.org/10.1021/acs.est.2c02765

Crowther, T.W., Todd-Brown, K.E.O., Rowe, C.W., Wieder, W.R., Carey, J.C., Machmuller, M.B. et al. (2016). Quantifying global soil carbon losses in response to warming. Nature 540(7631), 104-108. https://doi.org/10.1038/nature20150

Dar, M.A., Palsania, P., Satya, S., Dashora, M., Bhat, O.A., Parveen, S. et al. (2025). Microplastic pollution: A global perspective in surface waters, microbial degradation, and corresponding mechanism. Marine Pollution Bulletin 210, 117344. https://doi.org/10.1016/j.marpolbul.2024.117344

De Vos, J.M., Joppa, L.N., Gittleman, J.L., Stephens, P.R. and Pimm, S.L. (2015). Estimating the normal background rate of species extinction. Conservation Biology 29(2), 452-462. https://doi.org/10.1111/cobi.12380

Deng, L., Peng, C., Li, S., Yang, R., Yan, C., Li, M. et al. (2025). Comparative effects of chemical dispersants and rhamnolipid biosurfactants on oil biodegradation and microbial community in coastal sediments. International Biodeterioration & Biodegradation 196, 105913. https://doi.org/10.1016/j.ibiod.2024.105913

Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Agard, J., Arneth, A. et al. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. Science 366(6471), eaax3100. https://doi.org/10.1126/science.aax3100

Edrisi, S.A., Sarkar, P., Son, J., Prakash, N.T. and Baral, H. (2022). Assessing the realization of global land restoration: A meta-analysis. Anthropocene Science 1(1), 179-194. https://doi.org/10.1007/s44177-022-00018-0

Ekka, P., Patra, S., Upreti, M., Kumar, G., Kumar, A. and Saikia, P. (2023). Land degradation and its impacts on biodiversity and ecosystem services. In Land and Environmental Management through Forestry. 77-101. https://doi.org/10.1002/9781119910527.ch4

ELD Initiative (2015a). Report for Policy and Decision Makers: Reaping Economic and Environmental Eenefits from Sustainable Land Management. Economics of Land Degradation Initiative. https://mel.cgiar.org/reporting/downloadmelspace/hash/JIOY4YLL/v/27141a6d0b2beb1400736e1c9607b162

ELD Initiative (2015b). Report for Policy Makers: Key Facts and Figures. Economics of Land Degradation. https://www.eld-initiative.org/fileadmin/pdf/Key_facts_and_figures_-_Report_for_policy_and_decision_makers2015.pdf#:~:text=Benefits%20of%20sustainable%20land%20management.%20%E2%80%A2%20Annually%2C,of%20projects%20including%20soil%20and%20water%20conservation

Elena, F., Cristina, T. (2011). Quantification of greenhouse gas emissions from waste management processes for municipalities – A comparative review focusing on Africa. Waste Management Vol. 31, Issue 7, 1585-1596. https://doi.org/10.1016/j.wasman.2011.02.028

Encarnação, T., Pais, A.A.C.C., Campos, M.G. and Burrows, H.D. (2019). Endocrine disrupting chemicals: Impact on human health, wildlife and the environment. Science Progress 102(1), 3-42. https://doi.org/10.1177/0036850419826802

Eriksen, M., Cowger, W., Erdle, L.M., Coffin, S., Villarrubia-Gómez, P., Moore, C.J. et al. (2023). A growing plastic smog, now estimated to be over 170 trillion plastic particles afloat in the world's oceans—Urgent solutions required. PLOS ONE 18(3), e0281596. https://doi.org/10.1371/journal.pone.0281596

European Commission (2017). Global soil erosion. European Soil Data Centre. https://esdac.jrc.ec.europa.eu/content/global-soil-erosion

European Commission (2024a). Global Greenhouse Gas Emissions. EDGAR - Emissions Database for Global Atmospheric Research. https://edgar.jrc.ec.europa.eu/dataset_ghg80

European Commission (2024b). Global Air Pollutant Emissions. EDGAR - Emissions Database for Global Atmospheric Research. https://edgar.jrc.ec.europa.eu/dataset_ap81

Exposito-Alonso, M., Booker, T.R., Czech, L., Gillespie, L., Hateley, S., Kyriazis, C.C. et al. (2022). Genetic diversity loss in the Anthropocene. Science 377(6613), 1431-1435. https://doi.org/10.1126/science.abn5642

Fan, H., Wang, Y., Wang, Y. and Coyte, P.C. (2022). The impact of environmental pollution on the physical health of middle-aged and older adults in China. Environmental Science and Pollution Research 29(3), 4219-4231. https://doi.org/10.1007/s11356-021-15832-z

Fernández-Llamazares, Á., Lepofsky, D., Lertzman, K., Armstrong, C.G., Brondizio, E.S., Gavin, M.C. et al. (2021). Scientists' Warning to Humanity on Threats to Indigenous and Local Knowledge Systems. Journal of Ethnobiology 41(2), 144-169. https://doi.org/10.2993/0278-0771-41.2.144

Feron, S., Malhotra, A., Bansal, S., Fluet-Chouinard, E., McNicol, G., Knox, S.H. et al. (2024). Recent increases in annual, seasonal, and extreme methane fluxes driven by changes in climate and vegetation in boreal and temperate wetland ecosystems. Global Change Biology 30(1), e17131. https://doi.org/10.1111/gcb.17131

Food and Agriculture Organization (2022). The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. Rome. https://doi.org/10.4060/cc0461en

Food and Agriculture Organization (2023). World Food and Agriculture – Statistical Yearbook 2023. Rome: Food and Agriculture Organization. https://doi.org/10.4060/cc8166en

Food and Agriculture Organization of the United Nations, United Nations Environment Programme, World Health Organization and World Organisation for Animal Health (2022). One health Joint Plan of Action (2022–2026): Working Together for the Health of Humans, Animals, Plants and the Environment. https://iris.who.int/bitstream/handle/10665/363518/9789240059139-eng.pdf?sequence=1

Friedrich, E. and Trois, C., 2011. Quantification of greenhouse gas emissions from waste management processes for municipalities–A comparative review focusing on Africa. Waste management, 31(7), pp.1585-1596

Fruttero, A., Halim, D., Broccolini, C., Coelho, B., Gninafon, H. and Muller, N. (2023). Gendered Impacts of Climate Change: Evidence from Weather Shocks. Policy Research Working Paper. Washington, D.C: World Bank. https://wrd.unwomen.org/sites/default/files/2023-07/WB-gendered-impacts-climate-change.pdf

Fuentes, M.M.P.B., Hamann, M. and Limpus, C.J. (2010). Past, current and future thermal profiles of green turtle nesting grounds: Implications from climate change. Journal of Experimental Marine Biology and Ecology 383(1), 56-64. https://doi.org/10.1016/j.jembe.2009.11.003

Fuller, R., Landrigan, P.J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M. et al. (2022). Pollution and health: A progress update. The Lancet Planetary Health 6(6), e535-e547. https://www.doi.org/10.1016/S2542-5196(22)00090-0

Gibbs, H.K., Brown, S., Niles, J.O. and Foley, J.A. (2007). Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environmental Research Letters 2(4), 045023. https://iopscience.iop.org/article/10.1088/1748-9326/2/4/045023

Goulson, D., Nicholls, E., Botías, C. and Rotheray, E.L. (2015). Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. Science 347(6229), 1255957. https://doi.org/10.1126/science.1255957

Grantz, D.A., Garner, J.H.B. and Johnson, D.W. (2003). Ecological effects of particulate matter. Environment International 29(2), 213-239. https://doi.org/10.1016/S0160-4120(02)00181-2

Griffiths, P.T., Murray, L.T., Zeng, G., Shin, Y.M., Abraham, N.L., Archibald, A.T. et al. (2021). Tropospheric ozone in CMIP6 simulations. Atmos. Chem. Phys. 21(5), 4187-4218. https://doi.org/10.5194/acp-21-4187-2021

Gul, C., Mahapatra, P.S., Kang, S., Singh, P.K., Wu, X., He, C. et al. (2021). Black carbon concentration in the central Himalayas: Impact on glacier melt and potential source contribution. Environmental Pollution 275, 116544. https://doi.org/10.1016/j.envpol.2021.116544

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A. et al. (2013). High-Resolution Global Maps of 21st-Century Forest Cover Change. Science 342(6160), 850-853. https://data.csiro.au/collection/csiro:54237?q=BHI&_st=keyword&_str=1&_si=1'

Harwood, T., Ware, C., Hoskins, A., Ferrier, S., Bush, A., Golebiewski, M. et al. (2022). BHI v2: Biodiversity Habitat Index: 30s global time series. https://doi.org/10.25919/3j75-f539

Hasler, N., Williams, C.A., Denney, V.C., Ellis, P.W., Shrestha, S., Terasaki Hart, D.E. et al. (2024). Accounting for albedo change to identify climate-positive tree cover restoration. Nature Communications 15(1), 2275. https://doi.org/10.1038/s41467-024-46577-1

Hatje, V., Sarin, M., Sander, S.G., Omanović, D., Ramachandran, P., Völker, C. et al. (2022). Emergent interactive effects of climate change and contaminants in coastal and ocean ecosystems. Frontiers in Marine Science 9. https://doi.org/10.3389/fmars.2022.936109

Hayes, R.B., Lim, C., Zhang, Y., Cromar, K., Shao, Y., Reynolds, H.R. et al. (2020). $PM_{2.5}$ air pollution and cause-specific cardiovascular disease mortality. International Journal of Epidemiology 49(1), 25-35. https://doi.org/10.1093/ije/dyz114

Heringer, G., Thiele, J., do Amaral, C.H., Meira-Neto, J.A.A., Matos, F.A.R., Lehmann, J.R.K. et al. (2020). Acacia invasion is facilitated by landscape permeability: The role of habitat degradation and road networks. Applied Vegetation Science 23(4), 598-609. https://doi.org/10.1111/avsc.12520

Hoegh-Guldberg, O., Poloczanska, E.S., Skirving, W. and Dove, S. (2017). Coral Reef Ecosystems under Climate Change and Ocean Acidification. Frontiers in Marine Science 4. https://doi.org/10.3389/fmars.2017.00158

Horton, A.A. and Barnes, D.K.A. (2020). Microplastic pollution in a rapidly changing world: Implications for remote and vulnerable marine ecosystems. Science of The Total Environment 738, 140349. https://doi.org/10.1016/j.scitotenv.2020.140349

Houghton, R.A. (2020). Terrestrial fluxes of carbon in GCP carbon budgets. Global Change Biology 26(5), 3006-3014. https://doi.org/10.1111/gcb.15050

Huddart, J.E.A., Crawford, A.J., Luna-Tapia, A.L., Restrepo, S. and Di Palma, F. (2022). EBP-Colombia and the bioeconomy: Genomics in the service of biodiversity conservation and sustainable development. Proceedings of the National Academy of Sciences of the United States of America 119(4). https://doi.org/10.1073/pnas.2115641119

Intergovernmental Panel on Climate Change (2019). Summary for Policymakers. In: Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts et al. (eds.). Geneva

Intergovernmental Panel on Climate Change. https://www.ipcc.ch/site/assets/uploads/2019/11/SRCCL-Full-Report-Compiled-191128.pdf

Intergovernmental Panel on Climate Change (2021a). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger et al. (eds.). Geneva: Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FullReport.pdf

Intergovernmental Panel on Climate Change (2021b). Special Report on the Ocean and Cryosphere in a Changing Climate. Geneva: https://www.ipcc.ch/srocc/

Intergovernmental Panel on Climate Change (2022). Summary for Policymakers for Climate Change 2022 – Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría et al. (eds.). Cambridge, UK and NY, USA: Intergovernmental Panel on Climate Change. https://www.cambridge.org/core/books/climate-change-2022-impacts-adaptation-and-vulnerability/summary-for-policymakers/016527EADEE2178406C4A7CE7DEAEACA

Intergovernmental Panel on Climate Change (2023a). AR6 Synthesis Report: Climate Change 2023. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/sixth-assessment-report-cycle/

Intergovernmental Panel on Climate Change (2023b). Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Lee, H. and Romero, J. (eds.). Geneva, Switzerland: Intergovernmental Panel on Climate Change. https://doi.org/10.59327/IPCC/AR6-9789291691647.001

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2018a). Summary for Policymakers of the assessment report on land degradation and restoration of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Scholes, R., Montanarella, L., Brainich, A., Barger, N., Brink, B.T., Cantele, M. et al. (eds.). Bonn: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://zenodo.org/record/3237411#.Yx7eKnaxWUk

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2018b). The IPBES Assessment Report on Land Degradation and Restoration. Montanarella, L., Scholes, R. and Brainich, A. (eds.). Bonn: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://zenodo.org/records/3237393

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn: IPBES secretariat. https://zenodo.org/record/6417333

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2022). Methodological Assessment of the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Balvanera, P., Pascual, U., Christie, M., Baptiste, B. and González-Jiménez, D. (eds.). https://doi.org/10.5281/zenodo.6522522

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2024a). Summary for Policymakers of the Thematic Assessment Report on the Interlinkages among Biodiversity, Water, Food and Health of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. McElwee, P.D., Harrison, P.A., van Huysen, T.L., Alonso Roldán, V., Barrios, E., Dasgupta, P. et al. (eds.). Bonn. https://doi.org/10.5281/zenodo.13850290

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2024b). Models of drivers of biodiversity and ecosystem change. https://www.ipbes.net/models-drivers-biodiversity-ecosystem-change Accessed: 07/02/2024

International Labour Organization (2019). Working on a Warmer Planet: The Impact of Heat Stress on Labour Productivity and Decent Work. Geneva. https://www.ilo.org/sites/default/files/wcmsp5/groups/public/@dgreports/@dcomm/@publ/documents/publication/wcms_711919.pdf

IUCN. 2025. The IUCN Red List of Threatened Species. Version 2025-1. https://www.iucnredlist.org

Ivits, E. and Cherlet, M. (2013). Land-Productivity Dynamics Towards integrated assessment of land degradation at global scales. European Commission. https://publications.jrc.ec.europa.eu/repository/handle/JRC80541

Ivushkin, K. (2019). Global Soil Salinity Map. Information, I.-W.S., Wageningen https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/c59d0162-a258-4210-af80-777d7929c512' not 'https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/c59d0162-a258-4210-af80-777d7929c

Jahn, A., Holland, M.M. and Kay, J.E. (2024). Projections of an ice-free Arctic Ocean. Nature Reviews Earth & Environment 5(3), 164-176. https://doi.org/10.1038/s43017-023-00515-9

James, R.K., Keyzer, L.M., van de Velde, S.J., Herman, P.M.J., van Katwijk, M.M. and Bouma, T.J. (2023). Climate change mitigation by coral reefs and seagrass beds at risk: How global change compromises coastal ecosystem services. Science of The Total Environment 857, 159576. https://doi.org/10.1016/j.scitotenv.2022.159576

Jaureguiberry, P., Titeux, N., Wiemers, M., Bowler, D.E., Coscieme, L., Golden, A.S. et al. (2022). The direct drivers of recent global anthropogenic biodiversity loss. Science Advances 8(45), eabm9982. https://doi.org/10.1126/sciadv.abm9982

Jolly, C.J., Dickman, C.R., Doherty, T.S., van Eeden, L.M., Geary, W.L., Legge, S.M. et al. (2022). Animal mortality during fire. Global Change Biology. 28(6), 2053-2065. https://doi.org/10.1111/gcb.16044

Jones, E.R., van Vliet, M.T.H., Qadir, M. and Bierkens, M.F.P. (2020). Country-level and gridded wastewater production, collection, treatment and re-use. PANGAEA, https://doi.pangaea.de/10.1594/PANGAEA.918731

Kaandorp, M.L.A., Lobelle, D., Kehl, C., Dijkstra, H.A. and van Sebille, E. (2023). Global mass of buoyant marine plastics dominated by large long-lived debris. Nature Geoscience 16(8), 689-694. https://doi.org/10.1038/s41561-023-01216-0

Khoury, C.K., Brush, S., Costich, D.E., Curry, H.A., de Haan, S., Engels, J.M.M. et al. (2022). Crop genetic erosion: Understanding and responding to loss of crop diversity. New Phytologist 233(1), 84-118. https://doi.org/10.1111/nph.17733

Kim, Y.-H., Min, S.-K., Gillett, N.P., Notz, D. and Malinina, E. (2023). Observationally-constrained projections of an ice-free Arctic even under a low emission scenario. Nature Communications 14(1), 3139. https://doi.org/10.1038/s41467-023-38511-8

Kimmell, L.B., Fagan, J.M. and Havrilla, C.A. (2023). Soil restoration increases soil health across global drylands: A meta-analysis. Journal of Applied Ecology 60(9), 1939-1951. https://doi.org/10.1111/1365-2664.14459

Klein, A.M., Vaissière, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C. et al. (2007). Importance of pollinators in changing landscapes for world crops. Proceedings of the Royal Society B: Biological Sciences 274(1608), 303-313. http://doi.org/10.1098/rspb.2006.3721

Kopittke, P.M., Menzies, N.W., Wang, P., McKenna, B.A. and Lombi, E. (2019). Soil and the intensification of agriculture for global food security. Environment International 132, 105078. https://doi.org/10.1016/j.envint.2019.105078

Krampe, F., Kreutz, J. and Ide, T. (2025). Armed conflict causes long-lasting environmental harms. Environment and Security, 27538796251323739. https://doi.org/10.1177/27538796251323739

Lal, R. (2019). Carbon cycling in global drylands. Current Climate Change Reports 5(3), 221-232. https://doi.org/10.1007/s40641-019-00132-z

Lamboll, R.D., Nicholls, Z.R.J., Smith, C.J., Kikstra, J.S., Byers, E. and Rogelj, J. (2023). Assessing the size and uncertainty of remaining carbon budgets. Nature Climate Change 13(12), 1360-1367. https://doi.org/10.1038/s41558-023-01848-5

Lebreton, L.C.M., van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A. and Reisser, J. (2017). River plastic emissions to the world's oceans. Nature Communications 8(1), 15611. https://doi.org/10.1038/ncomms15611

Lee, D.-W., Jung, J., Park, S.-a., Lee, Y., Kim, J., Han, C. et al. (2024). Microplastic particles in human blood and their association with coagulation markers. Scientific Reports 14(1), 30419. https://doi.org/10.1038/s41598-024-81931-9

Leigh, D.M., Hendry, A.P., Vázquez-Domínguez, E. and Friesen, V.L. (2019). Estimated six per cent loss of genetic variation in wild populations since the industrial revolution. Evolutionary Applications 12(8), 1505-1512. https://doi.org/10.1111/eva.12810

Li, M., Cao, S., Zhu, Z., Wang, Z. and Myneni, R.B., Piao, S. (2023). Spatiotemporally consistent global dataset of the GIMMS Normalized Difference Vegetation Index (PKU GIMMS NDVI) from 1982 to 2022, Earth Syst. Sci. Data Discuss. https://doi.org/10.5194/essd-2023-1

Lim, X. (2021). Microplastics are everywhere - but are they harmful? Nature 593(7857), 22-25. https://doi.org/10.1038/d41586-021-01143-3

Lima, H. S. M., and H. F. A. Cunha. 2024. The Role of Women and the Obstacles to Biodiversity Conservation in Developed and Developing Countries. Environment, Development and Sustainability. https://doi.org/10.1007/s10668-024-05407-6

Luo, D., Guo, Y., Liu, Z., Guo, L., Wang, H., Tang, X. et al. (2024). Endocrine-Disrupting Chemical Exposure Induces Adverse Effects on the Population Dynamics of the Indo-Pacific Humpback Dolphin. Environmental Science and Technology 58(21), 9102-9112. https://doi.org/10.1021/acs.est.4c00618

Majumder, S., Paul, A., Kumar, A., Verma, C.K., Divekar, P.A., Rani, V. et al. (2021). Impact of Pesticides on Microbial Population. In Microbial Technology for Sustainable Environment. Bhatt, P., Gangola, S., Udayanga, D. and Kumar, G. (eds.). Singapore: Springer Singapore. 467-481. https://doi.org/10.1007/978-981-16-3840-4_24

Mayer, M., Prescott, C.E., Abaker, W.E.A., Augusto, L., Cécillon, L., Ferreira, G.W.D. et al. (2020). Tamm Review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. Forest Ecology and Management 466, 118127. https://doi.org/10.1016/j.foreco.2020.118127

McPhearson, T., M. Raymond, C., Gulsrud, N., Albert, C., Coles, N., Fagerholm, N. et al. (2021). Radical changes are needed for transformations to a good Anthropocene. npj Urban Sustainability 1(1), 5. https://doi.org/10.1038/s42949-021-00017-x

Meijer, L.J.J., van Emmerik, T., van der Ent, R., Schmidt, C. and Lebreton, L. (2021). More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Science Advances 7(18), eaaz5803. https://doi.org/10.1126/sciadv.aaz5803

Mies, M., Francini-Filho, R.B., Zilberberg, C., Garrido, A.G., Longo, G.O., Laurentino, E. et al. (2020). South Atlantic Coral Reefs Are Major Global Warming Refugia and Less Susceptible to Bleaching. Frontiers in Marine Science Volume 7 - 2020. https://doi.org/10.3389/fmars.2020.00514

Mirzabaev, A., J. Wu, J. Evans, F. García-Oliva, I.A.G. Hussein, M.H. Iqbal et al. (2019). Desertification. In Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security,and greenhouse gas fluxes in terrestrial ecosystems. P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts et al. (eds.). chapter 3. 249-343. https://www.ipcc.ch/site/assets/uploads/sites/4/2022/11/SRCCL_Chapter_3.pdf

Miyazaki, K. (2024). TROPESS Chemical Reanalysis O_3 Monthly 3-dimensional Product V1. Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC). https://disc.gsfc.nasa.gov/datasets/TRPSCRO3M3D_1/summary' not 'https://disc.gsfc.nasa.gov/datasets/TRPSCRO3M3D_1/summary Accessed 2024 October 2024

Mousavi, H., Moshir Panahi, D. and Kalantari, Z. (2024). Dust and climate interactions in the Middle East: Spatio-temporal analysis of aerosol optical depth and climatic variables. Science of The Total Environment 927, 172176. https://doi.org/10.1016/j.scitotenv.2024.172176

Naidu, R., Biswas, B., Willett, I.R., Cribb, J., Kumar Singh, B., Paul Nathanail, C. et al. (2021). Chemical pollution: A growing peril and potential catastrophic risk to humanity. Environment International 156, 106616. https://doi.org/10.1016/j.envint.2021.106616

Nakajima, R., Tsuchiya, M., Yabuki, A., Masuda, S., Kitahashi, T., Nagano, Y. et al. (2021). Massive occurrence of benthic plastic debris at the abyssal seafloor beneath the Kuroshio Extension, the Northwest Pacific. Marine Pollution Bulletin 166, 112188. https://doi.org/10.1016/j.marpolbul.2021.112188

Napper, I.E., Davies, B.F.R., Clifford, H., Elvin, S., Koldewey, H.J., Mayewski, P.A. et al. (2020). Reaching New Heights in Plastic Pollution—Preliminary Findings of Microplastics on Mount Everest. One Earth 3(5), 621-630. https://doi.org/10.1016/j.oneear.2020.10.020

Newbold, T., Hudson, L.N., Arnell, A.P., Contu, S., De Palma, A., Ferrier, S. et al. (2016). Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. Science 353(6296), 288-291. https://doi.org/10.1126/science.aaf2201

Newman, R. and Noy, I. (2023). The global costs of extreme weather that are attributable to climate change. Nature Communications 14(1), 6103. https://doi.org/10.1038/s41467-023-41888-1

Nowak, D.J., Hirabayashi, S., Doyle, M., McGovern, M. and Pasher, J. (2018). Air pollution removal by urban forests in Canada and its effect on air quality and human health. Urban Forestry & Urban Greening 29, 40-48. https://doi.org/10.1016/j.ufug.2017.10.019

Nowak, D.J., Jovan, S., Branquinho, C., Augusto, S., Ribeiro, M.C. and Kretsch, C.E. (2015). Biodiversity, air quality and human health. In Connecting Global Priorities: Biodiversity and Human Health: A State of Knowledge Review. Geneva: World Health Organization and Secretariat of the Convention on Biological Diversity. chapter 4. 63-74. https://www.cbd.int/health/sok-biodiversity-en.pdf

Noyes, P.D. and Lema, S.C. (2015). Forecasting the impacts of chemical pollution and climate change interactions on the health of wildlife. Current Zoology 61(4), 669-689. https://doi.org/10.1093/czoolo/61.4.669

Obada, D.O., Muhammad, M., Tajiri, S.B., Kekung, M.O., Abolade, S.A., Akinpelu, S.B. et al. (2024). A review of renewable energy resources in Nigeria for climate change mitigation. Case Studies in Chemical and Environmental Engineering 9, 100669. https://doi.org/10.1016/j.cscee.2024.100669

O'Hara, C.C., Frazier, M. and Halpern, B.S. (2021). At-risk marine biodiversity faces extensive, expanding, and intensifying human impacts. Science 372(6537), 84-87. https://doi.org/10.1126/science.abe6731

Olsson, L., Barbosa, H., Bhadwal, S., Cowie, A., Delusca, K., Flores-Renteria, D. et al. (2019). Land Degradation. In Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C. et al. (eds.). Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009157988.006

Orgiazzi, A. and Panagos, P. (2018). Soil biodiversity and soil erosion: It is time to get married. Global Ecology and Biogeography 27(10), 1155-1167. https://doi.org/10.1111/geb.12782

Oxera (2024). The Economic Cost of Extreme Weather Events: Prepared for the International Chamber of Commerce. https://www.oxera.com/wp-content/uploads/2024/11/Oxera_The-economic-cost-of-climate-related-extreme-weather.pdf

Pandey, M., Mishra, A., Swamy, S.L., Thakur, T.K. and Pandey, V.C. (2022). Impact of coal mining on land use dynamics and soil quality: Assessment of land degradation vulnerability through conjunctive use of analytical hierarchy process and geospatial techniques. Land Degradation & Development 33(16), 3310-3324. https://doi.org/10.1002/ldr.4390

Pandit, R., Parrotta John A., Chaudhary Ashok Kumar., Karlen Douglas L., Vieira Daniel Luis Mascia., Anker Yaakov. et al. (2020). A framework to evaluate land degradation and restoration responses for improved planning and decision-making. Ecosystems and People 16(1), 1-18. https://doi.org/10.1080/26395916.2019.1697756

Paruch, L., Paruch, A.M., Eiken, H.G. and Sørheim, R. (2019). Faecal pollution affects abundance and diversity of aquatic microbial community in anthropo-zoogenically influenced lotic ecosystems. Scientific Reports 9(1), 19469. https://doi.org/10.1038/s41598-019-56058-x

Pereira, H.M., Martins, I.S., Rosa, I.M.D., Kim, H., Leadley, P., Popp, A. et al. (2024). Global trends and scenarios for terrestrial biodiversity and ecosystem services from 1900 to 2050. Science 384(6694), 458-465. https://doi.org/10.1126/science.adn3441

Persson, L., Carney Almroth, B.M., Collins, C.D., Cornell, S., de Wit, C.A., Diamond, M.L. et al. (2022). Outside the safe operating space of the planetary boundary for novel entities. Environmental Science & Technology 56(3), 1510-1521. https://doi.org/10.1021/acs.est.1c04158

Pfenning-Butterworth, A., Buckley, L.B., Drake, J.M., Farner, J.E., Farrell, M.J., Gehman, A.-L.M. et al. (2024). Interconnecting global threats: climate change, biodiversity loss, and infectious diseases. 8(4), e270-e283. https://doi.org/10.1016/s2542-5196(24)00021-4

Phuong, T.T., Shrestha, R.P. and Chuong, H.V. (2017). Chapter 6 - Simulation of Soil Erosion Risk in the Upstream Area of Bo River Watershed. In Redefining Diversity & Dynamics of Natural Resources Management in Asia, Volume 3. Thang, T.N., Dung, N.T., Hulse, D., Sharma, S. and Shivakoti, G.P. (eds.). Elsevier. 87-99. https://www.sciencedirect.com/science/article/pii/B9780128054529000060

Pires, M.M. and Galetti, M. (2023). Beyond the "empty forest": The defaunation syndromes of Neotropical forests in the Anthropocene. Global Ecology and Conservation 41, e02362. https://doi.org/10.1016/j.gecco.2022.e02362

Poggio, L., de Sousa, L.M., Batjes, N.H., Heuvelink, G.B.M., Kempen, B., Ribeiro, E. et al. (2021). SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty. Soil 7(1), 217-240. https://doi.org/10.5194/soil-7-217-2021

Pörtner, H.O., Scholes, R.J., Agard, J., Archer, E., Arneth, A., Bai, X. et al. (2021). Scientific Outcome of the IPBES-IPCC Co-sponsored Workshop on Biodiversity and Climate Change. https://zenodo.org/records/5101125

Rengasamy, P. (2016). Soil Salinization. Oxford Research Encyclopedia of Environmental Science. https://doi.org/10.1093/acrefore/9780199389414.013.65

Ripple, W.J., Wolf, C., Gregg, J.W., Rockström, J., Newsome, T.M., Law, B.E. et al. (2023). The 2023 state of the climate report: Entering uncharted territory. BioScience 73(12), 841-850. https://www.doi.org/10.1093/biosci/biad080

Samapriya, R., Swetnam, T., Shen, C., Somasundaram, D. and Saah, A. (2024). Impact Observatory and Vizzuality. Biodiversity Intactness Index (BII) [Data set]. https://gee-community-catalog.org/projects/bii/#ancillary-dataset-citation

Sartori, M., Ferrari, E., M'Barek, R., Philippidis, G., Boysen-Urban, K., Borrelli, P. et al. (2024). Remaining loyal to our soil: A prospective integrated assessment of soil erosion on global food security. Ecological Economics 219, 108103. https://doi.org/10.1016/j.ecolecon.2023.108103

Sartori, M., Philippidis, G., Ferrari, E., Borrelli, P., Lugato, E., Montanarella, L. et al. (2019). A linkage between the biophysical and the economic: Assessing the global market impacts of soil erosion. Land Use Policy 86, 299-312. https://doi.org/10.1016/j.landusepol.2019.05.014

Sharma, S. and Chatterjee, S. (2017). Microplastic pollution, a threat to marine ecosystem and human health: a short review. Environmental Science and Pollution Research 24(27), 21530-21547. https://doi.org/10.1007/s11356-017-9910-8

Shrivastava, P. and Zsolnai, L. (2022). Wellbeing-oriented organizations: Connecting human flourishing with ecological regeneration. Business Ethics, the Environment & Responsibility 31(2), 386-397. https://doi.org/10.1111/beer.12421

Sigmund, G., Ågerstrand, M., Antonelli, A., Backhaus, T., Brodin, T., Diamond, M.L. et al. (2023). Addressing chemical pollution in biodiversity research. Global Change Biology 29(12), 3240-3255. https://doi.org/10.1111/gcb.16689

Simoni, M., Baldacci, S., Maio, S., Cerrai, S., Sarno, G. and Viegi, G. (2015). Adverse effects of outdoor pollution in the elderly. Journal of Thoracic Disease 7(1), 34-45. https://doi.org/10.3978/j.issn.2072-1439.2014.12.10

Smith, P., Calvin, K., Nkem, J., Campbell, D., Cherubini, F., Grassi, G. et al. (2020). Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? Global Change Biology 26(3), 1532-1575. https://doi.org/10.1111/gcb.14878

Spalding, C. and Hull, P.M. (2021). Towards quantifying the mass extinction debt of the Anthropocene. Proceedings of the Royal Society B: Biological Sciences 288(1949). https://doi.org/10.1098/rspb.2020.2332

Sylvester, F., Weichert, F.G., Lozano, V.L., Groh, K.J., Bálint, M., Baumann, L. et al. (2023). Better integration of chemical pollution research will further our understanding of biodiversity loss. Nature Ecology & Evolution 7(10), 1552-1555. https://doi.org/10.1038/s41559-023-02117-6

Talukder, B., Ganguli, N., Matthew, R., vanLoon, G.W., Hipel, K.W. and Orbinski, J. (2021). Climate change-triggered land degradation and planetary health: A review. Land Degradation & Development 32(16), 4509-4522. https://doi.org/10.1002/ldr.4056

Tang, F., McBratney, A., Maggi, F. and Lenzen, M. (2021). Global pesticide pollution risk data sets. https://figshare.com/articles/dataset/Global_pesticide_pollution_risk_data_sets/10302218/1

Thackeray, S.J., Sparks, T.H., Frederiksen, M., Burthe, S., Bacon, P.J., Bell, J.R. et al. (2010). Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. Global Change Biology 16(12), 3304-3313. https://doi.org/10.1111/j.1365-2486.2010.02165.x

Tomalka, J., Hunecke, C., Murken, L., Heckmann, T., Cronauer, C., Becker, R. et al. (2024). Stepping Back from the Precipice: Transforming Land Management to Stay within Planetary Boundaries. Potsdam Institute for Climate Impact Research. https://doi.org/10.48485/pik.2024.018

Tudge, S.J., Purvis, A. and De Palma, A. (2021). The impacts of biofuel crops on local biodiversity: A global synthesis. Biodiversity and Conservation 30(11), 2863-2883. https://doi.org/10.1007/s10531-021-02232-5

UK Centre of Ecology and Hydrology (2016). Air pollution information system. https://www.apis.ac.uk/

UNEP-WCMC (2020). Threatened species richness. Cambridge https://www.arcgis.com/home/item.html?id=08696954e5e441e5aecf4de16248a32f

United Nations Convention to Combat Desertification (2019a). Land in numbers 2019. Risks and opportunities. Bonn. https://catalogue.unccd.int/1202-Land%20in%20numbers_2%20new-web.pdf

United Nations Convention to Combat Desertification (2019b). Land-Based Adaptation and Resilience: Powered by Nature. Bonn. https://www.eld-initiative.org/fileadmin/pdf/Land_Based_Adaptation_ENG_Sall_web.pdf

United Nations Convention to Combat Desertification (2022). Global Land Outlook: Land Restoration for Recovery and Resilience. Summary for Decision Makers. Bonn. https://www.unccd.int/sites/default/files/2022-04/GLO2_SDM_low-res_0.pdf

United Nations Convention to Combat Desertification (2023). Global Drought Snapshot 2023: The Need for Immediate Action. Bonn. https://www.unccd.int/sites/default/files/2023-12/Global%20drought%20snapshot%202023.pdf

United Nations Convention to Combat Desertification (n.d.). UNCCD data dashboard. https://data.unccd.int/ Accessed: 16 April 2025

United Nations Environment Programme (2022). The Environmental Impact of the Conflict in Ukraine: A Preliminary Review. Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/40746/environmental_impact_Ukraine_conflict.pdf?sequence=3&isAllowed=y

United Nations Environment Programme (2023). Decades of Mangrove Forest Change: What does it mean for nature, people and the climate? Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/42254/mangrove_forest_change.pdf?sequence=3&isAllowed=y

United Nations Environment Programme (2024) Emissions Gap Report 2024: No more hot air … please! With a massive gap between rhetoric and reality, countries draft new climate commitments. Available at: https://wedocs.unep.org/20.500.11822/46404

United Nations Environment Programme (2024). Environmental Impact of the Conflict in Gaza: Preliminary Assessment of Environmental Impacts. Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/45739/environmental_impact_conflict_Gaza.pdf?sequence=3&isAllowed=y

United Nations Environment Programme (2024). Ministerial Declaration of the United Nations Environment Assembly at its Sixth Session. Effective, Inclusive and Sustainable Multilateral Actions to Tackle Climate Change, Biodiversity Loss and Pollution. UNEP/EA.6/HLS.1. Nairobi. https://docs.un.org/en/UNEP/EA.6/HLS.1

United Nations Framework Convention on Climate Change (2023). Nationally determined contributions under the Paris Agreement: Synthesis report by the secretariat. Bonn: United Nations Framework Convention on Climate Change. https://unfccc.int/documents/632334

United Nations Office for Disaster Risk Reduction (2023). Regional Assessment Report on Disaster Risk Reduction 2023: Europe and Central Asia. https://www.undrr.org/media/91609/download?startDownload=20241022

United States National Aeronautics and Space Administration (2024). Aerosol Optical Depth. The Earth Observatory, https://earthobservatory.nasa.gov/global-maps/MODAL2_M_AER_OD

United States National Centers for Environmental Information (2025). U.S. billion-dollar weather and climate disasters. [United States National Oceanic and Atmospheric Administration, https://www.ncei.noaa.gov/access/billions/ Accessed: 16 April 2025

University of East Anglia Climatic Research Unit, Harris, I.C., Jones, P.D. and Osborn, T. (2024). CRU TS4.08: Climatic Research Unit (CRU) Time-Series (TS) version 4.08 of high-resolution gridded data of month-by-month variation in climate (Jan. 1901- Dec. 2023). https://catalogue.ceda.ac.uk/uuid/715abce1604a42f396f81db83aeb2a4b/

Urban, M.C. (2015). Accelerating extinction risk from climate change. Science 348(6234), 571-573. https://doi.org/10.1126/science.aaa4984

Urban, M.C. (2024). Climate change extinctions. Science 386(6726), 1123-1128. https://doi.org/10.1126/science.adp4461

Vallero, D.A. (2019). Chapter 8 - Effect of Waste on Ecosystems. In Waste (Second Edition). Letcher, T.M. and Vallero, D.A. (eds.). Academic Press. 171-198. https://www.sciencedirect.com/science/article/pii/B9780128150603000086

Verhoeven, D., Berkhout, E., Sewell, A. and van der Esch, S. (2024). The global cost of international commitments on land restoration. Land Degradation & Development 35(16), 4864-4874. https://doi.org/10.1002/ldr.5263

Verones, F., Kuipers, K., Núñez, M., Rosa, F., Scherer, L., Marques, A. et al. (2022). Global extinction probabilities of terrestrial, freshwater, and marine species groups for use in Life Cycle Assessment. Ecological Indicators 142, 109204. https://doi.org/10.1016/j.ecolind.2022.109204

Vethaak, A.D. and Legler, J. (2021). Microplastics and human health. Science 371(6530), 672-674. https://doi.org/10.1126/science.abe5041

Willcock, S., Cooper, G.S., Addy, J. and Dearing, J.A. (2023). Earlier collapse of Anthropocene ecosystems driven by multiple faster and noisier drivers. Nature Sustainability 6(11), 1331-1342. https://doi.org/10.1038/s41893-023-01157-x

Williams, B.A., Venter, O., Allan, J.R., Atkinson, S.C., Rehbein, J.A., Ward, M. et al. (2020). Change in terrestrial human footprint drives continued loss of intact ecosystems. One Earth 3(3), 371-382. https://doi.org/10.1016/j.oneear.2020.08.009

Windfeld, E.S. and Brooks, M.S.-L. (2015). Medical waste management – A review. Journal of Environmental Management 163, 98-108. https://doi.org/10.1016/j.jenvman.2015.08.013

Winkler, K., Yang, H., Ganzenmüller, R., Fuchs, R., Ceccherini, G., Duveiller, G. et al. (2023). Changes in land use and management led to a decline in Eastern Europe's terrestrial carbon sink. Communications Earth & Environment 4(1), 237. https://doi.org/10.1038/s43247-023-00893-4

Worlanyo, A.S. and Jiangfeng, L. (2021). Evaluating the environmental and economic impact of mining for post-mined land restoration and land-use: A review. Journal of Environmental Management 279, 111623. https://doi.org/10.1016/j.jenvman.2020.111623

World Economic Forum (2020). Nature Risk Rising: Why the Crisis Engulfing Nature Matters for Business and the Economy. Cologny/Geneva. http://www3.weforum.org/docs/WEF_New_Nature_Economy_Report_2020.pdf

World Economic Forum (2023). Global Risks Report 2023. Geneva. https://www.weforum.org/publications/global-risks-report-2023/

World Meteorological Organization (2024a). State of the Climate 2024. Update for COP29. Geneva. https://library.wmo.int/viewer/69075/download?file=State-Climate-2024-Update-COP29_en.pdf&type=pdf&navigator=1

World Meteorological Organization (2024c). State of the Global Climate 2023. Geneva. https://library.wmo.int/viewer/68835/download?file=1347_Global-statement-2023_en.pdf&type=pdf&navigator=1

Xiao, H., Wang, B., Lu, S., Chen, D., Wu, Y., Zhu, Y. et al. (2020). Soil acidification reduces the effects of short-term nutrient enrichment on plant and soil biota and their interactions in grasslands. Global Change Biology 26(8), 4626-4637. https://doi.org/10.1111/gcb.15167

Xie, Y., Lin, M., Decharme, B., Delire, C., Horowitz, L.W., Lawrence, D.M. et al. (2022). Tripling of western US particulate pollution from wildfires in a warming climate. Proceedings of the National Academy of Sciences 119(14), e2111372119. https://doi.org/10.1073/pnas.2111372119

Yue, X. and Unger, N. (2018). Fire air pollution reduces global terrestrial productivity. Nature Communications 9(1), 5413. https://doi.org/10.1038/s41467-018-07921-4

Zaghloul, A., Saber, M., Gadow, S. and Awad, F. (2020). Biological indicators for pollution detection in terrestrial and aquatic ecosystems. Bulletin of the National Research Centre 44(1), 127. https://doi.org/10.1186/s42269-020-00385-x

Zhang, Z., Malik, M.Z., Khan, A., Ali, N., Malik, S. and Bilal, M. (2022). Environmental impacts of hazardous waste, and management strategies to reconcile circular economy and eco-sustainability. Science of The Total Environment 807, 150856. https://doi.org/10.1016/j.scitotenv.2021.150856

Wang, Z., Cui, N., Hung, C., Li, S., and Dong, F. (2025). A 150-Year Avian Extinction Debt Forewarns a Global Species Crisis and Highlights Conservation Opportunities. Conservation Letters Vol. 18, Issue 1. https://doi.org/10.1111/conl.13078

Credit: Image-Source/Envato

Indigenous Knowledge and Local Knowledge Chapeau B

Indigenous Peoples maintain a profound connection to the land, viewing it not merely as a resource but as living territories that form an essential part of their identity and existence (Nelson and Shilling 2018). Consequently, any change in natural processes directly affects their ways of life and well-being. Indigenous territories and cultures are threatened by the expansion of resource extraction, pollution, and appropriation that prevent traditional land-use practices (Ford et al. 2020; Ibarra et al. 2023). Industrial-scale mining, energy production and the agricultural, forest and fisheries sectors lead to landscape degradation, biodiversity loss and land dispossession (Scheidel et al. 2023), impacting Indigenous Peoples ways of life. Water pollution and poor governance compromise the quality of freshwater resources, increasing water insecurity and risks to public health and contributing to spiritual and cultural losses (Sajwan 2020). Land use change and degradation resulting from unsustainable practices contribute to habitat and biodiversity loss, affecting all aspects of ecosystem health including freshwater cycles and air quality with cascading effects on the health and well-being of Indigenous Peoples (Isbell et al. 2017; UNPFII 2023). Biological and cultural diversity are intertwined and are affected by extractive operations and resource appropriation that threaten the livelihoods of Indigenous Peoples, as well as their cultural and spiritual practices (UNESCO 2019; Kuklina et al. 2022; IK & LK Dialogues 2025).

Many Indigenous Peoples live in areas where the effects of the global environmental crises overlap (Leal Filho et al. 2021; IPCC 2023a; IPCC 2023b; Rockström et al. 2023; Reyes-García et al. 2024). Crossing Earth's tipping points can result in accelerated groundwater depletion, glacier melting, extreme heat or sea level rise, affecting or even displacing millions of people (Caesar et al. 2024). Indigenous Peoples living in remote drylands, mountains, deltaic and coastal communities from the Arctic to small islands are particularly at risk (IPCC 2023b). In this context, the Indigenous conceptualizations of Planetary Health and their understanding of the changes in the environment are crucial to addressing the unprecedented human-made drivers of the global environmental crises and their consequences (Nkuba et al. 2020). Prevention, coping, adaptive capacities and resilience inherent in Indigenous ways of life and their connection with the land have much to offer (Ford et al. 2020; Ibarra et al. 2023; UNESCO 2024).

Policy decisions can be better informed if Indigenous Peoples livelihoods and economies in relation to changes in nature climate change, biodiversity, land

Credit: jkraft5/Envato

and provision of ecosystem services are well understood and efforts are made to reverse harmful changes (Reyes-García et al. 2024). Since biological and cultural diversity are intertwined and the loss of one correlates with the loss of the other, revitalizing Indigenous worldviews, cultures and languages is crucial for the recovery of lands and the protection of biodiversity (Mathez-Stiefel et al. 2007; Eriksen 2021). Alleviating the consequences of climate change for Indigenous Peoples health and well-being requires a focus on Indigenous perspectives, emphasizing Indigenous Knowledge and movements for decolonization, health and human rights (IPCC 2023a). A multi-faceted approach is required, an approach that respects human rights, upholds Indigenous legal orders, fosters collaboration, recognizes Indigenous Knowledge and Local Knowledge and enhances communication (López-Maldonado et al. 2024). The SDG goals and corresponding targets framework are limited in this regard, as they lack Indigenous perspectives on sustainability and development and do not affirm collective rights over land, resources and territories (Odulaja and Halseth 2018; O'Sullivan 2023).

References

Caesar, L., Sakschewski, B., Andersen, L.S., Beringer, T., Braun, J., Dennis, D. et al. (2024). Planetary Health Check A Scientific Assessment of the State of the Plane. (PBScience), P.B.S. (ed.). Potsdam, Germany: Potsdam Institute for Climate Impact Research. https://policycommons.net/artifacts/16632857/planetaryhealthcheck2024_report/17517710/

Eriksen, T.H. (2021). The Loss of Diversity in the Anthropocene Biological and Cultural Dimensions. Frontiers in Political Science 3. https://doi.org/10.3389/fpos.2021.743610

Ford, J.D., King, N., Galappaththi, E.K., Pearce, T., McDowell, G. and Harper, S.L. (2020). The Resilience of Indigenous Peoples to Environmental Change. One Earth 2(6), 532-543. https://doi.org/10.1016/j.oneear.2020.05.014

Ibarra, J.T., Caviedes, J., Marchant, C., Mathez-Stiefel, S.L., Navarro-Manquilef, S. and Sarmiento, F.O. (2023). Mountain social-ecological resilience requires transdisciplinarity with Indigenous and local worldviews. Trends Ecol Evol 38(11), 1005-1009. https://doi.org/10.1016/j.tree.2023.07.004

IK & LK Dialogues (2025). Indigenous Knowledge and Local Knowledge Dialogues. Global Environment Outlook 7. https://copitarxives.fisica.unam.mx/SC0011EN/SC0011EN.php

Intergovernmental Panel on Climate Change [IPCC] (2023a). Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. https://www.cambridge.org/core/product/161F238F406D530891AAAE1FC76651BD

Intergovernmental Panel on Climate Change [IPCC] (2023b). Technical Summary. In Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. 37-118. https://www.cambridge.org/core/product/124D9019DECBF96BDB2979ABF494644D

Isbell, F., Gonzalez, A., Loreau, M., Cowles, J., Díaz, S., Hector, A. et al. (2017). Linking the influence and dependence of people on biodiversity across scales. Nature 546(7656), 65-72. https://doi.org/10.1038/nature22899

Kuklina, M., Savvinova, A., Filippova, V., Krasnoshtanova, N., Bogdanov, V., Fedorova, A. et al. (2022). Sustainability and Resilience of Indigenous Siberian Communities under the Impact of Transportation Infrastructure Transformation. Sustainability 14(10). https://doi.org/10.3390/su14106253

Leal Filho, W., Matandirotya, N.R., Lütz, J.M., Alemu, E.A., Brearley, F.Q., Baidoo, A.A. et al. (2021). Impacts of climate change to African indigenous communities and examples of adaptation responses. Nature Communications 12(6224), 2041-1723. https://doi.org/10.1038/s41467-021-26540-0

López-Maldonado, Y., Anstee, J., Neely, M.B., Marty, J., Mastracci, D., Ngonyani, H. et al. (2024). The contributions of Indigenous People's earth observations to water quality monitoring. Frontiers in Water 6. https://doi.org/10.3389/frwa.2024.1363187

Mathez-Stiefel, S. L., Boillat, S., & Rist, S. (2007). Promoting the diversity of worldviews: an ontological approach to biocultural diversity. Endogenous Development and Bio-cultural Diversity. The interplay of worldviews, globalization and locality. ETC/COMPAS, Leusden, 67-81. https://www.researchgate.net/publication/252168795_Promoting_the_diversity_of_worldviews_An_ontological_approach_to_bio-cultural_diversity

Nelson, M.K. and Shilling, D. (2018). Traditional Ecological Knowledge: Learning from Indigenous Practices for Environmental Sustainability. New York: Cambridge University Press. https://doi.org/10.1017/9781108552998

Nkuba, M.R., Chanda, R., Mmopelwa, G., Kato, E., Mangheni, M.N. and Lesolle, D. (2020). Influence of Indigenous Knowledge and Scientific Climate Forecasts on Arable Farmers' Climate Adaptation Methods in the Rwenzori region, Western Uganda. Environmental Management 65(4), 500-516. 1. https://doi.org/10.1007/s00267-020-01264-x

O'Sullivan, D. (2023). Indigeneity, culture and the UN sustainable development goals / Dominic O'Sullivan. 1st edn. Sustainable Development Goals Series. Singapore: Palgrave Macmillan. https://link.springer.com/book/10.1007/978-981-99-0581-2

Odulaja, O.O. and Halseth, R. (2018). The United Nations Sustainable Development Goals and Indigenous Peoples in Canada. Prince George, BC: National Collaborating Centre for Aboriginal Health. http://www.nccah-ccnsa.ca/docs/determinants/RPT-UN-SDG-IndPeoplesCanada-Halseth-Odulaja-EN.pdf

Reyes-García, V., García-del-Amo, D., Álvarez-Fernández, S., Benyei, P., Calvet-Mir, L., Junqueira, A.B. et al. (2024). Indigenous Peoples and local communities report ongoing and widespread climate change impacts on local social-ecological systems. Communications Earth & Environment 5(1), 29. https://doi.org/10.1038/s43247-023-01164-y

Rockström, J., Gupta, J., Qin, D., Lade, S.J., Abrams, J.F., Andersen, L.S. et al. (2023). Safe and just Earth system boundaries. Nature 619(7968), 102-111

Sajwan, A. (2020). Neeru and the Nilgiris. India water portal, https://www.indiawaterportal.org/articles/neeru-and-nilgiris

Scheidel, A., Fernández-Llamazares, Á., Bara, A.H., Bene, D.D., David-Chavez, D.M., Fanari, E. et al. (2023). Global impacts of extractive and industrial development projects on Indigenous Peoples' lifeways, lands, and rights. Science Advances 9(23), 2375-2548. https://doi.org/10.1126/sciadv.ade9557

United Nations Educational Scientific and Cultural Organization (2019). The Atateken Declaration: The North American Regional Declaration on Biocultural Diversity. https://www.cbd.int/portals/culturaldiversity/docs/north-american-regional-declaration-on-biocultural-diversity-en.pdf

United Nations Educational Scientific and Cultural Organization (2024). Guidance note on climate action for living heritage. Convention for the safeguarding of the intangible cultural heritage. LHE/24/19.COM/11

03 Air

Coordinating Lead Authors: Sotiris Vardoulakis (University of Canberra) and Min Hu (Peking University)

Lead Authors: Graciela Raga (Instituto de Ciencias de la Atmósfera y Cambio Climático, Universidad Nacional Autónoma de México), Stefan Reis (DLR-PT, Unit Environment and Sustainability), Pallavi Saxena (Department of Environmental Science, Hindu College, University of Delhi, India), Carol Zavaleta-Cortijo (Universidad Peruana Cayetano Heredia)

Contributing Lead Authors: Claudio Belis (European Commission, Joint Research Centre), Indu Murthy (CSTEP; Center for Study of Science, Technology and Policy), Mulako Kabisa (University of the Witwatersrand - Global Change Institute), Stephan Harrison (University of Exeter)

Fellows: Nadege Amizero (Environmental Pulse Institute)

Credit: Freedomnaruk/Envato

Chapter summary

Credit: SteveAllenPhoto999/Envato

The planet faces global, interconnected environmental crises of climate change, biodiversity loss and land degradation, and pollution and waste that affect the Earth's atmosphere in complex ways, posing a threat to sustainable development and to life on Earth.

Anthropogenic greenhouse gas emissions are not on target to limit global warming to 2°C above pre-industrial levels (*well established*). These emissions resulted in a warming planet, with an effective radiative forcing that averaged +2.79 W/m^2, the measure for solar irradiance, over the period 1750-2023. Efforts to reduce atmospheric pollution by reducing sulfur dioxide emissions from shipping have led to additional radiative forcing of +0.1 to +0.2 W/m^2, offsetting efforts to limit warming to 1.5°C and demonstrating the potential unintended consequences of some policy measures. Mobility restrictions and industry shutdowns during the COVID-19 pandemic led to a temporary reduction in global greenhouse gas (GHG) emissions. However, lifting restrictions resulted in a rapid increase in global emissions the following year. This highlights the importance of sustained reductions in GHG emissions from multiple sectors. Military operations and armed conflicts have generated additional GHG emissions and worsened air quality in Europe, Africa and the Middle East since the start of those conflicts {3.2.1} {3.2.4} {3.4.3}.

The average global surface temperature continues to rise and heatwaves are becoming more frequent and prolonged (*well established*). The average global temperature for 2014–2023 increased by an average of 1.19°C above the 1850–1900 baseline. This value masks considerable regional variability, with polar regions warming much faster than the global mean. Increasing global surface temperature resulted in the ten years between 2015 and 2024 being the warmest since records began in 1850, and the World Meteorological

Organization stating that 2024 was the hottest year on record, exceeding the 1.5°C threshold. The 2024 record-high global temperature was partly due to the 2023–2024 El Niño effect and likely related to decreased low-level cloudiness and albedo over the oceans, as a result of restrictions in the sulfur content of shipping fuels.

Extreme weather events, such as heatwaves – periods of hot weather exceeding a temperature threshold over consecutive days – are becoming more frequent and intense, affecting larger populations (*well established*). The urban heat island effect has also intensified, leading to night-time urban warming much greater than the average global warming, accompanied by increasing heat-related mortality and morbidity risks {3.2.2} {3.4.1}.

Intense precipitation events have increased globally, although there is also evidence of certain regions experiencing worsening droughts (*established but incomplete*). Precipitation over land has increased since 1950, with this trend accelerating since the 1980s. Extreme rainfall has caused flash flooding and landslides in regions such as southern Brazil, while warmer temperatures and reduced precipitation have resulted in prolonged droughts in other regions such as the Middle East and southern Australia. The intensity and frequency of extreme rainfall and drought will worsen as the climate continues to warm, with negative consequences for human health and infrastructure and for ecosystems {3.2.3}.

Globally, 99 per cent of the world's population is exposed to harmful levels of air pollution (*well established*). Outdoor and indoor air pollution have a combined effect equivalent to approximately eight million deaths every year. Outdoor air pollution trends vary substantially by pollutant and region. Global $PM_{2.5}$ concentrations slightly declined from 2000-2019 but increased in South Asia. Rising temperatures affected air pollution trends by contributing to higher tropospheric ozone (O_3) levels, particularly in cities, to more frequent and intense wildfires and related smoke events, and to longer pollen seasons. Global population exposure to O_3 increased mainly in southern and eastern China and central Africa, and the annual nitrogen dioxide mean concentration increased in 71 per cent of cities in those regions {3.2.4} {3.4.2}.

Wildfires, particularly in boreal forests, increased in frequency and intensity over the period 2002–2020 due to changes in climate, land use and fire management, destroying ecosystems and carbon sinks, and emitting large quantities of smoke (*well established*). Increased emissions from wildfires severely deteriorate air quality, leading to high levels of $PM_{2.5}$ and other pollutants. Wildfires also release large quantities of black carbon, which has a significant radiative-forcing effect. Beyond the immediate adverse effects of wildfires at a local scale, large fire events affect atmospheric composition on a regional to even hemispheric scale and constitute a persistent transboundary air pollution challenge. Without effective interventions, the probability of extreme wildfires will increase globally by a factor of 1.31 to 1.57 by the end of the century. Significant health impacts associated with wildfires include physical and mental health effects from direct exposure to fires, as well as from wildfire smoke. With a growing and ageing global population, the health effects of wildfire smoke are likely to become more substantial in the future {3.4.3}.

Climate change is affecting pollen and dust particle concentrations in certain regions (*established but incomplete*). The combination of rising temperatures and reduced rainfall due to climate change results in more severe sand and dust storms in regions such as Western Asia, Central Asia and Sub-Saharan Africa. Warmer temperatures and higher atmospheric concentrations of carbon dioxide (CO_2) tend to prolong and intensify the pollen season, increasing population exposure to airborne allergens and aggravating respiratory diseases such as rhinitis and asthma {3.4.6} {3.4.7}.

Changes in biodiversity affect the climate system, especially through the loss of carbon sinks, while climate change affects biodiversity through a decline in ecosystem functioning, integrity and resilience (*established but incomplete*). Tropical forests are vital for carbon storage and their capacity varies around the world. Tropical eastern Amazonian forests have declined as a carbon sink due to deforestation and fires, while African forests remained stable for three decades up to 2015. An estimated 10 to 47 per cent of Amazonian forest is exposed to a combination of warming temperatures, extreme droughts, deforestation and wildfires. This could result in an irreversible ecosystem transition if certain critical thresholds or tipping points are reached, potentially exacerbating regional climate change {3.3.1} {3.3.2}.

Food production is affected by climate change, extreme weather events and tropospheric ozone (*established but incomplete*). Specific crop yields are decreasing due to more frequent extreme events, particularly in low-income countries with lower adaptive capacity. Tropospheric ozone also damages crops, affecting yields and food security. Warmer temperatures could lead to an increased risk of the proliferation of microorganisms that cause food-borne diseases, such as Salmonella and Campylobacter {3.4.10}.

The global environmental crises disproportionally affect socioeconomically disadvantaged groups, especially women, children, the elderly, Indigenous Peoples, people with illness or disability and those living in informal settlements (*established but incomplete*). This creates a trend of widening socioeconomic inequalities and environmental injustice. For example, warming temperatures pose numerous risks to health, including cardiovascular, respiratory, neurological and mental, especially in ageing populations. Globally, around 489,000 heat-related deaths occurred every year over the period 2000–2019, with annual heat-related mortality for people over 65 years of age increasing by approximately 85 per cent in the period 2013–2022 compared with 1991–2000, due to climate and demographic changes. There is also emerging evidence that exposure to higher temperatures during pregnancy is linked to adverse perinatal health outcomes, including preterm birth, low birth weight and stillbirth, particularly in lower socioeconomic groups {3.4.1} {3.4.12}.

Indigenous Peoples' health and well-being are disproportionally affected by climate change due to limited access to healthcare services, socioeconomic inequities, historical trauma, land dispossession and loss of cultural identity (*established but incomplete*). Direct effects include increased mortality, injuries, respiratory diseases, mental health distress and poverty due to territorial displacement. Indigenous Peoples can experience anxiety, emotional grief and spiritual anguish from witnessing deterioration of their territories and culture, while increased risk of climate-related infectious diseases result from ecosystem damages and biodiversity loss. Changes in the availability and quality of Indigenous Peoples' food lead to multiple forms of malnutrition and increased risk of chronic health conditions. Conversely, Indigenous and local knowledge sources and their observations can be used to adapt to environmental change, for example by managing wildfires more effectively {3.4.12}.

The health benefits associated with reductions in air pollutant concentrations can provide a strong incentive for climate change mitigation through reductions in co-emitted greenhouse gases and short-lived climate pollutants (*well established*). When both co-benefits and trade-offs are fully considered, optimal climate change policies and air quality mitigation policies result in immediate net benefits globally. The most ambitious plausible transition to a net-zero society provides benefits for climate change mitigation and air quality from decadal to centennial timescales {3.4.13}.

Stratospheric ozone recovery continues, albeit with significant inter-annual variability (*established but incomplete*). Such variability was observed in Antarctic total column ozone, particularly in September annually, and is related to the dynamics of the polar vortex. Continued recovery is contingent upon full compliance with the Montreal Protocol {3.2.5} {3.4.9}.

Many countries have taken substantial steps to align their national climate policies with the Paris Agreement's objectives (*well established*). The Nationally Determined Contributions (NDCs) are vital tools for countries to outline their specific climate actions. The combined GHG emissions of the Parties could decrease by an average of 64 per cent by the year 2050 compared to the levels observed in 2019, if NDCs are fully implemented. These projected emissions reductions are inconsistent with restricting warming to 1.5°C. According to the 2024 United Nations Environment Programme (UNEP) Emissions Gap Report, current policies could lead to a 2.6–3.1°C increase in global mean surface temperature with full implementation of the unconditional and conditional NDCs. Furthermore, many countries are currently not on track to achieve their NDCs; to remain on the pathway to 1.5°C, current emissions must reduce by 42 per cent by 2030 and 57 per cent by 2035 {3.5.1}.

There is an urgent need for substantially increased commitments to NDCs by 2030, or for a significant overachievement of the most recent NDCs, to limit warming to 1.5°C (*well established*). A combination of both approaches is necessary to achieve the cost-effective emission levels proposed in numerous scenarios analysed by the Intergovernmental Panel on Climate Change that aim to keep global warming under 2°C or even limit it to 1.5°C {3.5.1}.

3.1 Introduction

Climate change affects the Earth system's primary biogeochemical cycles – carbon, hydrogen and water – and is intricately linked with risks to air quality, biodiversity and human health. Since the GEO-6 report (United Nations Environment Programme 2019), GHG concentrations in the atmosphere continued to increase due to human activities (Intergovernmental Panel on Climate Change [IPCC] 2021), reaching mixing ratios of 418 parts per million (ppm) for carbon dioxide (CO_2), 1923 parts per billion (ppb) for methane (CH_4), and 336 ppb for nitrous oxide (N_2O) in 2022 (World Meteorological Organization [WMO] 2023a).

The global surface temperature anomaly in 2011–2020 was +1.09 [0.95–1.20] °C with respect to 1850–1900, with larger increases over land than over the ocean. Moreover, the frequency and intensity of extreme events – such as heatwaves, wildfires and intense precipitation – have increased globally, with some of this attributable to climate change (IPCC 2021).

The GEO-6 report stated that emissions of stratospheric ozone-depleting substances (ODSs) had decreased substantially as a result of generalized compliance with the Montreal Protocol. Moreover, stratospheric ozone over Antarctica had shown signs of recovery.

The GEO-6 report also indicated that environmental concentrations of persistent organic pollutants had declined in Europe, North America, Asia and the Pacific, and the Arctic. However, it highlighted challenges related to emerging pollutants and cautioned that unless more substantial policy measures and environmental governance were adopted to address both air pollution and climate change, no significant improvements would occur. Indeed, climate change impacts have continued to become more severe, while additional interventions have led to improvements in air quality in many regions.

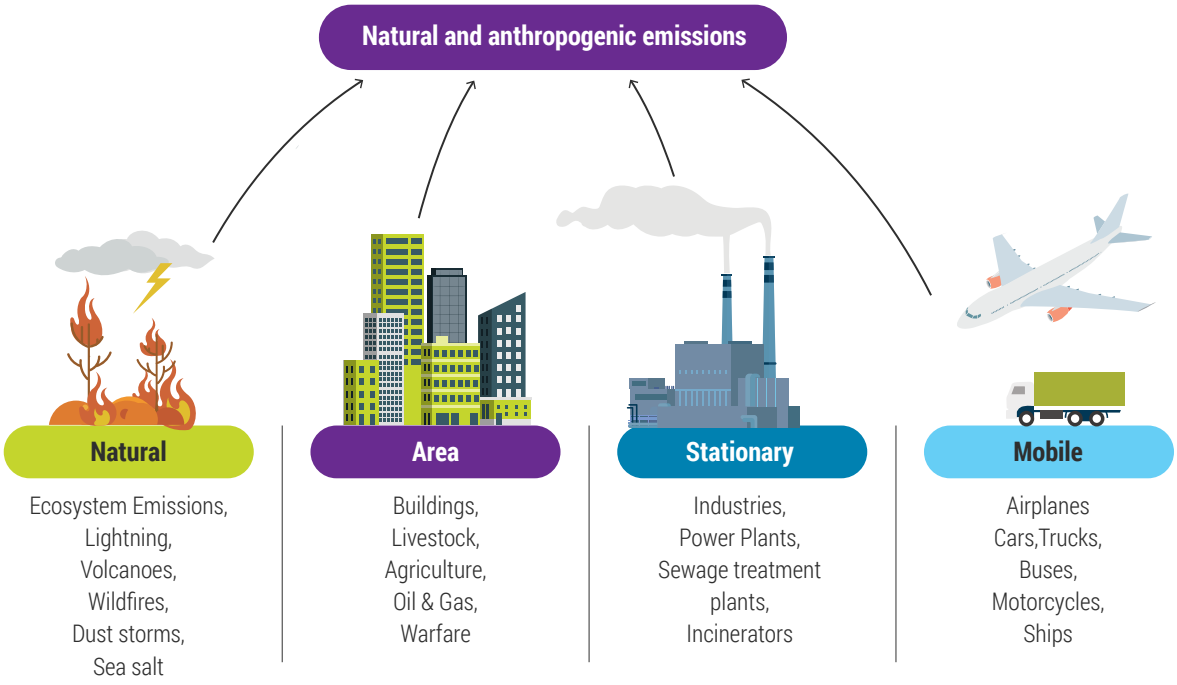
This chapter focuses on the state and trends of major atmospheric components and their interactions with multiple environmental variables such as air pollutants, including trace gases, particulate matter, heavy metals, ODSs and GHGs in the context of climate change. It also examines interactions between the atmosphere and human systems and ecosystems, and the progress towards the goals of relevant global agreements.

Atmospheric concentrations of long-lived GHGs, short-lived climate forcers, ODSs and chemical pollutants, including microplastics, influence air quality, stratospheric ozone and the climate, affecting human systems and ecosystems directly and indirectly.

Changes in biodiversity affect the climate, especially through their influence on the nitrogen, carbon and water cycles. These interactions can generate complex feedbacks between climate, biodiversity and human systems, potentially leading to adverse outcomes.

Credit: liufuyu/Envato

Figure 3.1: Sources of air pollutants and greenhouse gases



Source: National Park Service [NPS] (2018)

For example, higher temperatures and changes in evapotranspiration due to climate change make forests drier and more prone to wildfires, which in turn release gases, heavy metals like mercury, and fine particulate matter ($PM_{2.5}$). The risk of wildfires is increasing due to numerous factors, including climate change, changes in land use and land-management practices, and demographic change (United Nations Environment Programme [UNEP] 2022). In turn, wildfires release more CO_2 into the atmosphere, exacerbating the greenhouse effect and accelerating global warming. The effects of land degradation and biodiversity loss on climate change and air quality are also multifaceted and interconnected (Chapter 4).

This report includes a Global Environmental Crises Chapeau. explaining the main connections among the global environmental crises, the crisis of climate change, the crisis of biodiversity loss, land degradation and desertification, and the crisis of pollution and waste, as well as their stressors and effects.

Climate change strongly affects air pollution and waste generation, as represented by the large arrow. For example, tropospheric warming due to climate change directly affects tropospheric ozone (O_3) and secondary aerosol formation, since many chemical reactions are temperature dependent. Sources of air pollutants and greenhouse gases are illustrated in **Figure 3.1**.

Climate change greatly amplifies biodiversity loss and is a driver of species extinction. It also affects land degradation, since warmer temperatures and decreased water content in soils are associated with a reduction in organic matter. Precipitation patterns and intensity changes often lead to increased soil erosion, landslides and desertification, contributing to atmospheric dust concentrations.

This chapter also presents the progress towards internationally agreed environmental goals, regulations and targets aimed at reducing adverse effects on the atmosphere and the global environment, and consequently on human systems. These include the World Health Organization's updated air quality guidelines, including for harmful $PM_{2.5}$ and tropospheric O_3; outcomes from the Montreal Protocol on Substances that Deplete the Ozone Layer, which is located in the stratosphere and protects life from ultraviolet radiation; the Paris Agreement contributions to limiting GHG emissions; and pledges to reduce short-lived climate forcers.

3.2 State and trends of atmospheric composition

3.2.1 Long-lived and short-lived climate forcers

Atmospheric concentrations of long-lived (CO_2, N_2O) and short-lived (CH_4, O_3 and its precursors; some hydrofluorocarbons) GHGs and aerosols affect the Earth's radiative balance. Interactions with solar and terrestrial thermal radiation (Kramer et al. 2021) result in a substantial and positive Earth energy imbalance (Forster et al. 2021; Hansen et al. 2023). The estimated imbalance for 2011–2023 was +0.96 [0.67–1.26] W/m2 (Forster et al. 2023a). The resulting warming is attributable to emissions of well-mixed GHGs and other forcings, such as aerosol–radiation interaction, aerosol–cloud interaction, tropospheric ozone, black carbon deposited on snow, and land-use changes (Eyring et al. 2021).

Emissions of GHGs have continued to increase (Forster et al. 2024) **(Figure 3.2a**). However, widespread restrictions during the COVID-19 pandemic caused a temporary worldwide decline in GHG emissions in 2020 of 5.8 per cent (International Energy Agency [IEA] 2022). Methane emissions have increased by approximately 20 per cent in the period 2000–2020 (Saunois et al. 2024).

Short-lived climate forcers are reactive compounds with atmospheric lifetimes typically shorter than two decades that contribute to global warming and air pollution. Their emissions have also continued to increase (Szopa et al. 2021).

Tropospheric aerosols have a net cooling effect on the climate system (IPCC 2021) and degrade air quality (Fowler et al. 2020). The reduction in shipping emissions of sulfur dioxide (SO_2) due to restrictions in the sulfur content of fuel for maritime vessels contributed to a decrease in cloud condensation nuclei, which resulted in a reduction in low-level cloudiness and an albedo decrease over the oceans that accelerates global warming (Hansen et al. 2025). The additional radiative forcing was estimated to be approximately +0.1 to +0.2 W/m2, averaged over the global ocean (Yuan et al. 2024; Yoshioka et al. 2024; Gettelman et al. 2024).

Figure 3.2b shows an updated estimate of the contribution of each anthropogenic component to the effective radiative forcing from 1750 to 2023 (Forster et al. 2024). Land-use change and aerosols contribute negatively with a cooling effect, partially compensating for the GHG positive contributions with a warming effect, resulting in an effective radiative forcing of +2.79 [1.78–3.61] W/m_2.

3.2.2 Temperature

The Intergovernmental Panel on Climate Change (2021) reported a global mean surface temperature of +1.09°C [0.95–1.20] above the pre-industrial (1850–1900) levels for the period 2011–2020, with larger increases over land (1.59 [1.34–1.83] °C) than over the ocean (0.88 [0.68–1.01] °C). The World Meteorological Organization (WMO) reported that 2015–2024 was the warmest 10-year period since 1850, and 2024 the hottest year with temperature 1.5°C above pre-industrial levels (WMO 2025a).

While a cool La Niña effect dominated from 2020, the strong El Niño that developed in 2023 contributed to the warmest annual global surface temperature on record (WMO 2024a). The reduction in shipping emissions due to restrictions in the sulfur content of maritime fuel also likely contributed to this warming effect (Hansen et al. 2025).

The temperature anomaly reached +1.19°C [1.00–1.4] (above 1850–1900) for 2014–2023 (**Figure 3.3**, Forster et al. 2024). The temperature change over land for the same period was estimated as +1.65°C [1.36–1.90]. The mean surface global temperature rise masks considerable regional variability, with the Arctic warming up to four times faster (Rantanen et al. 2022).

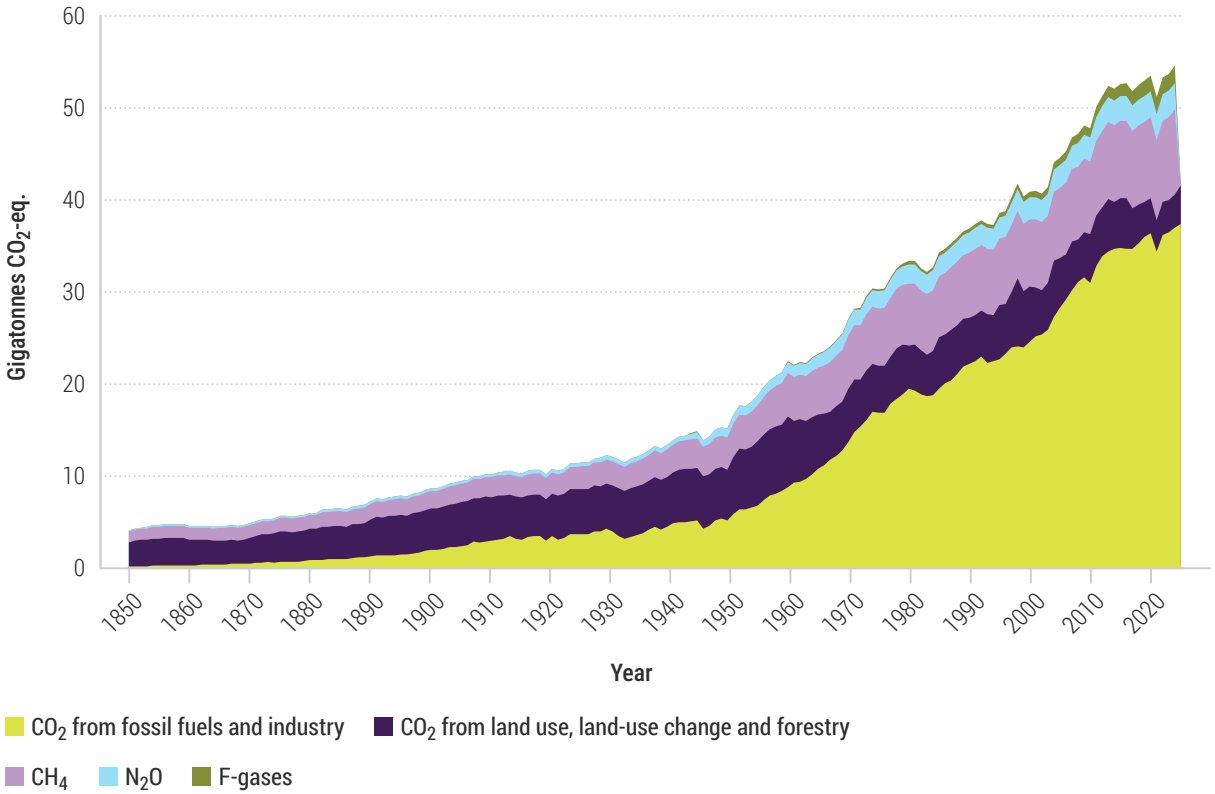
The current global average temperature trend is 0.26 [0.2–0.4] °C per decade over the period 2014–2023. The WMO (2025) confirmed that the global average temperature in 2024 was 1.55°C above pre-industrial levels.

The Earth energy imbalance has affected the whole atmosphere: the troposphere has warmed since at least the 1950s, and the stratosphere has cooled (IPCC 2021). The tropical upper-troposphere has warmed faster than the surface since 2001 and the height of the tropopause has risen globally over the period 1980–2018 (Ladstädter et al. 2023). This rise of the tropopause may have long-term effects on climate and weather by influencing stratosphere-troposphere exchanges (Meng et al. 2021).

Heatwaves – periods of hot weather exceeding a temperature threshold over consecutive days and nights – have increased in frequency and intensity globally (Seneviratne et al. 2021). Trends for heatwave

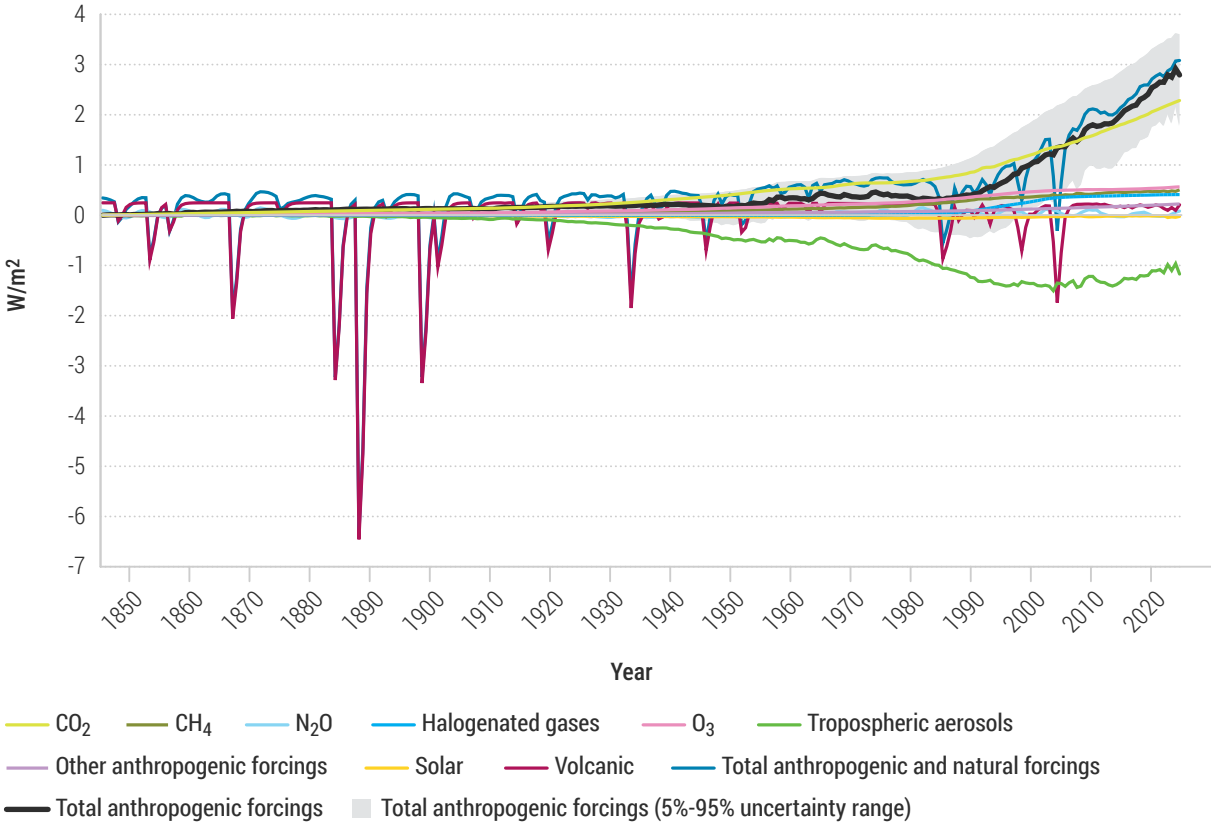
Figure 3.2: Total global greenhouse gas emissions and global radiative forcing from anthropogenic and natural sources

a) Total global greenhouse gas emissions from 1850 to 2023



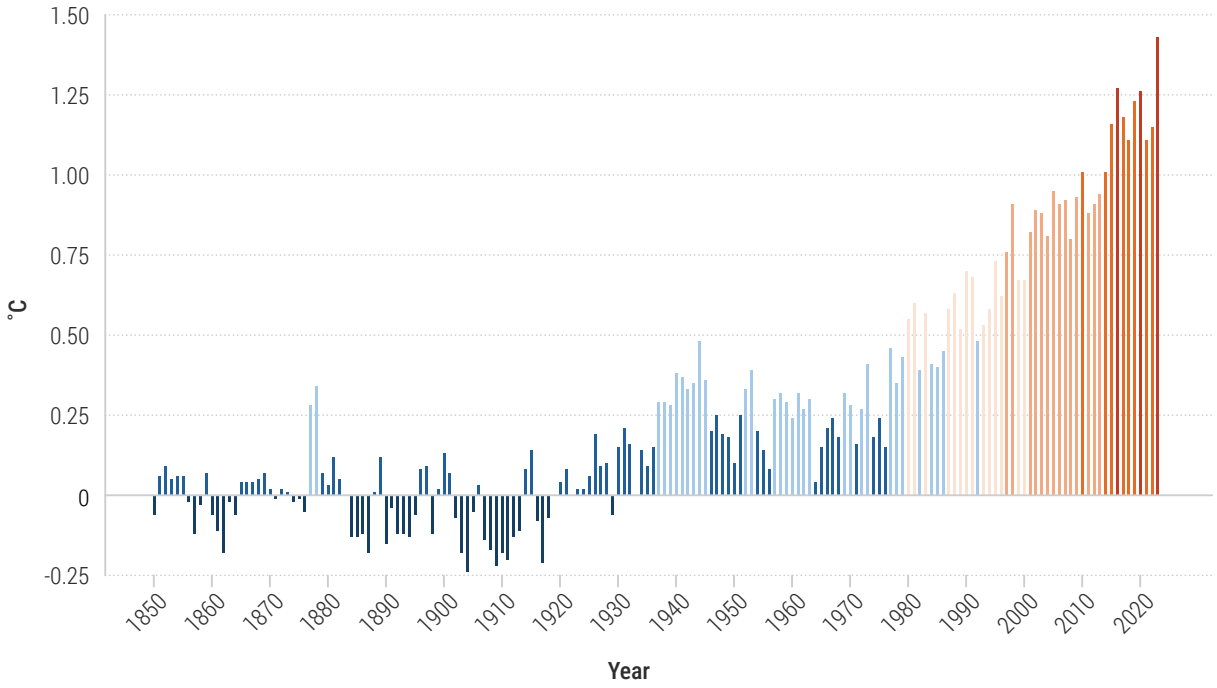
Source: Climate Change Tracker (2025)

b) Anthropogenic and natural radiative forcings from 1750 to 2023



Source: Forster et al. (2024)

Figure 3.3: Evolution of temperature anomaly with respect to 1850-1900 baseline



Source: Forster et al. (2024)

frequency, duration and intensity vary spatially, with average intensity increased in northern Canada and Greenland by 0.4–0.6°C per decade for the period 1970–2014 (Perkins-Kirkpatrick and Lewis 2020; Han et al. 2022). Three heatwaves were observed during boreal spring–summer 2023 affecting southwestern North America, Europe and southwestern and Central Asia (WMO 2024a), and temperatures in Beijing exceeded 40°C for three consecutive days (Qian et al. 2024).

3.2.3 Precipitation, cyclones and drought

Increased global temperatures and additional atmospheric moisture have contributed to changes in regional precipitation patterns and intensity. Precipitation over land has likely increased since 1950 and this trend has accelerated since the 1980s (Szopa et al. 2021).

Extreme precipitation events have increased in frequency and intensity, resulting in floods and soil erosion (Seneviratne et al. 2021). Intense rainfall resulted in several floods in 2023 in Europe (WMO 2024a).

The Global South was heavily affected in 2024 by changes in the precipitation seasonal cycle and intensity, leading to flash floods and landslides. Dry conditions in South America were interrupted by persistent heavy rainfall that resulted in flooding in southern Brazil. Precipitation increased by 50 per cent in the Sahel in 2024, resulting in flooding in the wider region (WMO 2025).

Rapid intensification of tropical cyclones has increased (Li et al. 2023) and intensity at landfall has doubled between 1982 and 2020 (Wang and Toumi 2022), with increased damages to coastal regions (WMO 2025).

Globally, 12-month droughts have increased from 15–26 per cent over the period 1980–2020 (Ndehedehe et al. 2023), partly driven by increases in the southern hemisphere since 2000 (Douville et al. 2021). Multi-year droughts have become more frequent in Chile (Fuentealba et al. 2021), while Europe's 2018–2020 drought was unprecedented over the past 250 years (Rakovec et al. 2022).

3.2.4 Air pollution

Air pollutants are hazardous to human health (WHO 2021), ecosystems and crops (UNEP 2019a), and their emissions from anthropogenic sources affect atmospheric composition.

Polluting particles in the atmosphere are categorized as primary if they come from combustion processes, industrial activities, fires, brake and tyre wear, road wear,

soil erosion and resuspension. Secondary particles form from gaseous precursors such as SO_2, nitrogen oxides, ammonia and non-methane volatile organic compounds. These atmospheric particles vary in size from ultrafine to coarse and in composition, which determine their radiative effect. Their composition typically includes sulfates, nitrates, ammonium, carbonaceous compounds and toxic metals. Black carbon, a primary particulate pollutant emitted from the combustion of fossil fuels and biomass, absorbs solar radiation, contributing to climate warming. By contrast, most inorganic components of particulate matter scatter solar radiation, resulting in cooling.

In Western Europe and North America, SO_2 and nitrogen dioxide (NO_2) has decreased between 2000 and 2019, but increased in regions of Asia (Aas et al. 2019; Aas et al. 2024). From satellite measurements, global SO_2 emissions trends over 2005–2021 are negative (Fioletov et al. 2023). By contrast, CH_4 emissions from human activities increased by around 20 per cent from 2000–2020 (Saunois et al. 2024). Landfills and waste management facilities are one of the top three global sources of methane (IPCC 2021). Landfill methane emissions can be two to three times larger than reported due to unmonitored leaks (Wang et al. 2024), underreporting (Balasus et al. 2025) and emissions from legacy landfills (Fraser-McDonald et al. 2022).

Trends in population-weighted mean 8-hour tropospheric ozone (O_3) concentrations are variable around the world. Estimates from 250 cities indicate decreases between 2000 and 2019 in North and Central America, Eastern Europe, the Middle East and some regions in China. Cities in South America, Africa, Western Europe and south and South east Asia show more than 24 per cent increases. Estimates of attributable mortality show a 46 per cent increase worldwide between 2000 and 2019 (Malashock et al. 2022).

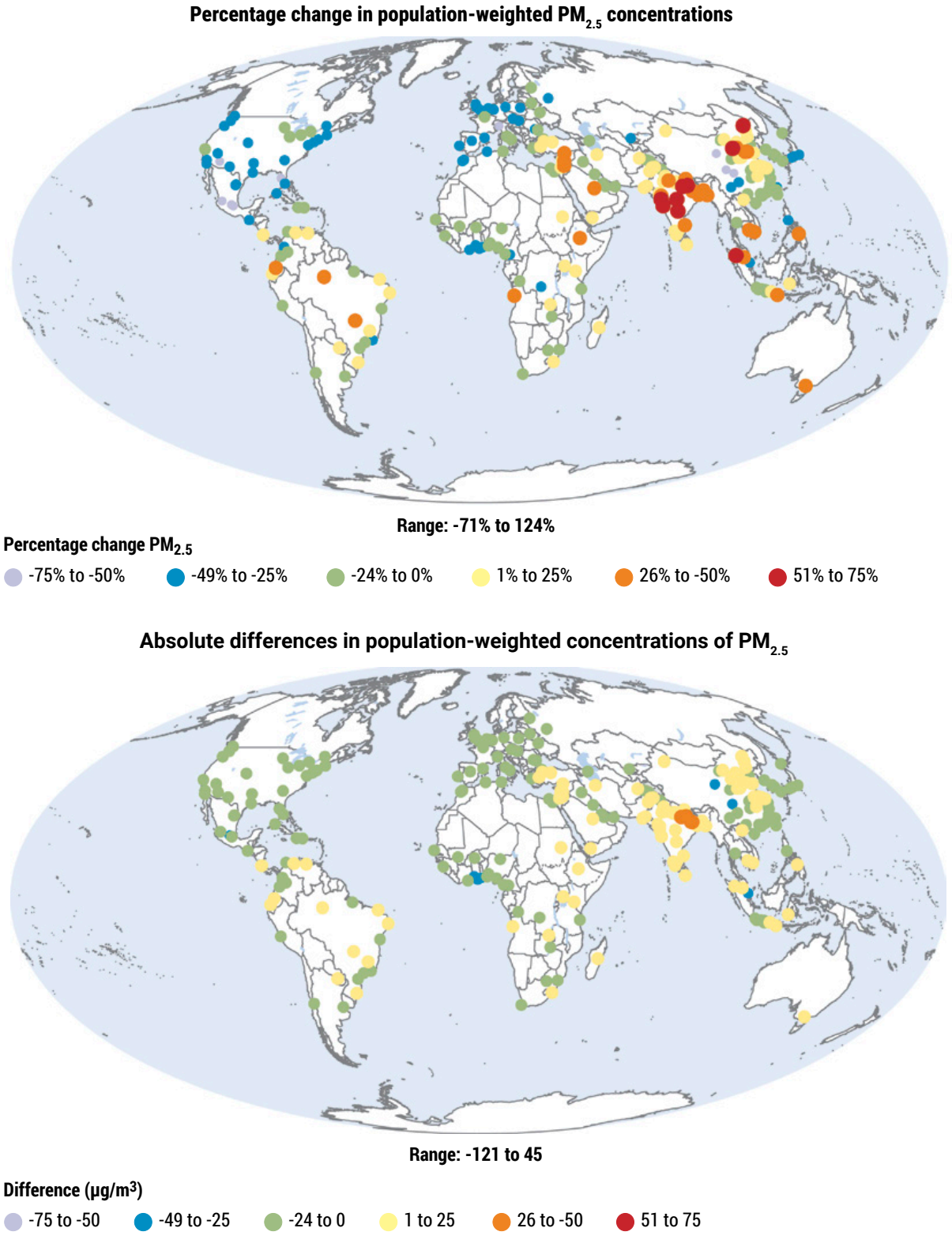
Trends in $PM_{2.5}$ concentrations from 13,160 cities for 2000–2019 indicate a decrease in regional averages in North and Central America, Europe, sub-Saharan Africa and southeastern Asia. Decreases in most regions coincide with O_3 reduction, except in Africa (Southerland et al. 2022) (**Figure 3.5**).

Air pollution control actions in several megacities, such as London and Beijing, have delivered improvements in air quality. Monthly averages of $PM_{2.5}$ in Beijing were reduced by two-thirds between 2013 and 2019 (Li et al. 2020) but high levels of air pollution persisted in other megacities in Asia and Africa, such as Tehran, Delhi and Lagos (Fuller et al. 2022).

The control of pollutants emitted from point industrial sources is more straightforward than line sources, such as road transport, and area sources, such as agriculture and domestic emissions (Vardoulakis et al. 2018). The control of O_3 is complex, with no single mitigation option. For example, while daily maximum O_3 decreased in Mexico City from peak concentrations in 1990 due to systematic

Credit: Pasanheco/Envato

Figure 3.4: Change in population-weighted $PM_{2.5}$ concentrations between 2000 and 2019



Source: Southerland et al. (2022)

measures implemented – gasoline reformulation, catalytic converters, vehicular restrictions – annual O_3 and $PM_{2.5}$ concentrations have levelled in the last 15 years (Velasco and Retama 2017; Molina, Retama and Zavala 2023).

Fireworks emissions substantially increase particulate matter concentrations during traditional or religious celebration days in Mexico and India (Retama et al. 2019; Yadav, Mishra and Gurjar 2022).

Open burning of waste in landfills and other spaces remains one of the uncontrolled sources of pollution, mainly of particulate matter containing heavy metals and black carbon, in low- and middle-income countries. Burning of plastics also produces toxic, persistent and bioaccumulative pollutants such as volatile organic compounds, furans and dioxins (Weidinmyer et al. 2014; Patak et al. 2023; Kreel et al. 2021).

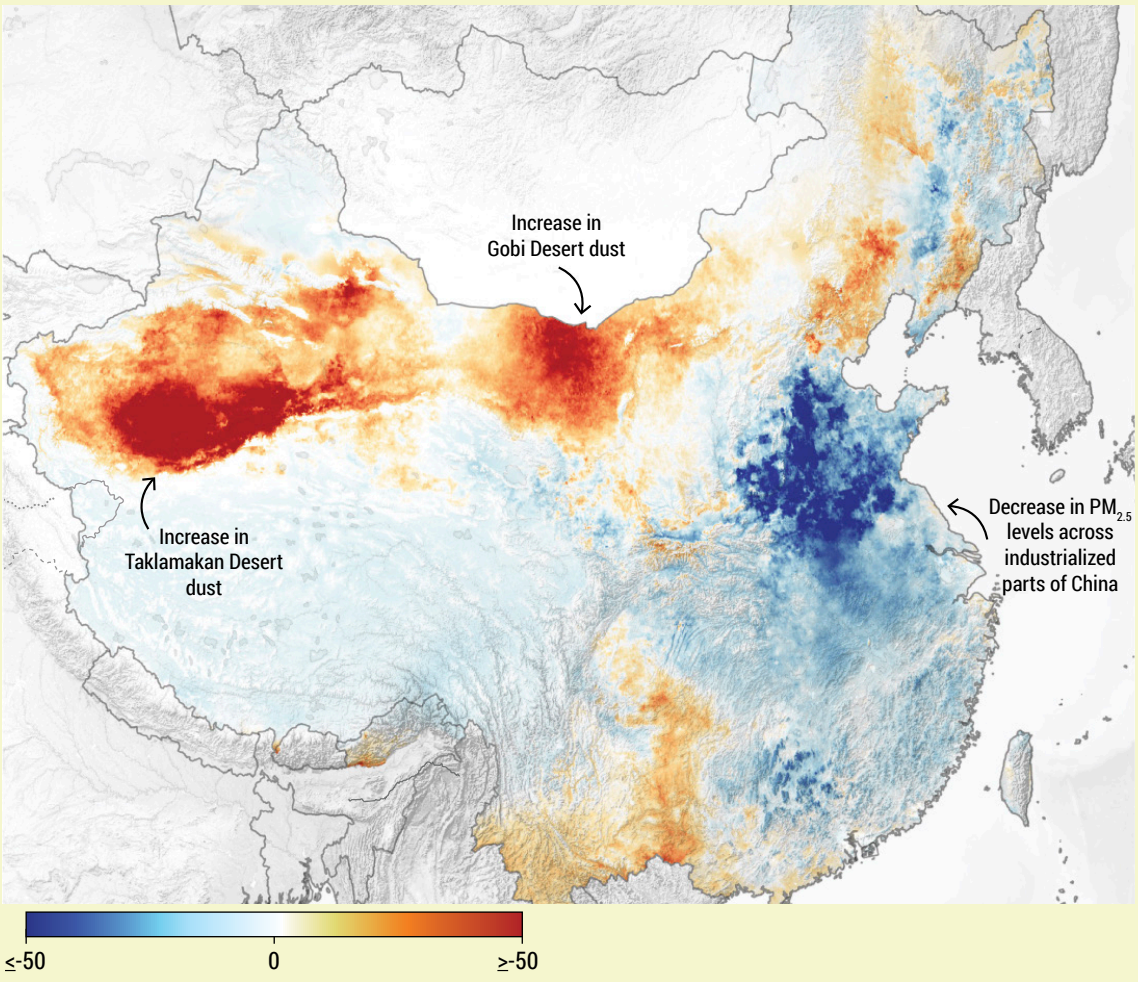
The COVID-19 pandemic and related mobility restrictions reduced atmospheric emissions of combustion-related air pollutants and GHGs, leading to a global decrease in NO_2 and $PM_{2.5}$ concentrations in many cities (**Box 3.1**). However, these reductions were short-lived, as emissions increased again soon after the lifting of restrictions (Salmond et al. 2022).

Box 3.1: Various examples of air pollution during the COVID-19 pandemic

During the COVID-19 lockdowns, clean skies were observed globally (Sokhi et al. 2021) and in many cities, due to reductions in $PM_{2.5}$, NO_2 and SO_2 (Dai et al. 2021; Pratap et al. 2021) (**Figure 3.5**). This short-lived urban air quality improvement averted premature mortality in many cities, with a 60 per cent reduction in $PM_{2.5}$ and O_3 attributable deaths in Delhi (Maji et al. 2021), and a 27 per cent reduction in NO_2-attributable deaths in Australian cities (Chaston et al. 2024).

However, tropospheric O_3 concentrations increased or did not significantly change during lockdowns in several cities, for example in eastern China (Wang et al. 2022) and Mexico City (Peralta et al. 2021). In these cases, high O_3 concentrations partially offset health benefits mainly associated with NO_2 reductions.

Figure 3.5: Changes in $PM_{2.5}$ concentrations over China for February 2019 and 2020 (pre- and post-COVID-19 lockdowns) derived from satellite observations



Source: Modified from NASA Earth Observatory (2021)

Credit: PhotoHedge/Envato

While not routinely measured in current air quality networks, the presence of nanoparticles in urban areas is an emerging health concern. Energy generation from fossil fuels, vehicle transport and industrial activities can produce nanoparticles that deteriorate air quality. Additionally, growing evidence indicates that microplastics can impact regional (Sridharan et al. 2021) and transboundary (Peries et al. 2024) air quality and affect human systems (Chen, Chen and Liao 2025).

Another emerging concern is associated with particles in the stratosphere that contain metals from the burn-up of satellites and rocket stages during re-entry into the atmosphere. While the presence of particles may have implications for stratospheric composition, health effects on humans at the surface are unlikely. With increasing numbers of satellites and rocket launches planned in coming decades, metals from their re-entry could change stratospheric composition (Murphy et al. 2023).

3.2.5 Stratospheric ozone

A small increasing trend in total column ozone of 12 per cent per decade in September over the period 2000–2019 was observed over Antarctica, consistent with the decreasing trend in concentration of most ODSs (WMO 2022). Recovery is expected to continue, contingent upon full compliance with the Montreal Protocol (Section 3.5.2). Unreported emissions of trichlorofluoromethane (CFC-11) over 2012–2019, increased emissions of chloromethane (CH_3Cl) in China over 2000–2020 (Hu, Yao and Fang 2022), and of halocarbons in Tibet (Cong et al. 2024), if they persist, could slow the rate of recovery by up to three years (WMO 2022).

Over the Arctic, total column ozone has shown a non-significant increasing trend. Outside the polar regions, total column ozone shows a small statistically significant increasing trend (0.4±0.2 per cent per decade) over 1996–2020, driven mostly by changes in the southern hemisphere.

Volcanic eruptions may sporadically introduce gases and particles and change atmospheric composition. The Hunga Tonga-Hunga Ha'apai eruption in January 2022 injected large amounts of water vapour into the stratosphere (Nedoluha et al. 2023), modifying the tropical tropopause height and decreasing stratospheric ozone (Evan et al. 2023). Warming due to water vapour added to the stratosphere was offset mainly by the increased attenuation of solar radiation by stratospheric aerosol (Schoeberl et al. 2023). The climate forcing of the injected water vapour decreased to near zero by the end of 2023.

Unprecedented wildfires in Australia in 2019–2020 injected gases and aerosols into the stratosphere that contributed to stratospheric ozone depletion (Wang et al. 2023).

3.3 Connections between the atmosphere and biodiversity loss and land degradation

3.3.1 How biodiversity loss and land degradation affect the atmosphere

Changes or loss in biodiversity affect the climate system, primarily through their impacts on nitrogen, carbon and water cycles. The interplay among climate, biodiversity and human activities can result in intricate feedback loops (Handa et al. 2014). For example, there is evidence that the fertilizing effect of elevated atmospheric CO_2 concentrations resulting from deforestation has enhanced the water-use efficiency of boreal forests in the northern hemisphere (Keenan et al. 2013; Allen et al. 2024; Liu et al. 2024). Different ecosystem responses highlight the various adaptive strategies employed by different vegetation types, which play a crucial role in the climate system's biosphere–atmosphere interactions (Oki and Kanae 2006; Joos et al. 2024).

The higher biodiversity of some ecosystems, such as marine and forest ecosystems, increases their potential and stability as carbon sinks (Kinnunen et al. 2025). Natural processes mitigate global climate change by absorbing over half of human-generated CO_2 through photosynthesis and subsequent carbon storage in biomass and organic matter. Of that, oceans absorb approximately 30 per cent and land, including forests and soils, absorbs around 25–30 per cent of the CO_2 emitted into the atmosphere (Malhi et al. 2002; Crisp et al. 2022). However, CO_2 absorption by oceans often leads to ocean acidification (Abbasi and Abbasi 2011), and natural carbon sinks are declining (Blunden and Boyer 2022; Curran and Curran 2025). Ignoring the interrelationship of climate, biodiversity and humans will lead to suboptimal solutions that aggravate planetary crises (Pörtner et al. 2021).

Over the past two decades, the annual net carbon emissions from deforestation and land degradation have remained relatively stable. However, compared to the steadily increasing fossil fuel emissions, their proportion has decreased (Houghton 2012). A possible decline in estimated emissions resulted from declining tropical deforestation rates (IPCC 2023).

3.3.1.1 Forest ecosystems

Amazonia, Earth's largest tropical forest and an important carbon sink (Brienen et al. 2015; Philips, Brienen and the Rainfor Collaboration 2017; Hubau et al. 2020), is currently in decline due to deforestation, warming and moisture stress. This is particularly the case in eastern Amazonia during the dry season, with the South East experiencing most of the decline (Barkhordarian et al. 2019; Leite-Filho, de Sousa Pontes and Costa 2019; Flores et al. 2024).

An estimated 10 to 47 per cent of the Amazon's forests are exposed to a combination of warming temperatures, extreme droughts, deforestation and wildfires, which could result in an irreversible ecosystem transition if certain critical thresholds or tipping points are crossed, potentially exacerbating regional climate change (Flores et al. 2024).

Deforestation caused by industrial-scale cattle farming in the Brazilian Amazon significantly affects biodiversity. Increased deforestation was associated with increased wildfire count by 39 per cent from 2012 to 2019 in the Brazilian Amazon, negatively affecting regional air quality (Butt et al. 2021). In addition to deforestation, temperature increases and precipitation reductions in Amazonia increased carbon emissions due to forest degradation (Artaxo et al. 2022; Artaxo 2023; Oliveira et al. 2023). After 2010, deforestation in Amazonia surged, peaking in 2018 at rates reminiscent of the early 21st century, highlighting its role in biomass burning emissions, particularly $PM_{2.5}$ from deforestation fires (Mataveli et al. 2021).

In contrast to the Amazon rainforests, which have shown a long-term decline in carbon sequestration capacity, African tropical forests have consistently maintained their ability to absorb carbon. Over a three-decade period ending in 2015, these African forests have continuously captured 0.66 tons of carbon per hectare each year (Hubau et al. 2020). The Amazon forests were adversely affected due to extreme drought in 2023, whereas tropical Africa remained wetter than normal (Espinoza et al. 2024). For example, during the months of October to December 2023, drastic carbon losses occurred in the Amazon and were reported as the largest contributor to the decline in the yearly global terrestrial carbon sink (Ke et al. 2024). Moreover, in Southeast Asia, both bottom-up and top-down models reported a net carbon sink that approaches zero in October to December (Ke et al. 2024). Additionally, Ke et al. (2024) reported overall extreme heat in 2023 would lead to a gross carbon loss of 1.73 gigatons across terrestrial regions globally, signalling a substantial adverse effect of climate warming on land ecosystems as carbon sinks.

Biodiversity loss and land degradation also affect the climate by changing the albedo or reflectivity of the Earth's surface (Duveiller, Hooker and Cescatti 2018; Mirzabaev et al. 2019). For example, darker forests induce positive radiative forcing, reducing the cooling effect of carbon sequestration (Zhao and Jackson 2014). Therefore, reducing deforestation in high latitudes could potentially increase warming. By contrast, deforestation in the tropics leads to a total global warming effect due to reduced evapotranspiration, which outweigh the cooling effects produced by increased albedo (Perugini et al. 2017; Butt et al. 2023).

As part of its nationally determined contributions to the Paris Agreement, India aims to generate an additional carbon sink of 2.5–3.0 billion tons of CO_2 equivalent (CO_2eq) by 2030 by enhancing its forest and tree cover From 2005 to 2019, India had achieved an extra carbon sink of 1.97 billion tons of CO_2eq (Government of India 2024). Furthermore, forests are a contributor to atmospheric particulate matter removal. In addition, 1361.28 tons of $PM_{2.5}$ were removed by forests in India in 2019 (Bagaria et al. 2023). Deposition of particulate matter was high in swamp forests, tropical semi-evergreen forests, and moist deciduous and subtropical pine forests.

Several countries aim to increase their forest cover. For example, Pakistan launched its ecosystem restoration initiative Ten Billion Tree Tsunami Project in 2019, which aimed to plant 10 billion trees by 2023 to prevent land degradation and restore ecosystems (UNEP 2021). Saudi Arabia has undertaken significant initiative to increase forest cover, aiming to plant 10 billion trees across the country to rehabilitate over 74 million hectares of land. This initiative aims to restore important ecosystem services, improve air quality and reduce sandstorms (El-Juhany et al. 2022).

Effective conservation measures like afforestation and reforestation can increase forest cover through the dynamic distribution of carbon sinks (Yu et al. 2022). For example, the forest carbon sink has increased significantly in northern China, showing an average increase in net ecosystem productivity between 2000 and 2020 of 7.0 gCm^{-2} yr^{-1} (Huang, Rodríguez-Iturbe and Calabrese 2024). Land-use and land-cover changes in China, characterized by rapid forest expansion from 1980 to 2019, contributed to nearly 44 per cent of the national terrestrial carbon sink (Yu et al. 2022).

Grassland ecosystems also play an important role by storing carbon in soil. The goal of the Bonn Challenge and Initiative 2020 is to restore 350 million hectares of degraded landscapes through grassland restoration globally by 2030 (van der Esch et al. 2022). Forest landscape restoration and encouraging tree planting should not be the reason for the loss or conversion of open, non-forested ecosystems like grasslands (Schweizer, van Kuijk and Ghazoul 2021). Letting land rest from livestock grazing, seeding it with native grasses and clearing woody encroachment are the most effective methods for restoring grasslands and protecting their capacity to store carbon and help mitigate climate change. For grasslands restoration, the most efficient method is to control overgrazing, planting native grasses and clearing woody encroachment, which contributes to climate change mitigation by storing carbon (Bai et al. 2024; Parr et al. 2024).

3.3.1.2 Soils

The global soil carbon sink is over three times greater than the combined carbon content of the atmosphere and biosphere, positioning soil as a vital component of the Earth's carbon cycle (Jones et al. 2020; Yu, Weintraub and Hall 2021). Subsoil can store more carbon than topsoil, underscoring the depth of soil's carbon sequestration capacity (Luo et al. 2020). Recognizing soil's ability to sequester approximately 2,500 gigatons of CO_2, its role is pivotal in climate change mitigation strategies (Kumar, Ananta and Ashutosh 2020). Implementing soil regenerative practices has a vital role in improving soil health and increasing soil organic carbon sequestration, and they contribute to the European Union's goal of increasing healthy soils by 75 per cent by 2030 (Villat and Nicholas 2024).

Changes in carbon fluxes and reserves, mainly due to alterations in land use and land cover, as well as the burning of fossil fuels and biomass, have a significant effect on the long-term viability of ecosystem services at both regional and global scales. The accuracy of terrestrial carbon sink estimates is further complicated by political and socioeconomic factors, along with varying carbon sequestration potentials of different management approaches (IPCC 2022).

Annually, soil emissions contribute 6.8–7.9 gigatons of CO_2eq to the atmosphere. These emissions primarily consist of CH_4 from undisturbed peatlands and rice cultivation, N_2O from both managed and unmanaged

soils, and CO_2 from changes in land use. Additionally, other wetlands release CH_4, accounting for an extra 1.6–3.8 gigatons of CO_2eq (He et al. 2024).

Since 1990, cultivated cropland soils have experienced a 20–60 per cent reduction in organic carbon content (Scharlemann et al. 2014). Traditional agricultural practices continue to contribute to GHG emissions. The primary sources of non-CO_2 GHGs are agricultural lands and wetlands (Chen et al. 2018). Climate change is intensified by the significant effects and associated emissions from the growth of rice farming that increases CH_4 sources, the expansion of ruminant populations and manure management that increases CH_4, N_2O and NH_3 emissions, and excessive nitrogen fertilization coupled with soil acidification that increases N_2O emissions (Oertel et al. 2016).

Regarding emissions from peatland, Indonesia, China and the Russian Federation contributed 31 per cent of the global peatland emissions of carbon. Europe is a net exporter of 104 Mt CO_2eq/yr of embodied peatland emissions, and Africa and the Middle East regions are the largest net importers (64 Mt CO_2eq/yr) (Mattila 2024). Another critical factor is emissions from paddy fields in Asia, where single-season rice contributes more than 80 per cent of the total carbon emissions. However, CH_4 emissions from Monsoon Asia have remarkably declined since 2007 with the adoption of three mitigation methods: waste management techniques, off-season straw return, and straw-to-biochar, which can reduce CH_4 emissions by 27, 23, and 21.78 per cent, respectively (Zhou et al. 2024a).

Mangrove forests, marshes and seagrasses, common in sediment accumulation areas, represent crucial coastal ecosystems. The deterioration or substitution of these ecosystems with alternative vegetation is causing a significant release of carbon, estimated between 0.15 and 1.02 gigatons per year globally (Rosentreter et al. 2023).

The depletion of organic carbon in soil is a key indicator of land degradation, which poses a significant threat to sustainable development, biodiversity conservation, and efforts to address climate change through mitigation and adaptation strategies. Land degradation is the diminishment or loss of the land's biological or economic productivity and complexity. In arid regions, this phenomenon is called desertification (Caretta et al. 2022) (Chapter 4). Soil erosion, the most common type of soil degradation, removes the top layer of soil that typically contains the highest concentration of organic carbon. This process can promote the conversion of carbon into CO_2 through mineralization. However, counteracting mechanisms like carbon burial may offset this effect, potentially making soil erosion a long-term carbon sink (Wang et al. 2017). Both natural and human-caused erosion can lead to net carbon storage in highly stable buried reservoirs at deposition sites. Consequently, degradation in these areas has a significant potential for carbon release. The radiative effect of dust particles released by human activities from degraded land appears to have both positive and negative radiative-forcing effects (Mousavi et al. 2024).

The Earth's surface albedo exhibits significant variation depending on the types of surfaces and vegetation present. Of all the physical consequences of land degradation, alterations in surface albedo have the most important consequences for the global net radiative balance and overall climate warming or cooling (Zhang et al. 2022). For example, in a study conducted in Michigan, it was observed that croplands and forests had on average 7.8 per cent higher and 0.7 per cent lower albedo than other land covers, respectively (Sciusco et al. 2020). Additionally, most urban areas, particularly in industrialized countries, encourage investment in vegetation cover to counter the urban heat island effect and they are also decreasing reflectivity of radiation back into the atmosphere (Wu et al. 2024). These urban centres are likely to experience greater (positive) surface radiative forcing. The effects on albedo resulting from forest deterioration or removal are heavily influenced by the specific latitudinal and climatic zone in which these events occur (Lodh and Haldar 2024).

Changes in surface albedo since 1750, primarily attributed to deforestation, have resulted in a global average radiative forcing of approximately −0.2 W/m^2, leading to a cooling effect. This has played a moderate role in the overall global net anthropogenic radiative forcing, estimated at around 1.6 W/m^2 (Zelinka et al. 2023). In the case of boreal forests, the destruction or deterioration of tree cover leads to an increase in albedo, producing a net cooling effect as the reflective snow beneath becomes visible. This cooling effect can potentially surpass the net radiative effect of the associated carbon released into the atmosphere (Salisbury et al. 2023).

3.3.2 How changes in the atmosphere affect biodiversity loss and land degradation

Anticipated shifts in climate and the introduction of non-native species are expected to constrain the ability of

The Snake River basin of southwest Idaho is a diverse, arid landscape. Repeated cycles of fire and invasive annual grasses threaten the unique assemblage of native plants and wildlife, posing a wildfire risk. Removing invasive grasses that promote fires and restoring native species such as perennial forbs, sagebrush and other shrubs are critical to the health of the ecosystem. Credit: Bureau of Land Management of the United States of America

particular species to migrate, consequently accelerating the loss of biodiversity.

Invasive species in the terrestrial and freshwater ecosystems of the Antarctic and Southern Ocean region, where approximately 13 per cent of species are considered locally invasive, are an example of changes in biodiversity due to climate change (Hughes and Convey 2022; Leihy et al. 2023). An additional example from the Sikkim Himalayas shows that up to 87 per cent of 124 endemic species have undergone geographical shifts due to warming, posing a risk of extinction for these species (Telwala et al. 2013).

Climate change has significantly influenced changes in species richness (Bhattacharjee et al. 2017). Vegetation species like *Betula utilis* (Himalayan birch) exhibit a trend of moving towards the Eastern Himalayas, while showing a decline in numbers towards the west (Hamid et al. 2018). Moreover, climate change combines with biological invasions to hamper biodiversity. For example, in California, nitrogen deposition, climate-change-induced plant invasions, high CO_2 concentrations and fire interact in various complex ways to change ecosystem processes (Harrison et al. 2024). Invasive annual grasses lead to novel fire regimes in California's deserts, resulting in adverse ecological effects (Abatzoglou and Kolden 2011; Weber et al. 2019; Harrison et al. 2024). Climate change is also expected to promote and increase this grass–fire cycle (Abatzoglou and Kolden 2011).

In certain ecosystems, the growth of forests may increase as atmospheric levels of CO_2 increase. However, climate change could force species to adjust their ranges much more rapidly than they can (Sáenz-Romero et al. 2020; Zhang et al. 2023a). Consequently, some species might become extinct. For instance, in Canada, it is improbable that white spruce populations will be able to migrate at a speed that keeps up with the rate of climate change (Lima, Lenoir and Hylander et al. 2024).

Forests are also threatened by pests, pathogens and wildfires, rendering them more susceptible to invasive species (Panzavolta et al. 2021). Climate change contributes to biodiversity loss and consequently leads to decline in ecosystem functioning and services. Moreover, acute and synchronous climate impacts can harm biodiversity. For example, a study of the timing and synchronicity of climate effects on around 30,000 species worldwide and found that long-term increases in average annual temperatures threatened their viability (Trisos et al. 2020). Also, increased sunshine

Credit: bilanol/Envato

significantly affects vegetation growth, evapotranspiration and water cycle processes, which affect ecosystem functions and services (Zhou et al. 2024b).

Changes in air quality also cause biodiversity loss due to the effects of different primary and secondary air pollutants. For instance, tropospheric ozone as a secondary air pollutant harms plants and diminishes biodiversity. In 2020, critical thresholds necessary for forest protection were surpassed in 59 per cent of the total forest area of the 32 European Environment Agency (EEA) Member nations (Maes et al. 2023). From 2000 to 2020, there was a general decline in the proportion of agricultural land in EEA Member countries exposed to ozone levels above the protective target for vegetation, reaching a minimum of 6 per cent in 2020 (Sonwani et al. 2022). However, in 2019, the economic damage incurred from the effects of ground-level ozone on wheat production amounted to €1,418 million across 35 European countries.

While 2020's harmful levels of nitrogen deposition were detected in 75 per cent of the total ecosystem across the 27 European Union Member States, this marked a decrease of 12 per cent since 2005 (EEA 2022) The zero-pollution action plan has established a goal of reducing nitrogen deposition by 25 per cent from 2005 levels by 2030 (Etzold et al. 2020). In 2020, only 4 per cent of the European ecosystem experienced deposition levels of sulfur dioxide, nitrogen oxides and ammonia that surpassed the thresholds leading to ecosystem acidification, owing to effective emission reduction efforts for sulfur dioxide (EEA 2024).

3.3.2.1 Stratospheric ozone and UV radiation

Decreased stratospheric ozone results in increased ultraviolet (UV) radiation at the Earth's surface with detrimental effects on biodiversity, GHG emissions (Silva et al. 2021; Shiraishi and Hirata 2021), carbon storage, ecological resilience, and the productivity of forests and crops, leading to species replacement and potential deterioration of ecosystem functioning (Bornman et al. 2019). Excessive UV-B radiation combined with other potential stressors, such as heat and drought, may harm plant growth and chances of survival (Zandalinas et al. 2021).

The annual Antarctic stratospheric ozone hole and periodic severe Arctic ozone depletion result in increased solar UV radiation at ground level, which may harm vegetation, although these events generally occur in early spring when many plant species are dormant (Bernhard and Stierle 2020). However, when record-breaking increases in UV radiation and the Antarctic ozone hole occur simultaneously, plants and animals may be damaged. For example, in 2020, the return of many migrating animals to breed in Antarctica coincided with the persistent ozone hole, which risked exposing them to an unusually

high UV index from mid-November to late December (Robinson et al. 2024).

3.3.2.2 Snow cover and land degradation

Extreme high temperatures generally lead to less snowfall and accelerated snow melt in cold regions, exposing ground flora and fauna to solar UV radiation earlier in the spring. However, UV radiation received by organisms around the snowpack may sometimes be reduced due to decreases in reflection when the snowpack melts (Robson and Aphalo 2019).

When black carbon, which absorbs solar radiation, is deposited over snow-covered mountains, the heat released accelerates the melting of snow (Grogan et al. 2020; Slatyer, Umbers and Arnold 2022; Roychoudhury et al. 2022; Yang et al. 2022; Hugelis et al. 2024).

Although the threshold for a global temperature, above which extensive and irreversible tipping-point thawing of permafrost could occur is uncertain, permafrost thaw is likely to increase gradually with climate warming (Nitzbon et al. 2024). This could lead to substantial CO_2 emissions by releasing stored carbon and CH_4, potentially accelerating climate change (Huissteden 2020; Natali et al. 2021; Miner et al. 2022).

3.4 Impacts on human systems

Atmospheric emissions affect air quality, the stratospheric ozone layer and the climate, which all affect human systems – including health and well-being, agriculture, education, tourism, the built environment, transport and other services – and in many cases exacerbate inequities directly and indirectly.

3.4.1 Heat and heatwaves

One of the main effects of climate change is the increased frequency, duration and intensity of heatwaves, as well as a general increase in ambient temperatures, which directly affect physical and mental health (Romanello et al. 2023). Globally, around 489,000 heat-related deaths occurred every year over the period 2000–2019 (Zhao et al. 2021), with annual heat-related mortality for people over 65 years of age increasing by approximately 85 per cent in the period 2013–2022 compared with 1991–2000, due to climate and demographic changes (Romanello et al. 2023).

Rising temperatures pose a risk to cardiovascular, neurological and mental health (Liu et al. 2021; Thompson et al. 2023; Byun et al. 2024), especially in ageing populations (Chang et al. 2022), with data showing elderly women at higher risk of mortality compared to men (van Steen et al. 2019). Higher temperatures also increase the risk of kidney disease, particularly in agricultural workers (El Khayat et al. 2022). There is emerging evidence of associations between higher temperature exposure during pregnancy and adverse perinatal health outcomes, including preterm birth, low birth weight and stillbirth, particularly in lower socioeconomic groups (Chersich et al. 2020).

In Indigenous communities, extreme temperatures cause an increase in acute and chronic physiological impacts, such as the prevalence of cardiovascular, nephrological and respiratory diseases, including asthma (Ford et al. 2010; McNamara, Westoby and Chandra 2021; Sahu et al. 2022). Mental health challenges were also reported – emotional responses of worry, sadness, anger and emotional distress – and were often more prevalent in Indigenous Peoples compared to their non-Indigenous counterparts (Middleton et al. 2020; Sahu et al. 2022; Romanello et al. 2024).

The urban heat island effect, associated with urban, anthropogenic heat sources and the use of absorbing materials together with the climate change-related warming trend, has led to night-time urban warming much higher than the global average (IPCC 2021; Li and Chen 2023). Urban heat islands contribute to heat-related deaths, heat cramps, heat exhaustion, heat strokes, and the exacerbation of respiratory health conditions (Heaviside, Macintyre and Vardoulakis 2017). Without adequate adaptation, heat-related mortality is projected to increase substantially (Gasparrini et al. 2017; Lüthi et al. 2023).

3.4.2 Air pollution

Air pollution, predominantly from the fine particles termed $PM_{2.5}$, was the leading contributor to the global disease burden in 2021, contributing 8.0 per cent of total disability-adjusted life years (GBD 2021 Risk Factors Collaborators 2024). Outdoor and indoor – or ambient and household respectively – air pollution was associated with approximately 8.1 million deaths in 2021 (Health Effects Institute 2024).

Globally, 99 per cent of the world's population is exposed to harmful levels of air pollution (Health Effects Institute 2024), which causes substantial adverse health effects and related economic losses. Emissions of combustion-related pollutants, including $PM_{2.5}$., nitrogen oxides and sulfur dioxide, as well as the formation of secondary pollutants such as tropospheric ozone, contribute to local and regional air pollution that affects multiple human systems (Manisalidis et al. 2020).

The effects of outdoor air pollution on respiratory and cardiovascular health are well established, even at low concentrations of air pollutants, including $PM_{2.5}$ (Hoffmann et al. 2021). Cognitive decline, including an increased risk of dementia, has also been associated with air pollution (Delgado-Saborit et al. 2021). Emerging evidence indicates that air pollution is a significant risk factor for diabetes, with approximately 20 per cent of the global burden of Type 2 diabetes attributable to $PM_{2.5}$ (GBD 2019 Diabetes and Air Pollution Collaborators 2022).

Children are more vulnerable to air pollution because of its impact on lung growth and function. Preterm birth and low birthweight have been associated with maternal exposure to air pollution (Niu et al. 2022; O'Sharkey et al. 2023; Aziz et al. 2024). Smaller particles (PM_1) may have greater short-term effects on childhood pneumonia in comparison to larger particles ($PM_{2.5}$ and PM_{10}) (Wang et al. 2021). Furthermore, in-utero $PM_{2.5}$ exposure has been associated with stunted growth in children (deSouza et al. 2022).

Outdoor air quality has improved in some regions, such as Western Europe, eastern North America and China in recent years (Yang and Zhong 2022; EEA 2023a). For example, the number of deaths attributable to $PM_{2.5}$ in the European Union in 2020 declined by 45 per cent, compared to 2005 (EEA 2023a). Consequently, the European Union is likely to meet its zero-pollution action plan target of reducing premature deaths attributable to $PM_{2.5}$ by 55 per cent by 2030, compared to 2005 (EEA 2023a). The progress made in these regions should motivate collective action to improve air quality globally. However, these improvements have been mainly observed in high-income cities and neighbourhoods, with socioeconomically disadvantaged or vulnerable population groups, such as the elderly, children and those in poor health, typically being exposed to higher air pollution levels (EEA 2023a). Further improvements in air quality require a stronger focus on disadvantaged and vulnerable population groups. They will also need to counterbalance the effect of population ageing, since most adverse health outcomes attributable to $PM_{2.5}$ exposure are in people aged 75 and above (Chen et al. 2023).

Compliance with the WHO 2021 guidelines could prevent 549,715 (95 per cent CI: 276,204–815,023) deaths attributable to NO_2 in cities around the world (Song et al. 2023). The age-standardized mortality rate per 100,000 people attributable to NO_2 ranged from 51.3 (95 per cent CI: 25.8–76.0) in Central Asia to 3.4 (95 per cent CI: 1.7–5.1) in Oceania. Although there was a substantial decrease in premature mortality attributable to NO_2 globally, driven by decreases in NO_2 emissions from road transport and power plants, particularly in high-income countries in North America and Western Europe, certain cities in Central Asia and Latin America exhibited an upward trend (Song et al. 2023). Regionally, the number of deaths attributable to NO_2 was highest in East Asia (139,989, 95 per cent CI:70477–207,241), followed by South Asia (75,397, 95 per cent CI: 37,812–111,942), and Eastern Europe (46,840, 95 per cent CI: 23,597–69,307) (Song et al. 2023).

Population exposure to O_3 has increased worldwide at a rate of 0.25 ppb from 2000 to 2019 (Malashock et al. 2022). Tropospheric O_3, generated through chemical reactions in the atmosphere, adversely affects respiratory health in humans (Zhang et al. 2019), as well as vegetation and crops, thus affecting ecosystem services and food security (Manisalidis et al. 2020). It has been estimated that in 2021, exposure to O_3 caused half a million premature deaths worldwide (Health Effects Institute 2024). Atmospheric concentrations of methane have increased over the last decades (Lan et al. 2025) and are currently contributing about 35 per cent of the O_3 burden globally (Butler et al. 2020). While O_3 peaks have declined, baseline O_3 levels are increasing because the reduction of NO_2 emissions is counterbalanced by the increasing role of CH_4 (Bessagnet et al. 2024).

3.4.3 Wildfires

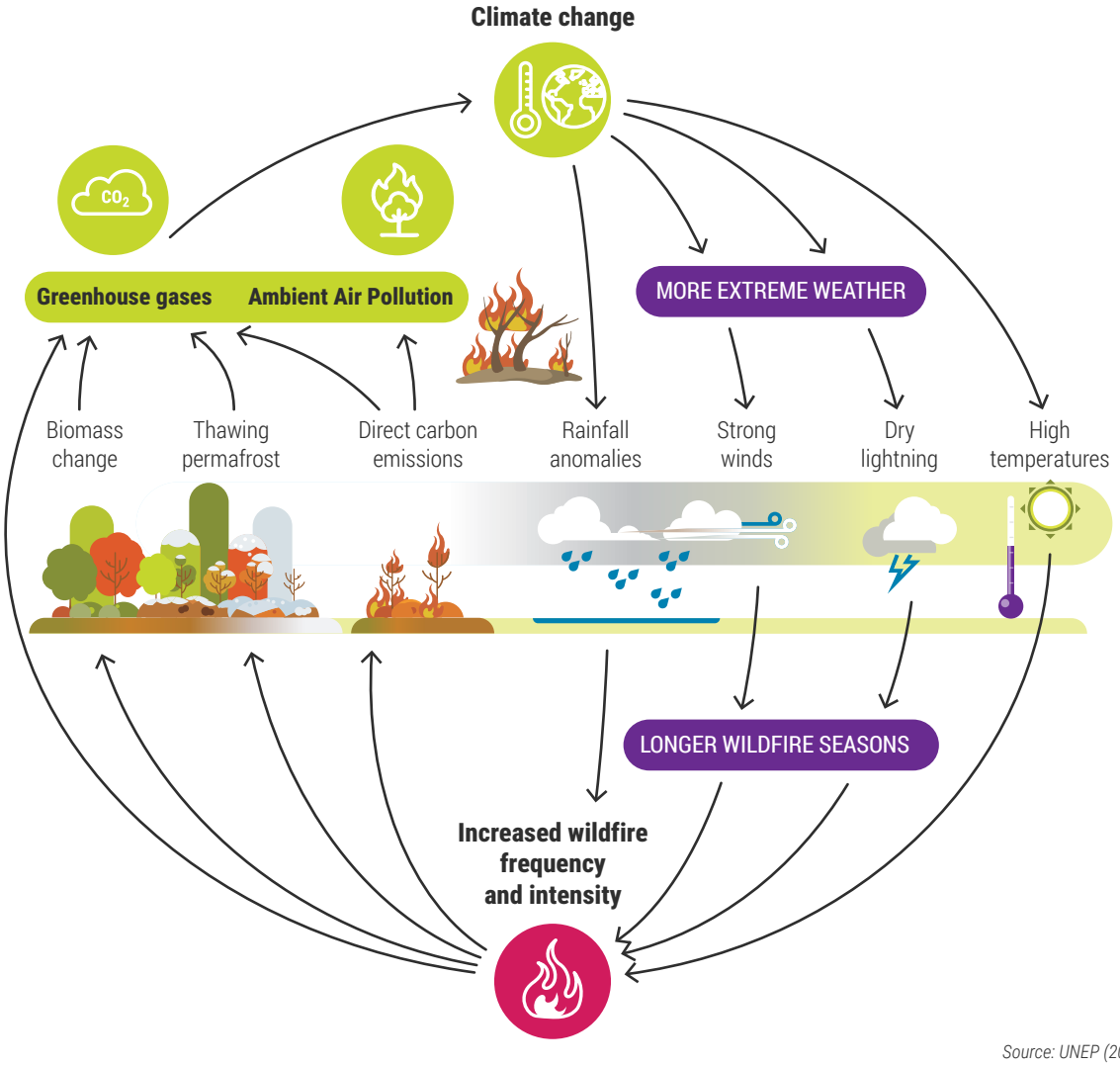
Climate change, wildfires and air pollution create a vicious cycle with negative repercussions for human health, ecosystems and agriculture (WMO 2024c). Climate change directly affects the frequency and magnitude of extreme weather, including high temperatures

and prolonged droughts, that are conducive to the outbreak and spread of wildfires in many regions (Xie et al. 2022; Jones et al. 2024; Burton et al. 2025). It also leads to wildfires of higher intensity and to longer wildfire seasons. Wildfire activity has increased worldwide over the last several decades and is likely to continue to increase due to climate and land-use change, and fire suppression, that is, removing less-extreme fires (Bowman et al. 2020; Cunningham et al. 2024; Kreider et al. 2024). Without effective interventions, the probability of wildfires will increase globally by a factor of 1.31 to 1.57 by the end of the century (UNEP 2022). Increased wildfire activity exacerbates GHG emissions and forest loss, reinforcing climate change drivers (**Figure 3.6**) (UNEP 2022).

Emissions from bush and forest fires, as well as from agricultural burning, vary spatially across the world (van Wees et al. 2022), and smoke plumes lead to poor regional air quality and increased $PM_{2.5}$, and O_3 concentrations, as well as toxic metals including mercury, affecting human health. Wildfires also emit black carbon, which has a significant radiative-forcing effect. The health risks associated with wildfires include direct dangers from exposure to fires, as well as exposure to the smoke (Xu et al. 2020). Wildfires also release viable bioaerosols or microbes that can be transported long distances in plumes, with human-health implications (Kobziar et al. 2022). In combination with a growing and ageing global population, adverse health effects associated with wildfire smoke are likely to become more significant in the future (Reid and Maestas 2019).

In the period 2010–2019, population-weighted average $PM_{2.5}$ and tropospheric O_3 concentrations associated with fire emissions were about 6.1 per cent of all-source $PM_{2.5}$ and 3.6 per cent of all-source O_3, representing a slight increase in $PM_{2.5}$ compared to 2002–2009, but not

Figure 3.6: Potential reinforcing feedback loop of climate change on wildfires



Source: UNEP (2022)

Box 3.2: Local and Indigenous practices in biomass burning

Weather and climate parameters control wildfire activities in the presence of vegetation, atmospheric oxygen and numerous ignition sources (Grillakis et al. 2022). Over 90 per cent of fires in most biomes are caused by human activities (Chuvieco et al. 2021). Due to climate change, frequent-fire-prone areas are likely to increase by 29 per cent globally and the fire season will lengthen significantly by the end of the 21st century (Senande-Rivera, Insua-Costa and Miguez-Macho 2022). Several region-specific practices, including those of Indigenous Peoples, have been used to manage biomass burning on different continents.

Africa

Wildfires in Africa predominantly occur in the savannah ecosystem and contribute approximately 29 per cent of global fire emissions (Russell-Smith et al. 2021; Dabengwa et al. 2022). Emission reductions are possible through cooler, early dry-season fire-management programmes. For example, the Khwe and Mbukushu communities of Namibia already use early-season fires for historical and livelihood reasons, highlighting the relevance of ancestral practices in fire policy planning (Humphrey, Gillson and Ziervogel 2021; Tear et al. 2021). Environmental communication through folk theatre, as with the Shona people of Zimbabwe using the song Ndiani apisa moto (Who has caused a veld fire?), is incorporated in social gatherings to combat biomass burning (Chari 2020).

Oceania

Image 3.1: A controlled fire burn occurs near Whitfield in the King Valley, Victoria, Australia. Credit: FiledIMAGE/envato

In the fire-prone regions of Australia, Indigenous Knowledge and Local Knowledge is used to manage savannah fires. Indigenous rangers work across multiple Indigenous Protected Areas, burning biomass to reduce the fuel load before the bushfire season. Biomass burning emissions are managed by developing seasonal calendars for fire management with ecological indicators and seasonal conditions that integrate natural and cultural values (McKemey et al. 2020; McKemey et al. 2021). Applying Indigenous Knowledge to develop collaborative fire-management strategies that respect local practices can provide mutually beneficial outcomes for biodiversity, cultural heritage and human assets (Rodrigues et al. 2022).

Meso and South America

Indigenous communities in the Chiapas pyrobiocultural landscapes of Mexico and Lomerío in Bolivia use

Indigenous Knowledge for fire management to reduce extreme wildfire events. Indigenous Peoples apply their observations and memories of major extreme events and integrate cultural fire-management practices rooted in the Indigenous way of life, emphasizing harmony and the relationship between humans and nature (Pasiecznik and Goldammer 2022; Rodríguez et al. 2023). Pyrocultural refers to the strong relationship between traditional fire practices, territorial knowledge, and management (Pasiecznik and Goldammer 2022).

Indigenous Knowledge integrates a seasonal calendar with local weather patterns to optimize food production. This practice involves using the land in cycles: 2–3 years for crop production followed by a long rest period of at least 10 years after an initial burning to allow the soil to recover (Tschakert, Coomes and Potvin 2007). This system is deeply intertwined with Indigenous sociocultural and spiritual practices, reflecting a holistic approach to land management that prioritizes ecological balance and cultural continuity (Catacora-Vargas et al. 2015; Fundación Xavier Albó and Centro de Investigación y Promoción del Campesinado 2017).

The Pantanal area in South America has experienced a severe drought since 2019 (Marengo et al. 2021) that resulted in intense and widespread fires in 2020 (Garcia et al. 2021). Predominantly intentional fires (Libonati et al. 2020; Oliviera et al. 2022) consumed large areas of converted and Indigenous lands, even in regions inhabited by the Kadiwéu, who are trained in fighting fires in their territory (UNEP 2022).

North America

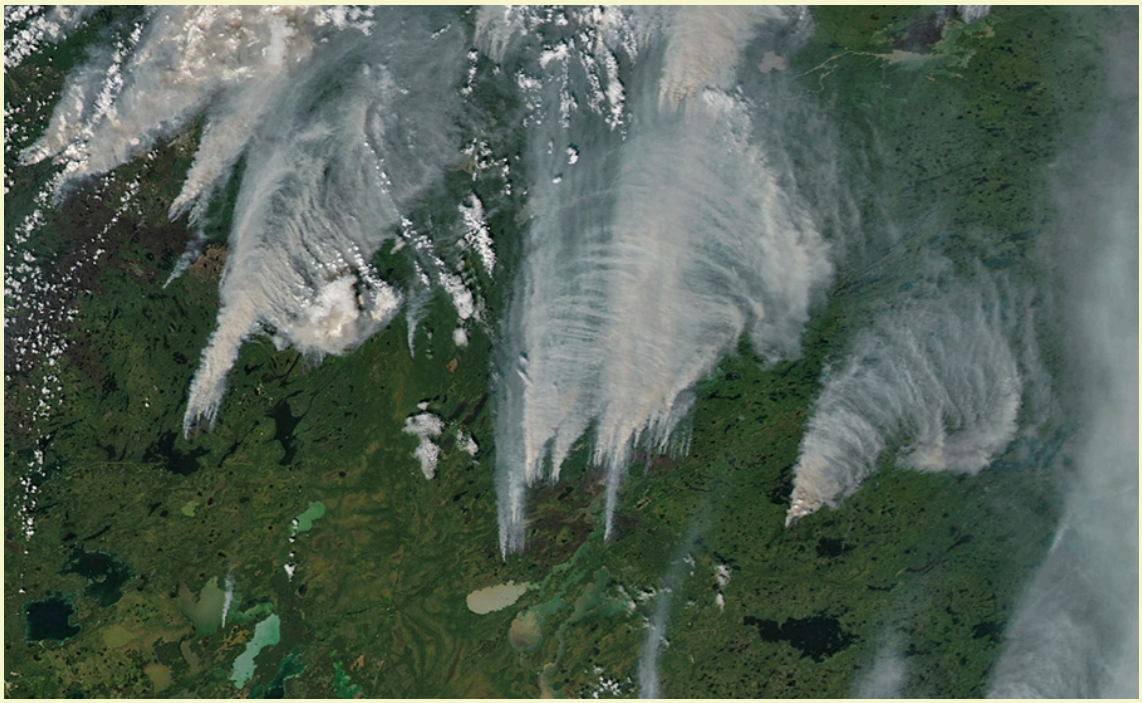


Image 3.2: Dense smoke plumes from large fires in the Manitoba province of Canada on 9 July 2025 - Source: NASA Earth Observatory

Indigenous fire management has contributed to the development of fire-adapted landscapes in Canada, strengthening cultural connections and protecting the well-being of future generations (Nikolakis and Roberts 2020). In British Columbia, Indigenous fire practices were historically used to promote ungulate browsing, reduce understory vegetation, and control the overgrowth of conifers and sagebrush (Nikolakis et al. 2020). The revitalization of Indigenous cultural burning practices can present an alternative that reduces wildfire risk and enhances community protection, while maintaining a balanced relationship between fire, humans and other beings (Hoffman et al. 2021).

for O_3 (Xu et al. 2023). Central Africa, Southeast Asia, South America and Siberia had the highest $PM_{2.5}$ and O_3 concentrations associated with fires, with pollutant levels approximately four times higher in low-income countries compared to high-income countries.

Wildfire-driven increases in $PM_{2.5}$ concentrations are likely to grow as the climate continues to warm (Burke et al. 2023). However, current trends show significant regional variability in wildfire-related atmospheric emissions. Furthermore, increases in O_3 formation due to wildfires have been reported in the literature (Byrne et al. 2024; Cooper et al. 2024; Lee and Jaffee 2024). Wildfires in Australia in 2019–2020 and Canada in 2023 resulted in extremely poor regional air quality, affecting population health in much of eastern Australia (Borchers-Arriagada et al. 2020) and North America (McArdle et al. 2023) and highlighting environmental and health disparities (Vardoulakis et al. 2020a; Yu et al. 2024).

People with pre-existing cardiovascular, neurological and respiratory diseases, the elderly, women often as primary caregivers, young children, pregnant women and infants, and outdoor workers are at higher risk from wildfire smoke and face additional burdens during and after wildfires (Holm, Miller and Balmes 2021; Vardoulakis et al. 2020a; Elser et al. 2025; White 2024).

Indigenous communities are disproportionately affected by wildfires as well (Casey et al. 2024). Between 2014 and 2019, exposure to smoke from fires in South America was greater in the Indigenous territories of the Amazon compared to the rest of South America (Bonilla et al. 2023). Amazon's Indigenous territories experienced 1.1 [± 0.4] $\mu g/m^3$ higher total $PM_{2.5}$ and 0.64 [± 0.21] $\mu g/m^3$ higher fire-related $PM_{2.5}$ (Bonilla et al. 2023). More research is needed to understand the long-term health effects of extreme wildfires in the general population and in Indigenous and at-

Box 3.3: Air pollution from fires caused by the conflict in Gaza

Many fires have broken out in Gaza since the start of the bombing in October 2023. Fires that occur at chemical storage sites pose a high risk of toxic pollutant emissions (Griffiths et al. 2022). In temporary shelters with a high density of displaced people, air pollution increases the risk of respiratory and cardiovascular distress, as well as longer-term risks of respiratory and cardiovascular disease and cancer (Velis and Cook 2021). Armed conflict escalations bring further environmental degradation, harming people and ecosystems (UNEP 2024a).

Image 3.3 Fires burning in Gaza, 16 November 2023 Source: Sentinel 2 [10 m resolution] retrieved by GRID Geneva, March 2024 (UNEP 2024a)

risk communities. It is also essential to understand Indigenous Knowledge and Local Knowledge practices in biomass burning that may help reduce the extent and impact of wildfires (**Box 3.2**).

3.4.4 Conflict and atmospheric emissions

Wars and conflicts have deteriorated air quality in particular regions, including parts of Europe (Meng et al. 2023), Africa (Solomon et al. 2018), and the Middle East (UNEP 2024a) (**Box 3.3**). Conversely, reduced economic activity due to armed conflict in East Africa may have reduced NO_2 levels in certain cities in Sudan (Abushama et al. 2023).

Russia's war on Ukraine led to an average $PM_{2.5}$ increase of approximately 9.8 per cent, an NO_2 increase of 10.1 per cent, and an average decrease in tropospheric ozone of approximately 7.9 per cent in cities in the war zones. Emissions from military activities have also contributed to degraded air quality in the Middle East and Africa. The increase in atmospheric emissions of harmful pollutants caused by war poses a substantial challenge to regional air quality in Europe (Meng et al. 2023).

The use of explosive munitions generates large quantities of dust that causes an additional health hazard during armed conflicts, as well as during post-conflict clean-up and recovery operations. Inhalation of the dust generated during the bombing of buildings or other infrastructure can be harmful because of potential contamination with asbestos, organic chemicals, heavy metals from munitions, and other toxic substances (UNEP 2024a).

The GHG emissions of the world's militaries, apart from the direct consequences of combat, such as fires and other damage to infrastructure and ecosystems, are estimated to be approximately 5.5 per cent of global GHG emissions (Parkinson and Cottrell 2022). These emissions are likely to have grown in the wake of Russia's war on Ukraine (Bun et al. 2024) and conflicts in the Middle East and Africa (Neimark et al. 2024).

3.4.5 Household air pollution from solid fuels and other indoor sources

Household air pollution caused by the burning of solid fuels – firewood, coal, charcoal, animal dung, crop residues, and plastic waste – or kerosene in inefficient stoves indoors affects approximately 2.3 billion people, around a third of the global population (Lee et al. 2020; Khavari et al. 2023; WHO 2024b). These people mainly live in low and middle-income countries in sub-Saharan Africa, Asia and Latin America, where there is limited access to clean energy for cooking and heating (WHO 2024). For example, around 20 per cent of rural households in India used solid fuels exclusively for cooking in 2020 (Mani et al. 2021), while in Paraguay, 49 per cent of rural households still relied on solid fuels for cooking in 2022 (Paraguayan Government 2022). Household air pollution from these sources is associated with around 3.2 million deaths each year, including over 237,000 deaths of children under the age of 5 years (WHO 2024). Polluting fuels and technologies disproportionately affect women and children in low-income households, as they are typically involved in household chores such as collecting firewood and cooking, and they spend more time indoors exposed to harmful smoke from inefficient stoves (WHO 2024).

From 2000 to 2021, there has been a 61 per cent reduction in the death rate from household air pollution (Health Effects Institute 2024). Although the burden of maternal and child illnesses linked to household air pollution declined by a third worldwide from 2000 to 2017, it remains high in the lowest-income countries and regions, particularly in Southeast Asia and Africa (Lee et al. 2020). The African and Western Pacific regions experienced modest reductions in the related disease burden, with larger reductions in India and China (Lee et al. 2020). The patterns of diseases associated with household air pollution varied substantially, with respiratory infections nearly halved, but noncommunicable diseases such as lung cancer increasing (Lee et al. 2020).

Particulate emissions from wood heaters persist as a significant environmental and public health problem in many countries. For example, in Australia, wood heaters contribute about 13 per cent of ambient $PM_{2.5}$ concentrations annually (Borchers-Arriagada et al. 2024). Emissions of formaldehyde and other volatile organic compounds from indoor sources, such as furniture, timber, paints, adhesives and cleaning products, have a deleterious effect on the household environment (Vardoulakis et al. 2020b). More airtight houses in the future may result in higher indoor air pollution and overheating, unless adequate air ventilation, filtration and cooling are provided.

3.4.6 Sand and dust storms

Particles from sand and dust storms affect human health and degrade materials and visibility. There is a significant association between this type of dust and adverse respiratory and cardiovascular health effects (Lwin et al. 2023). Sand and dust storms are strongly linked to climate change due to the combined effect of rising temperatures and reduced rainfall, which lead to droughts, land degradation, and desertification (Wu et al. 2021). Droughts are a major threat to sustainable development in dryland Asia, with drought conditions projected to worsen for climate scenarios consistent with 1.5 and 2.0°C warming, particularly for Northwest China and Kazakhstan (Miao et al. 2020).

Sand and dust storms in many world regions, including Africa and Asia, present an increasing threat to global health (United Nations Convention to Combat Desertification [UNCCD] 2022; Touré et al. 2024; Li et al. 2025). The main component of sand and dust storms that threaten human health is inhalable particles (PM_{10}), which are associated with all-cause mortality and morbidity, especially from respiratory and cardiovascular illnesses. These storms can also expose individuals to harmful microorganisms and allergens present in coarse particles (Wu et al. 2021). Concurrent heatwaves and drought conditions in the past two decades, particularly over inner East Asia and West Asia, have exacerbated the soil drying that causes sandstorms (Zhang et al. 2020).

3.4.7 Aeroallergens

Airborne allergens such as pollen degrade both outdoor and indoor air quality (Beggs et al. 2023). Climate and weather affect plant phenology, which refers to the timing of recurring biological events in the plant life cycle, and airborne pollen concentrations. Atmospheric CO_2 that causes climate warming also promotes plant growth, with associated releases of airborne allergens, such as pollen (Dhimal et al. 2021).

Various weather and climate variables affect the pollen concentration in the atmosphere and the timing and duration of the pollen season for different plant species (Schramm et al. 2021). Precipitation, for example, may increase grass pollen levels in the air. Ongoing increases in temperature extremes might contribute to longer pollen seasons and greater allergenic pollen loads in regions across the northern hemisphere (Ziska et al. 2019). Overall, warmer temperatures and higher atmospheric concentrations of CO_2 tend to prolong and increase the intensity of the pollen season, which may affect allergic respiratory diseases such as rhinitis and asthma, especially in sensitive individuals with pre-existing respiratory conditions (D'Amato et al. 2020).

3.4.8 Vector-borne diseases

Climate change will likely extend the geographical range and length of the transmission season of several vector-borne diseases (Caminade et al. 2019). Temperature and precipitation both affect the distribution of climate-sensitive vector-borne diseases transmitted by mosquitoes and ticks. Warmer temperatures generally favour vector-borne disease transmission, while precipitation creates adequate vector breeding sites for mosquitoes and ticks (Caminade et al. 2019). Furthermore, climate change affects infectious disease dynamics for several pathogens (Wu et al. 2016).

The transmission potential of some mosquito-borne diseases, such as malaria, dengue, Zika and chikungunya, is expected to increase, particularly under higher GHG emission scenarios (Semenza et al. 2022). Climate change is also projected to contribute to the wider distribution of tick-borne diseases, such as Lyme disease and tick-borne encephalitis (Semenza et al. 2022).

3.4.9 Stratospheric ozone and UV irradiance effects

Stratospheric ozone, affected by ODS emissions and climate change, may contribute to changes in UV-B exposure patterns at ground level and related skin cancer incidence (Parker 2021). The universal ratification of the Montreal Protocol has led to the regulation and phase-out of ODSs (3.5.2). In addition to protecting the ozone layer and hence human health from harmful UV radiation that can cause erythema and skin cancer (Tang et al. 2024), the Montreal Protocol is making a substantial contribution to reducing stratospheric ozone-depleting GHGs also included in this treaty (Bernhard et al. 2020). Although the Montreal Protocol has prevented significant increases in UV-B irradiance and related skin cancer cases (Neale et al. 2021; Neale et al. 2023), there are substantial uncertainties in the future evolution of UV exposure patterns at ground level due to climate change (Zerefos et al. 2023).

Credit: Ivankmit/Envato

3.4.10 Food security and safety

Food security is affected by climate change, extreme weather events and tropospheric ozone, all of which can affect food production, availability, access and affordability. Increasing atmospheric CO_2 concentrations and temperatures could produce greater crop yields (Mirón, Linares and Díaz 2023). However, the increasing frequency and intensity of climate-related extreme events, such as floods, heatwaves and droughts, can cause more frequent crop failures, particularly in low-income countries that have lower adaptive capacity. Agriculture absorbed 26 per cent of the overall effect of medium- to large-scale natural disasters over the period 2000–2018 in low and middle-income countries (Monteleone et al. 2023). Tropospheric ozone also damages vegetation and reduces the yield of crops such as wheat in Asia (Anagha and Kuttippurath 2025; Xu et al. 2024), threatening global food security (von Schneidemesser et al. 2020).

Low-income households and particularly women are disproportionately affected by food insecurity, given their vulnerability to extreme weather events and restricted access to resources in certain regions (Food and Agriculture Organization of the United Nations 2015). Food security and climate change have strong gender and equity dimensions, with women disproportionately affected by price spikes (Mbow et al. 2019). Furthermore, warmer temperatures due to climate change could lead to an increased risk of proliferation of microorganisms that cause food-borne diseases, such as Salmonella and Campylobacter, affecting food safety (Mirón, Linares and Díaz 2023), as well as increased risks for the spread of food pathogens (Tirado et al. 2010).

Overall, the agriculture sector has been adversely affected by climate change, resulting in crop losses and food insecurity (Pande et al. 2023). Adopting traditional knowledge of preserving ecosystem services from Indigenous Peoples' practices and lifestyles provides insights into biodiversity restoration and climate change adaptation. The adoption of such practices can be promoted through sustainable resource management and local community engagement, encouraging Indigenous Peoples' full and effective participation in decision-making (Zurba and Papadopoulos 2023; Edwards et al. 2024).

3.4.11Biodiversity

Anticipated impacts of climate change on biodiversity include a decline in ecosystem functioning, integrity and resilience, beginning

at about 1.5°C of global warming. This will lead to the degradation of nature-based economic livelihoods and to food insecurity (IPCC 2022). Communities reliant on ecosystems and species that cannot easily establish themselves in different habitats and are already close to reaching the maximum extent to which they can adapt to climate change, are disproportionately affected by biodiversity loss (Pörtner et al. 2021).

3.4.12 Indigenous Peoples and local communities

Some of the primary mechanisms of how climate change affects Indigenous Peoples include their close relationship with the environment and their reliance on natural resources for livelihoods, food, water and health security that are compounded by the historical effects of socioeconomic and political marginalization (IPCC 2022; Redvers et al. 2023). Changes in precipitation and water quality and increased temperatures lead to more injuries, more airborne and waterborne diseases, and more malnutrition. They also cause mental distress due to disruptions in cultural and spiritual practices, and in community cohesion (Middleton et al. 2020; Reyes-García et al. 2024a). Climate change poses the risk of increasing Indigenous Peoples' exposure to harmful levels of heavy metals, including mercury, by altering their transport pathways (Stern et al. 2012), creating food security and safety issues for Indigenous diets (Feingold et al. 2020; Adlard et al. 2024).

Additionally, the loss of traditional lands and resources disrupts access to medicinal plants and jeopardizes cultural continuity, further affecting health and community well-being, especially when access to culturally appropriate healthcare services is lacking (Oster et al. 2014; Bourke et al. 2018; Rolleston et al. 2020; IPCC 2022). Similarly, due to biodiversity loss from climate change or other environmental factors, Indigenous Peoples' livelihoods were reportedly altered as a loss of ecosystem services, particularly provisioning and cultural services, also brought changes in ecosystem structure and function (Loring and Gerlach 2015; Kipp et al. 2019).

Rising temperatures, drought-related dust storms and degraded infrastructure lead to poor air quality, as observed among Indigenous communities in Arizona and New Mexico (Gamble et al. 2016). People living in Indigenous territories within the Amazon region are twice as likely to die prematurely from smoke exposure compared to the general population (Bonilla et al. 2023). Indigenous Peoples' respiratory health has been affected by industrial air pollution, land dispossession, and other socioeconomic structural conditions that have exacerbated inflammatory responses in the body's airways (Fernández-Llamazares et al. 2020; Ayejoto et al. 2023; Smirnova et al. 2023; Kamurasi et al. 2024). Climate change, through wildfires, presents a new threat that risks creating compounding effects for Indigenous Peoples' health.

Despite the disproportionate effects of climate change on the health of Indigenous Peoples and local communities, and the often-overlooked value of their knowledge by mainstream science, emerging evidence indicates that observations from Indigenous Peoples and local communities are crucial for supporting global analyses of climate change and its environmental impacts (Reyes-García et al. 2024b). Indigenous Peoples and local communities have noted a decline in crop production and quality, an increase in pest and plant diseases, shifts in animal migration patterns, disruption of the life cycles of wild animals, and changes in the timing of fruiting in plants (Savo et al. 2016). Such changes have implications for both local and global food security and the health of ecosystems (Savo et al. 2016).

Indigenous Peoples' observations and knowledge are central to their adaptive capacity to identify, predict and manage environmental changes, including adjusting to changing climatic conditions (Ford et al. 2020). Indigenous Peoples' knowledge, institutions and collective action have underpinned climate change adaptation to protect their health and well-being (Vidal-Cuellar et al. 2024; Leal Filho et al. 2022). Indigenous Peoples have long recognized the crucial and complementary roles that both women and men play in responding to environmental changes, highlighting the importance of valuing context-specific gender Indigenous perspectives for climate change adaptation (UNEP 2024b).

Climate change effects on Indigenous Peoples' health can be worsened by pre-existing health inequities and limited healthcare access (Romanello et al. 2022). Indigenous populations still experience historical trauma based on their respective first encounters with colonizers or dominant country governments. These experiences have exacerbated climate change impacts

on Indigenous health and well-being (Redvers, Aubrey, Celidwen and Hill 2023; Matthews et al. 2023). Trauma memories, such as marginalization of their Indigenous health practices, can be manifest in different aspects of their health; for example, past experiences can prevent Indigenous community members from visiting and seeking healthcare in their respective official health systems (Knibb-Lamouche 2012; Mbuzi, Fulbrook and Jessup 2017; Curtis et al. 2019; Arotoma et al. 2022).

Furthermore, the implications of climate change for Indigenous Peoples' health may span multiple generations. One aspect relates to the medium- and long-term effects on Indigenous children and adolescents who have been exposed to heat stress early in life (Olson and Metz 2020). Emergent literature investigates the potential impact of meteorological variations, such as high temperatures and precipitation levels, on fetal development (MacVicar et al. 2017). These effects are influenced by the combination of various pre-existing socioeconomic and health challenges, particularly among low- and middle-income countries, where populations are transitioning from a resource-poor condition to one of plentiful resources (Popkin et al. 2012). Climate change may worsen this transition, affecting nutritional status and overall mental well-being (Middleton et al. 2020; Vecchio et al. 2023).

3.4.13 Human system co-benefits from actions to reduce atmospheric emissions

Policy action to reduce GHG and air pollutant emissions and waste and chemicals in the environment can provide multiple co-benefits for human systems. Air quality improvements in the outdoor and indoor environment are essential in reducing the global burden of noncommunicable diseases (Campbell-Lendrum and Prüss-Ustün 2018). Integrated clean energy and health interventions are needed to reduce the health burden of household air pollution in low and middle-income countries (Lee et al. 2020). For example, introducing cleaner technologies and fuels for heating, cooking and lighting (WHO 2024b) can reduce the burden of household air pollution on maternal and child health (Woolley et al. 2021).

The health benefits of reductions in air pollutant concentrations can provide a strong incentive for climate change mitigation through reductions in co-emitted GHGs and short-lived climate pollutants (Szopa et al. 2021; UNEP 2023b). For example, reducing emissions of CO_2, $PM_{2.5}$ and nitrogen oxides from road transport through increased use of electric vehicles and more active travel, such as cycling and walking in cities, will directly benefit public health by improving local air quality (Vardoulakis et al. 2018), as well as mitigating climate change (IPCC 2023). Reducing GHG and air pollutant emissions from power generation can also benefit both climate and public health (Tong et al. 2021). Policies aiming to reduce emissions of short-lived climate pollutants, such as methane emissions from the agriculture and waste sectors, can have substantial co-benefits in terms of climate change mitigation and the reduction of ground-level ozone pollution (UNEP & Climate and Clean Air Coalition [CCAC] 2021; EEA 2023b).

However, reducing air pollutant emissions from industry, transport and power generation may also have unintended consequences, as some associated secondary atmospheric aerosols prevent warming by scattering sunlight rather than absorbing it. Globally, aerosols offset around one-third of the atmospheric warming imposed by anthropogenic GHGs (IPCC 2021), although substantial atmospheric warming occurs in regions such as South America and East and South Asia where the proportion of absorbing aerosols is relatively high compared to scattering aerosols (Li et al. 2022). When both co-benefits and unintended consequences are fully considered, combined air quality and climate change mitigation policies result in net benefits globally (Scovronick et al. 2019; Shindell and Smith 2019; Szopa et al. 2021). Therefore, ambitious and well-integrated climate change mitigation and air quality management policies are needed to maximize their co-benefits and minimize any unintended consequences (Karlsson et al. 2020).

3.5 Progress towards the goals of global agreements

3.5.1 Paris Climate Agreement and Sustainable Development Goals

The Paris Agreement, adopted in 2015 at the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC), marked a significant turning point in the global effort to combat climate change. Its central aim is to limit global warming to well below 2°C above pre-

industrial levels, with the objectives of GHG emissions peaking before 2025 at the latest and declining by 43 per cent by 2030. This ambitious target is closely linked to Sustainable Development Goal 13 (SDG 13) which calls for urgent action to combat climate change and its impacts, as well as SDG 7 for affordable and clean energy. As of 2025, all but three of the 196 countries that negotiated the agreement have ratified it. The impacts and implications of the United States Government's decision in January 2025 to withdraw from the Paris Agreement have yet to be assessed.

Since adopting the Paris Agreement, many countries have taken substantial steps to align their national policies with the accord's objectives. The Nationally Determined Contributions (NDCs) serve as vital tools for countries to outline their specific climate actions. Notable advances have been the growing commitment to afforestation and renewable energy. The declining costs of solar, wind and other clean energy sources have made renewables increasingly competitive with fossil fuels (Osman et al. 2023). Many nations have expanded their renewable energy capacities and set targets for achieving carbon neutrality. The rise of electric vehicles, innovations in battery storage and investments in green technologies further underline progress towards decarbonization.

The NDC Synthesis report suggests that the combined GHG emissions of the Parties could decrease by around 64 per cent, within a range of 59–69 per cent, by the year 2050 compared to the levels observed in 2019 (UNFCCC 2023), if NDCs are fully implemented. However, many countries are currently not on track to achieve their NDCs. To be on the pathway to 1.5°C, current emissions need to be reduced by 42 per cent by 2030 and 57 per cent by 2035. According to the UNEP Emissions Gap Report (UNEP 2024d), current policies could lead to an increase of global mean surface temperature of 2.6–3.1°C, even with full implementation of the conditional and unconditional NDCs.

Further variability in GHG mitigation potentials is rooted in the difference between conditional and unconditional contributions, which may affect the actual emission reductions achieved. By 2050, the average individual emissions per year would be approximately 2.4 metric tons of CO_2eq. In scenarios where efforts are made to limit global warming to below 2°C, which holds a likelihood of over 67 per cent, the yearly per capita emissions would be around 2.2 metric tons of CO_2eq. Research has shown that many key indicators are consistent with emission scenarios that keep temperatures below 2°C. However, the continued lack of large-scale action on reducing emissions – for instance, through CO_2 removal measures such as carbon capture and storage – threatens 2030 targets and the longer-term Paris ambition of net-zero emissions (Peters et al. 2017).

The outcomes of the Global Stocktake, a process under the Paris Agreement to assess collective progress towards its goals, state, regarding mitigation, that "…significant collective progress towards the Paris Agreement temperature goal has been made, from an expected global temperature increase of 4°C according to some projections prior to the adoption of the Agreement to an increase in the range of 2.1–2.8°C with the full implementation of the latest nationally determined contributions" (UNFCCC 2025). However, significant challenges remain. While the Paris Agreement is vital, implementation has proven to be complex. At the same time, the impacts of climate change are becoming more evident and severe (UNEP 2023a), as GHG emissions reach new highs (Friedlingstein et al. 2020), temperature records continue to be broken, and sea levels rise.

Developing nations and Small Island Developing States are often the least responsible for historical GHG emissions; however, they are disproportionately threatened by the impacts of changing climate. This consequence highlights the need for capacity development as well as financial and technological support from developed countries to achieve implementation of the agreement on a global scale.

In the context of SDG 13, progress is closely linked to progress on the other SDGs because climate action intersects with poverty eradication, health, education, and gender equality and equity. Integrated approaches that consider multiple dimensions of development are crucial for achieving meaningful progress. Furthermore, SDG 7 calls for affordable, reliable, sustainable and modern energy for all by 2030, which is directly relevant in the context of national reduction targets for GHG emissions.

To track progress towards emission targets more robustly, the WMO is establishing a new monitoring initiative, Global Greenhouse Gas Watch, to support

WMO Members in mitigation actions with respect to the Paris Agreement (WMO 2024b).

3.5.2 Montreal Protocol

The Montreal Protocol on Substances that Deplete the Ozone Layer was adopted in 1987 and entered into force on 1 January 1989 (**Figure 3.7**). Since then, it has been revised in several steps, most recently in 2016 in Kigali. The 2007 Montreal Amendment covered the agreement to an accelerated phase-out schedule for hydrochlorofluorocarbons, with the aim to achieve full compliance by developed countries by 2020 and developing countries by 2030. In 2016, the phase down of hydrofluorocarbons was agreed in the Kigali Amendment. While hydrofluorocarbons are not considered to deplete the stratospheric ozone layer, their high Global Warming Potential (12,000–14,000) justified adding them to the list of controlled substances to protect the global climate system.

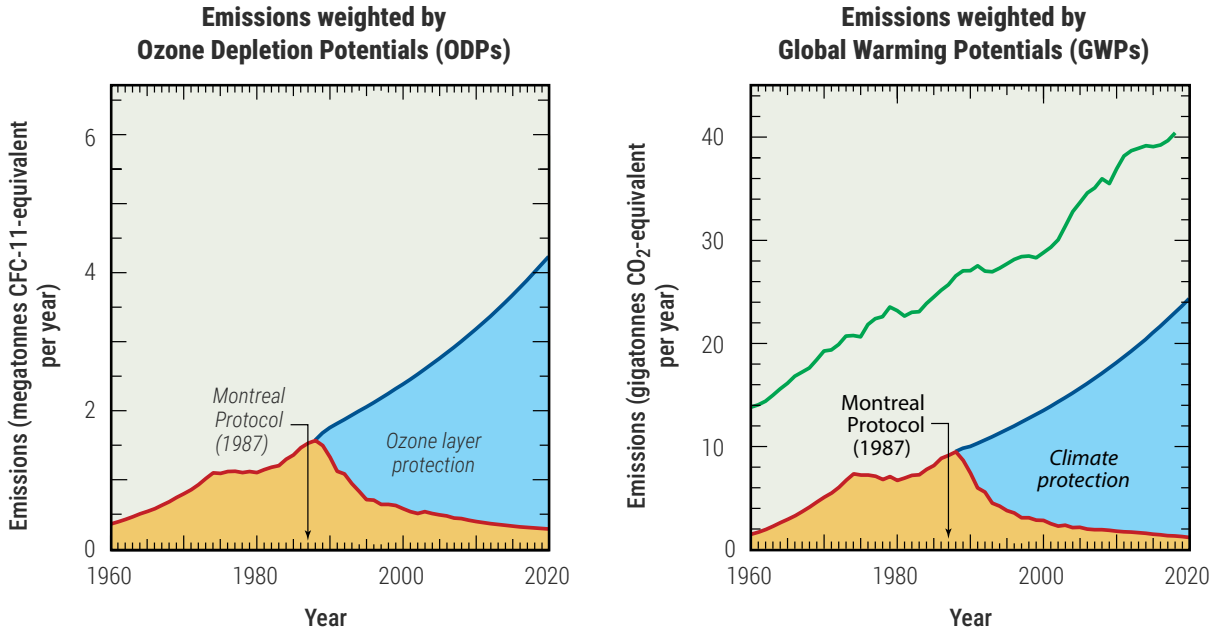
In its 2022 Scientific Assessment of Ozone Depletion, the WMO (2022) and its partner organizations associated with the Protocol, emphasized that "Science has been one of the foundations of the Montreal Protocol's success." Among the achievements highlighted by the report, the reduction in emissions of ODS has contributed to a recovery of total ozone column measurements, which are projected to return to 1980 levels within the following decades. In addition, the reduction in ODS emissions has avoided global warming by approximately 0.5–1°C by the mid-21st century, compared to a scenario of unregulated ODS increase of emissions by 3–3.5 per cent annually. Without global controls, hydrofluorocarbons were projected to contribute 0.3–0.5°C to global surface warming in 2100. The controls of the Kigali Amendment reduced this to 0.04°C in 2100 (Velders et al. 2022).

Overall, the Montreal Protocol and its Amendments have contributed to phasing out 98 per cent of ODS globally, relative to 1990 levels, and it is estimated that it has contributed to preventing up to 0.5°C of global temperature rise overall by 2100, in addition to reversing the depletion of stratospheric ozone. However, emerging challenges such as detecting unexpected emissions of CFC-11 and other ODS (Lickley et al. 2021) require further scientific research and regulatory policy attention. Additional gaps in scientific understanding (Dhomse et al. 2019; Lickley et al. 2020) and data for monitoring progress towards emission and ozone layer recovery targets remain.

3.5.3 WHO guidelines for ambient and indoor air quality

Air quality, despite its global role in public health as identified by the Global Burden of Disease studies,

Figure 3.7: Montreal Protocol protection of ozone and climate



Source: Salawitch et al. 2019

does not have a dedicated SDG and only one SDG indicator (SDG 11.6.2), which is solely focused on $PM_{2.5}$ (GBD 2019, GBD 2021). While $PM_{2.5}$ is a key driver of air pollution-related human health impacts, it may not be sufficient to capture the full range of air pollution consequences for human health and even less so on ecosystems. In addition, progress in epidemiological and toxicological evidence suggests that adverse effects of particulate air pollution on human health occur at much lower concentrations than previously thought (Papadogeorgou et al. 2019; Hoffmann et al. 2021; Stafoggia et al. 2022). Consequently, the WHO adjusted its guidelines (WHO 2021) for air quality in 2021, reducing the guideline value for annual mean concentrations of $PM_{2.5}$ as shown in **Table 3.1**. In addition, the WHO 2021 guidelines for PM_{10} and NO_2 are more stringent than the 2005 guidelines. While these guidelines do not have defined target dates, WHO has set interim targets for several pollutants, highlighting the importance of stepwise improvements in air quality and the reduction of exposure to air pollution over time.

Table 3.1: WHO 2005 and 2021 Air Quality Guidelines

Pollutant	Averaging time	2005 AQGs	2021 AQGs
$PM_{2.5}$ (µg/m^3)	Annual	10	5
	24–hour	25	15
PM_{10} (µg/m^3)	Annual	20	15
	24–hour	50	45
O_3 (µg/m^3)	Peak season		60
	8–hour	100	100
NO_2 (µg/m^3)	Annual	40	10
	24–hour		25
SO_2 (µg/m^3)	24–hour	20	40
CO (mg/m^3)	24–hour		4

Note: µg = microgram, a is 99th percentile (i.e. 3–4 exceedance days per year); b is Average of daily maximum 8-hour mean O_3 concentration in the six consecutive months with the highest six-month running-average O_3 concentration; Annual and peak season is long-term exposure, while 24 hour and 8 hour is short-term exposure (WHO 2021).

According to estimates (Pai et al. 2022), in 2019, 90 per cent of the global population were exposed to ambient concentrations of $PM_{2.5}$ in exceedance of the 2021 guideline. The State of Global Air Report 2024 states that 99 per cent of the global population is exposed to unhealthy air pollution (Health Effects Institute 2024). By 2030, the target year for achieving the SDGs, a general reduction of population-weighted concentrations of $PM_{2.5}$ could be achieved in most world regions, according to recent modelling studies (Yue et al. 2024). However, long-term increases in air pollution-related mortality are estimated by other studies under different climate scenarios (Chen et al. 2023).

Although people typically spend more than 90 per cent of their time indoors, most countries do not have legislated indoor air quality standards for public or private spaces (Morawska et al. 2024). The WHO published indoor air quality guidelines for selected chemicals in 2010 (WHO 2010), but indoor air is still mainly regulated through building codes and ventilation standards. The importance of indoor air quality for human health is becoming increasingly evident in high-income countries (Vardoulakis et al. 2020b), particularly in relation to airborne infectious disease transmission since the COVID-19 pandemic (Morawska et al. 2024), as well as in low- and middle-income settings concerning solid fuel use for domestic cooking and heating (Section 3.4.5).

3.5.4 Stockholm Convention

Persistent organic pollutants (POPs) continue to be a challenge since the incorporation of new pollutants on the original list of 12 chemicals and their derivatives in the Stockholm Convention (UNEP 2023a). One challenge is the ability of POPs to travel large distances in the atmosphere from their sources. Evidence of the effectiveness of the measures proposed by the Convention is the global monitoring plan (GMP) which monitors POPs in the atmosphere through passive and active sampling (Secretariat of the Stockholm Convention 2019).

The GMP has already performed three rounds of monitoring on background sites, providing sufficient data to determine trends for many of the listed POPs, but not all. Overall, concentrations are declining and starting to level off where regulatory action was taken decades ago. However, in some cases, such

as hexachlorobenzene, slight increases, likely due to releases from secondary sources and the effects of climate change, can be identified. The patterns and trends for POPs listed since 2009 are complex and vary across chemicals, media and areas. Analyses linking to localized actions could assist in understanding such variability. There is insufficient data to detect trends for many newly listed POPs (UNEP 2023a). Exposure to chemical mixtures, including both known and unknown chemicals that are similar to persistent organic pollutants and their transformation products, can impair human health and the environment. Increased accessibility to high-resolution analytical equipment is rapidly enabling advanced research in this area (UNEP 2023b).

3.5.5 Minamata Convention

The Minamata Convention regulates mercury as a global pollutant. Atmospheric transport is the primary transmission pathway for this chemical. The current most important sources of mercury releases into the atmosphere are gold mining and coal combustion. The Background Report to the Global Mercury Assessment in 2018 estimated that human activities have increased total atmospheric mercury concentrations by about 450 per cent above levels common before 1450 A.D. (UNEP 2018; UNEP 2019b). Recent research shows the increase in mercury emissions to be 40 per cent larger than previously estimated, indicating the need for further emission reduction efforts (Zhang et al. 2023b). Furthermore, there are potential co-benefits of GHG strategies for mercury and other heavy metal emissions control (Pan et al. 2024).

3.5.6 Other relevant agreements and conventions

The United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution, signed in Geneva on 13 November 1979 (United Nations Economic Commission for Europe 2025) has been instrumental in driving air pollution control efforts primarily in the northern hemisphere. The Air Convention is implemented through several protocols and activities at the science-policy interface addressing emissions, monitoring and modelling of transboundary air pollution, and its effects on human and ecosystem health. With the establishment of a new Forum for International Cooperation on Air Pollution in 2023, knowledge exchange and engagement with other world regions beyond the original geographical scope of the Transboundary Air Pollution Convention are a new objective.

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (2025) is the only legally binding global environmental agreement on hazardous and other wastes. It regulates transboundary movements of hazardous and other wastes and addresses plastic pollution. By reducing waste at the source, its implementation will substantially contribute to the reduction of atmospheric emissions of air pollutants and GHGs.

Finally, the Rotterdam Convention on the prior informed consent procedure for certain hazardous chemicals and pesticides in international trade (2025) is a multilateral treaty to promote shared responsibilities concerning the importation of hazardous chemicals.

In addition to these conventions and agreements, further activities will likely affect emissions of pollutants and greenhouse gases into the atmosphere, either directly or indirectly. For instance, the United Nations Global Framework on Chemicals (2025) fosters global collaborative actions to reduce pollution. In June 2025 a new Global Science-Policy Panel on Chemicals, Waste, and Pollution (2025) has been established, following an earlier agreement by the United Nations Environment Assembly in 2022. The resulting body, similar to the IPCC and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), will offer independent scientific assessments, identify knowledge gaps, and provide policy-relevant advice, particularly to support countries – especially in the Global South – in managing chemicals and waste more effectively. This marks a significant step in strengthening the global framework for tackling pollution comprehensively, in an integrated context with climate change and biodiversity loss (UNEP 2024c).

References

Aas, W., Fagerli, H., Alastuey, A., Cavalli, F., Degorska, A., Feigenspan, S. et al. (2024). Trends in air pollution in Europe, 2000–2019. Aerosol and Air Quality Research 24(4), 230237. https://doi.org/10.4209/aaqr.230237

Aas, W., Mortier, A., Bowersox, V., Cherian, R., Faluvegi, G., Fagerli, H. et al. (2019). Global and regional trends of atmospheric sulfur. Scientific Reports 9(1), 953. https://doi.org/10.1038/s41598-018-37304-0

Abatzoglou, J.T. and Kolden, C.A. (2011). Climate change in western US Deserts: Potential for increased wildfire and invasive annual grasses. Rangeland Ecology & Management 64(5), 471-478. https://doi.org/10.2111/REM-D-09-00151.1

Abushama, H., Guo, Z., Siddig, K., Kirui, O.K., Abay, K.A. and You, L. (2023). Monitoring indicators of economic activity in Sudan amidst ongoing conflict using satellite data. Washington, DC: International Food Policy Research Institute (IFPRI). https://doi.org/10.2499/p15738coll2.136724

Abbasi, T. and and Abbasi, S.A. (2011). Ocean acidification: The newest threat to the global environment. Critical Reviews in Environmental Science and Technology 41(18), 1601-1663. https://doi.org/10.1080/10643389.2010.481579

Adlard, B., Bonefeld-Jørgensen, E.C., Dudarev, A.A., Olafsdottir, K., Abass, K., Ayotte, P. et al. (2024). Levels and trends of metals in human populations living in the Arctic. International Journal of Circumpolar Health 83(1), 2386140. https://doi.org/10.1080/22423982.2024.2386140

Allen, R.J., Samset, B.H., Wilcox, L.J. and Fisher, R.A. (2024). Are Northern Hemisphere boreal forest fires more sensitive to future aerosol mitigation than to greenhouse gas–driven warming? Science Advances 10(13), eadl4007. https://www.science.org/doi/10.1126/sciadv.adl4007

Anagha, K.S. and Kuttippurath, J. (2025). Surface ozone pollution-driven risks for the yield of major food crops under future climate change scenarios in India. Environmental Research 275, 121390. https://doi.org/10.1016/j.envres.2025.121390

Arotoma-Rojas, I., Berrang-Ford, L., Zavaleta-Cortijo, C., Ford, J.D. and Cooke, P. (2022). Indigenous Peoples' perceptions of their food system in the context of climate change: A case study of Shawi Men in the Peruvian Amazon. Sustainability 14(24). https://doi.org/10.3390/su142416502

Artaxo, P. (2023). Amazon deforestation implications in local/regional climate change. Proceedings of the National Academy of Sciences 120(50), e2317456120. https://doi.org/10.1073/pnas.2317456120

Artaxo, P., Hansson, H.C., Machado, L.A.T. and Rizzo, L.V. (2022). Tropical forests are crucial in regulating the climate on Earth. PLOS Clim 1(8), e0000054. https://doi.org/10.1371/journal.pclm.0000054

Ayejoto, D.A., Agbasi, J.C., Nwazelibe, V.E., Egbueri, J.C. and Alao, J.O. (2023). Understanding the connections between climate change, air pollution, and human health in Africa: Insights from a literature review. Journal of Environmental Science and Health 41(3-4), 77-120. https://pubmed.ncbi.nlm.nih.gov/37880976/

Aziz, N., Stafoggia, M., Stephansson, O., Roos, N., Kovats, S., Chersich, M. et al. (2024). Association between ambient air pollution a week prior to delivery and preterm birth using a nationwide study in Sweden. International Journal of Hygiene and Environmental Health 262, 114443. https://doi.org/10.1016/j.ijheh.2024.114443

Bagaria, P., Mahapatra, P.S., Bherwani, H. and Pandey, R. (2023). Environmental management: A country-level evaluation of atmospheric particulate matter removal by the forests of India. Environmental Monitoring and Assessment 195(11), 1306. https://link.springer.com/article/10.1007/s10661-023-11928-w

Bai, Y., Wang, L., Zhang, H. and Li, D. (2024). Restore vegetation, graze animals properly or apply new technologies? How to effectively restore degraded land based on carbon trading. Sustainable Futures 7, 100228. https://doi.org/10.1016/j.sftr.2024.100228

Balasus, N. et al. (2025) Satellite monitoring of annual US landfill methane emissions and trends. Environmental Research Letters, 20(2), p. 024007. https://doi.org/10.1088/1748-9326/ada2b1

Barkhordarian, A., Saatchi, S.S., Behrangi, A., Loikith, P.C. and Mechoso, C.R. (2019). A recent systematic increase in vapor pressure deficit over tropical South America. Scientific Reports 9(1), 15331. https://doi.org/10.1038/s41598-019-51857-8

Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (2025). https://www.basel.int/ Accessed: 12 July 2025

Beggs, P.J., Clot, B., Sofiev, M. and Johnston, F.H. (2023). Climate change, airborne allergens, and three translational mitigation approaches. EBioMedicine 93, 104478. https://doi.org/10.1016/j.ebiom.2023.104478

Bernhard, G.H., Neale, R.E., Barnes, P.W., Neale, P.J., Zepp, R.G., Wilson, S.R. et al. (2020). Environmental effects of stratospheric ozone depletion, UV radiation and interactions with climate change. UNEP Environmental Effects Assessment Panel, update 2019. Photochemical & Photobiological Sciences 19(5), 542-584. https://doi.org/10.1039/d0pp90011g

Bernhard, G. and Stierle, S. (2020). Trends of UV radiation in Antarctica. Atmosphere 11(8). https://doi.org/10.3390/atmos11080795

Bessagnet, B., Belis, C.A., Crippa, M., Dentener, F., van Dingenen, R. and Thunis, P. (2024). Trends of methane emissions and their impact on ozone concentrations at the European and Global levels. Luxembourg: Publications Office of the European Union. https://data.europa.eu/doi/10.2760/376659

Bhattacharjee, A., Anadón, J.D., Lohman, D.J., Doleck, T., Lakhankar, T., Shrestha, B.B. et al. (2017). The Impact of Climate Change on Biodiversity in Nepal: Current Knowledge, Lacunae, and Opportunities. Climate 5(4), 80. https://www.mdpi.com/2225-1154/5/4/80

Blunden, J. and Boyer, T. (2022). State of the climate in 2021. Bulletin of the American Meteorological Society 103(8). https://doi.org/10.1175/2022BAMSStateoftheClimate.1

Bonilla, E.X., Mickley, L.J., Raheja, G., Eastham, S.D., Buonocore, J.J., Alencar, A. et al. (2023). Health impacts of smoke exposure in South America: increased risk for populations in the Amazonian Indigenous territories. Environmental Research: Health 1(2), 021007. https://dx.doi.org/10.1088/2752-5309/acb22b

Borchers Arriagada, N., Palmer, A.J., Bowman, D.M., Morgan, G.G., Jalaludin, B.B. and Johnston, F.H. (2020). Unprecedented smoke-related health burden associated with the 2019–20 bushfires in eastern Australia. Medical Journal of Australia 213(6), 282-283. https://doi.org/10.5694/mja2.50545

Borchers-Arriagada , N., Vander Hoorn, S., Cope, M., Morgan, G., Hanigan, I., Williamson, G. et al. (2024). The mortality burden attributable to wood heater smoke particulate matter ($PM_{2.5}$) in Australia. Science of The Total Environment 921, 171069. https://doi.org/10.1016/j.scitotenv.2024.171069

Bornman, J.F., Barnes, P.W., Robson, T.M., Robinson, S.A., Jansen, M.A.K., Ballaré, C.L. et al. (2019). Linkages between stratospheric ozone, UV radiation and climate change and their implications for terrestrial ecosystems. Photochemical & Photobiological Sciences 18(3), 681-716. https://doi.org/10.1039/c8pp90061b

Bourke, S., Wright, A., Guthrie, J., Russell, L., Dunbar, T. and Lovett, R. (2018). Evidence review of Indigenous culture for health and wellbeing. The International Journal of Health, Wellness, and Society 8(4), 11-27. https://doi.org/10.18848/2156-8960/CGP/v08i04/11-27

Bowman, D.M.J.S., Kolden, C.A., Abatzoglou, J.T., Johnston, F.H., van der Werf, G.R. and Flannigan, M. (2020). Vegetation fires in the Anthropocene. Nature Reviews Earth & Environment 1(10), 500-515. https://doi.org/10.1038/s43017-020-0085-3

Brienen, R.J.W., Phillips, O.L., Feldpausch, T.R., Gloor, E., Baker, T.R., Lloyd, J. et al. (2015). Long-term decline of the Amazon carbon sink. Nature 519(7543), 344-348. https://doi.org/10.1038/nature14283

Bun, R., Marland, G., Oda, T., See, L., Puliafito, E., Nahorski, Z. et al. (2024). Tracking unaccounted greenhouse gas emissions due to the war in Ukraine since 2022. Science of The Total Environment 914, 169879. https://doi.org/10.1016/j.scitotenv.2024.169879

Burke, M., Childs, M.L., de la Cuesta, B., Qiu, M., Li, J., Gould, C.F. et al. (2023). The contribution of wildfire to PM2.5 trends in the USA. Nature 622(7984), 761-766. https://doi.org/10.1038/s41586-023-06522-6

Burton, C., Ciavarella, A., Kelley, D.I., Hartley, A.J., McCarthy, M., New, S. et al. (2025). Very high fire danger in UK in 2022 at least 6 times more likely due to human-caused climate change. Environmental Research Letters 20(4), 044003. https://doi.org/10.1088/1748-9326/adb764

Butt, E.W., Baker, J.C.A., Bezerra, F.G.S., von Randow, C., Aguiar, A.P.D. and Spracklen, D.V. (2023). Amazon deforestation causes strong regional warming. Proceedings of the National Academy of Sciences 120(45), e2309123120. https://doi.org/10.1073/pnas.2309123120

Butt, E.W., Conibear, L., Knote, C. and Spracklen, D.V. (2021). Large air quality and public health impacts due to Amazonian deforestation fires in 2019. Geohealth 5(7), e2021GH000429. https://doi.org/10.1029/2021GH000429.

Byrne, B., Liu, J., Bowman, K.W., Pascolini-Campbell, M., Chatterjee, A., Pandey, S. et al. (2024). Carbon emissions from the 2023 Canadian wildfires. Nature 633(8031), 835-839. https://doi.org/10.1038/s41586-024-07878-z

Byun, G., Choi, Y., Foo, D., Stewart, R., Song, Y., Son, J.-Y. et al. (2024). Effects of ambient temperature on mental and neurological conditions in older adults: A systematic review and meta-analysis. Environment International 194, 109166. https://doi.org/10.1016/j.envint.2024.109166

Caminade, C., McIntyre, K.M. and Jones, A.E. (2019). Impact of recent and future climate change on vector-borne diseases. Annals of the New York Academy of Sciences 1436(1), 157-173. https://doi.org/10.1111/nyas.13950

Campbell-Lendrum, D. and Prüss-Ustün, A. (2019). Climate change, air pollution and noncommunicable diseases. Bulletin of the World Health Organization 97(2), 160-161. https://pmc.ncbi.nlm.nih.gov/articles/PMC6357572/

Caretta, M.A., Mukherji, A., Arfanuzzaman, M., Betts, R.A., Gelfan, A., Hirabayashi, Y. et al. (2022). Water. In Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría et al. (eds.). Cambridge University Press. chapter 4. https://doi.org/10.1017/9781009325844.006

Casey, J.A., Kioumourtzoglou, M.A., Padula, A., González, D.J.X., Elser, H., Aguilera, R. et al. (2024). Measuring long-term exposure to wildfire PM(2.5) in California: Time-varying inequities in environmental burden. Proceedings of the National Academy of Sciences of the United States of America 121(8), e2306729121. https://doi.org/10.1073/pnas.2306729121

Catacora-Vargas, G., Piepenstock, A., Sotomayor, C., Cuentas, D., Cruz, A. and Delgado, F. (2017). Del conocimiento indígena y campesino a la regulación nacional: breve reseña de la historia de la agroecología en Bolivia. Agroecología 10(2), 85-92. https://revistas.um.es/agroecologia/article/view/300851

Chang, A.Y., Tan, A.X., Nadeau, K.C. and Odden, M.C. (2022). Aging Hearts in a Hotter, More Turbulent World: The Impacts of Climate Change on the Cardiovascular Health of Older Adults. Current Cardiology Reports 24(6), 749-760. https://doi.org/10.1136/bmj.m3811

Chari, T. (2020). Harnessing folk media for effective environmental communication: The case of biomass burning in Sub-Saharan Africa. In Biomass Burning in Sub-Saharan Africa: Chemical Issues and Action Outreach. Mammino, L. (ed.). Dordrecht: Springer Netherlands. 107-119. https://doi.org/10.1007/978-94-007-0808-2_9

Chaston, T.B., Knibbs, L.D., Morgan, G., Jalaludin, B., Broome, R., Dennekamp, M. et al. (2024). Air pollution mortality benefits of sustained COVID-19 mobility restrictions in Australian cities. Public Health 226, 152-156. https://doi.org/10.1016/j.puhe.2023.10.050

Chen, B., Chen, L., Huang, B., Michishita, R. and Xu, B. (2018). Dynamic monitoring of the Poyang Lake wetland by integrating Landsat and MODIS observations. ISPRS Journal of Photogrammetry and Remote Sensing 139, 75-87. https://doi.org/10.1016/j.isprsjprs.2018.02.021

Chen, C.-Y., Chen, S.-Y. and Liao, C.-M. (2025). Regional and population-scale trends in human inhalation exposure to airborne microplastics: Implications for health risk assessment. Environmental Pollution 371, 125950. https://doi.org/10.1016/j.envpol.2025.125950

Chen, W., Lu, X., Yuan, D., Chen, Y., Li, Z., Huang, Y. et al. (2023). Global $PM_{(2.5)}$ prediction and associated mortality to 2100 under different climate change scenarios. Environmental Science & Technology 57(27), 10039-10052. https://doi.org/10.1021/acs.est.3c03804

Chersich, M.F., Pham, M.D., Areal, A., Haghighi, M.M., Manyuchi, A., Swift, C.P. et al. (2020). Associations between high temperatures in pregnancy and risk of preterm birth, low birth weight, and stillbirths: systematic review and meta-analysis. British Medical Journal 371, m3811. https://doi.org/10.1136/bmj.m3811

Chuvieco, E., Pettinari, M.L., Koutsias, N., Forkel, M., Hantson, S. and Turco, M. (2021). Human and climate drivers of global biomass burning variability. Science of The Total Environment 779, 146361. https://doi.org/10.1016/j.scitotenv.2021.146361

Conversation Media Group (2023). Indigenous rangers are burning the desert the right way – to stop the wrong kind of intense fires from raging. https://theconversation.com/indigenous-rangers-are-burning-the-desert-the-right-way-to-stop-the-wrong-kind-of-intense-fires-from-raging-211900 (Accessed: 25 October 2024)

Cooper, O.R., Chang, K.-L., Bates, K., Brown, S.S., Chace, W.S., Coggon, M.M. et al. (2024). Early season 2023 wildfires generated record-breaking surface ozone anomalies across the U.S. upper Midwest. Geophysical Research Letters 51(22), e2024GL111481. https://doi.org/10.1029/2024GL111481

Crisp, D., Dolman, H., Tanhua, T., McKinley, G.A., Hauck, J., Bastos, A. et al. (2022). How well do we understand the land-ocean-atmosphere carbon cycle? Reviews of Geophysics 60(2), e2021RG000736. https://doi.org/10.1029/2021RG000736

Curran, J.C. and Curran, S.A. (2025). Natural sequestration of carbon dioxide is in decline: Climate change will accelerate. Weather 80(3), 85-87. https://doi.org/10.1002/wea.7668

Curtis, E., Jones, R., Tipene-Leach, D., Walker, C., Loring, B., Paine, S.J. et al. (2019). Why cultural safety rather than cultural competency is required to achieve health equity: A literature review and recommended definition. International Journal for Equity in Health 18(1), 174. https://doi.org/10.1186/s12939-019-1082-3

Dabengwa, A.N., Archibald Sally., Finch Jemma., Scott Louis., Gillson Lindsey. and and Bond, W.J. (2022). Sedimentary charcoal studies from southern Africa's grassy biomes: a potential resource for informing the management of fires and ecosystems. African Journal of Range & Forage Science 39(1), 27-43. https://doi.org/10.2989/10220119.2021.2016965

D'Amato, G., Chong-Neto, H.J., Monge Ortega, O.P., Vitale, C., Ansotegui, I., Rosario, N. et al. (2020). The effects of climate change on respiratory allergy and asthma induced by pollen and mold allergens. Allergy 75(9), 2219-2228. https://doi.org/10.1111/all.14476

Dai, Q., Hou, L., Liu, B., Zhang, Y., Song, C., Shi, Z. et al. (2021). Spring festival and COVID-19 lockdown: Disentangling PM sources in major Chinese cities. Geophysical Research Letters 48(11), e2021GL093403. https://doi.org/10.1029/2021GL093403

Delgado-Saborit, J.M., Guercio, V., Gowers, A.M., Shaddick, G., Fox, N.C. and Love, S. (2021). A critical review of the epidemiological evidence of effects of air pollution on dementia, cognitive function and cognitive decline in adult population. Science of The Total Environment 757, 143734. https://doi.org/10.1016/j.scitotenv.2020.143734

deSouza, P.N., Hammer, M., Anthamatten, P., Kinney, P.L., Kim, R., Subramanian, S.V. et al. (2022). Impact of air pollution on stunting among children in Africa. Environmental Health 21(1), 128. https://doi.org/10.1186/s12940-022-00943-y

Dhimal, M., Kramer, I.M., Phuyal, P., Budhathoki, S.S., Hartke, J., Ahrens, B. et al. (2021). Climate change and its association with the expansion of vectors and vector-borne diseases in the Hindu Kush Himalayan region: A systematic synthesis of the literature. Advances in Climate Change Research 12(3), 421-429. https://doi.org/10.1016/j.accre.2021.05.003

Dhomse, S.S., Feng, W., Montzka, S.A., Hossaini, R., Keeble, J., Pyle, J.A. et al. (2019). Delay in recovery of the Antarctic ozone hole from unexpected CFC-11 emissions. Nature Communications 10(1), 5781. https://doi.org/10.1038/s41467-019-13717-x

Douville, H., K. Raghavan, J. Renwick, R.P. Allan, P.A. Arias, M. Barlow et al. (2023). Water cycle changes. In Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Change, I.P.o.C. (ed.). Cambridge: Cambridge University Press. chapter 8. 1055-1210. https://www.cambridge.org/core/product/1E7F2B90411645E36048670B826F131A

Duveiller, G., Hooker, J. and Cescatti, A. (2018). The mark of vegetation change on Earth's surface energy balance. Nature Communications 9(1), 679. https://doi.org/10.1038/s41467-017-02810-8

Edwards, P., Juhola, S., Saxena, P., Balag'kutu, T., Bastos, A., Capon, A. et al. (2024). Towards Sustainable Transformation: Research Priorities in Climate Change and Biodiversity. European Union. https://pure.iiasa.ac.at/id/eprint/19798/

El Khayat, M., Halwani, D.A., Hneiny, L., Alameddine, I., Haidar, M.A. and Habib, R.R. (2022). Impacts of Climate Change and Heat Stress on Farmworkers' Health: A Scoping Review. Frontiers in Public Health 10, 782811. https://doi.org/10.3389/fpubh.2022.782811

El-Juhany, L., Ahmad, I., Baig, M.B., Nawaz, M.F., Asif, M., Rashid, M.H.U. et al. (2022). Fostering the sustainable forest management in Saudi Arabia from resilience and mitigation perspectives. In The Food Security, Biodiversity, and Climate Nexus. Behnassi, M., Gupta, H., Barjees Baig, M. and Noorka, I.R. (eds.). Cham: Springer International Publishing. 287-308. https://doi.org/10.1007/978-3-031-12586-7_15

Elser, H., Frankland, T.B., Chen, C., Tartof, S.Y., Mayeda, E.R., Lee, G.S. et al. (2025). Wildfire smoke exposure and incident dementia. JAMA Neurology 82(1), 40-48. https://doi.org/10.1001/jamaneurol.2024.4058

Espinoza, J.-C., Jimenez, J.C., Marengo, J.A., Schongart, J., Ronchail, J., Lavado-Casimiro, W. et al. (2024). The new record of drought and warmth in the Amazon in 2023 related to regional and global climatic features. Scientific Reports 14(1), 8107. https://doi.org/10.1038/s41598-024-58782-5

Etzold, S., Ferretti, M., Reinds, G.J., Solberg, S., Gessler, A., Waldner, P. et al. (2020). Nitrogen deposition is the most important environmental driver of growth of pure, even-aged and managed European forests. Forest Ecology and Management 458, 117762. https://doi.org/10.1016/j.foreco.2019.117762

European Environment Agency (2022). Emissions of the main air pollutants in Europe. https://www.eea.europa.eu/en/analysis/indicators/emissions-of-the-main-air Accessed: 14 May 2025

European Environment Agency (2023a). Air quality in Europe 2022. https://www.eea.europa.eu/publications/air-quality-in-europe-2022/ Accessed: 1 April 2025

European Environment Agency (2023b). Methane emissions in the EU: The key to immediate action on climate change. European Environment Agency. https://www.eea.europa.eu/publications/methane-emissions-in-the-eu Accessed: 31 March 2025

Evan, S., Brioude, J., Rosenlof, K.H., Gao, R.-S., Portmann, R.W., Zhu, Y. et al. Rapid ozone depletion after humidification of the stratosphere by the Hunga Tonga Eruption. Science 382(6668), eadg2551. https://doi.org/10.1126/science.adg2551

Eyring, V., Mishra, V., Griffith, G.P., Chen, L., Keenan, T., Turetsky, M.R. et al. (2021). Reflections and projections on a decade of climate science. Nature Climate Change 11(4), 279-285. https://doi.org/10.1038/s41558-021-01020-x

Feingold, B.J., Berky, A., Hsu-Kim, H., Rojas Jurado, E. and Pan, W.K. (2020). Population-based dietary exposure to mercury through fish consumption in the Southern Peruvian Amazon. Environmental Research 183, 108720. https://doi.org/10.1016/j.envres.2019.108720

Fernández-Llamazares, Á., Garteizgogeascoa, M., Basu, N., Brondizio, E.S., Cabeza, M., Martínez-Alier, J. et al. (2020). A state-of-the-art review of Indigenous Peoples and environmental pollution. Integrated Environmental Assessment and Management 16(3), 324-341. https://doi.org/10.1002/ieam.4239

Fioletov, V.E., McLinden, C.A., Griffin, D., Abboud, I., Krotkov, N., Leonard, P.J.T. et al. (2023). Version 2 of the global catalogue of large anthropogenic and volcanic SO_2 sources and emissions derived from satellite measurements. Earth Systems Science Data 15(1), 75-93. https://essd.copernicus.org/articles/15/75/2023/

Flores, B.M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R.A. et al. (2024). Critical transitions in the Amazon forest system. Nature 626(7999), 555-564. https://doi.org/10.1038/s41586-023-06970-0

Food and Agriculture Organization of the United Nations (2015). Climate Change and Food Security: Risks and Responses. https://openknowledge.fao.org/server/api/core/bitstreams/a4fd8ac5-4582-4a66-91b0-55abf642a400/content

Ford, J.D., Berrang-Ford, L., King, M. and Furgal, C. (2010). Vulnerability of Aboriginal health systems in Canada to climate change. Global Environmental Change 20(4), 668-680. https://doi.org/10.1016/j.gloenvcha.2010.05.003

Ford, J.D., King, N., Galappaththi, E.K., Pearce, T., McDowell, G. and Harper, S.L. (2020). The resilience of Indigenous Peoples to environmental change. One Earth 2(6), 532-543. https://doi.org/10.1016/j.oneear.2020.05.014

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D. et al. (2021). The earth's energy budget, climate feedbacks, and climate sensitivity. In Climate Change 2021: The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (eds.). Intergovernmental Panel on Climate Change. chapter 7. 923–1054. https://doi.org/10.1017/9781009157896.009

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.L., Frame, G. et al. (2023a). The earth's energy budget, climate feedbacks and climate sensitivity. In Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate, C. (ed.). Cambridge: Cambridge University Press. chapter 7. 923-1054. https://www.cambridge.org/core/product/AE57C97E588FF3060C7C7E47DD4F3C6E

Forster, P.M., Smith, C.J., Walsh, T., Lamb, W.F., Lamboll, R., Hauser, M. et al. (2023b). Indicators of global climate change 2022: Annual update of large-scale indicators of the state of the climate system and human influence. Earth System Science Data 15(6), 2295-2327. https://doi.org/10.5194/essd-15-2295-2023

Forster, P.M., Smith, C., Walsh, T., Lamb, W.F., Lamboll, R., Hall, B. et al. (2024). Indicators of Global Climate Change 2023: Annual update of key indicators of the state of the climate system and human influence. Earth System Science Data 16(6), 2625-2658. https://doi.org/10.5194/essd-16-2625-2024

Fowler, D., Brimblecombe, P., Burrows, J., Heal, M.R., Grennfelt, P., Stevenson, D.S. et al. (2020). A chronology of global air quality. Philosophical Transactions: Mathematical, Physical and Engineering Sciences 378(2183), 20190314. https://doi.org/10.1098/rsta.2019.0314

Fraser-McDonald, A., Boardman, C., Gladding, T., Burnley, S. and Gauci, V. (2022) Methane emissions from forested closed landfill sites: Variations between tree species and landfill management practices. Science of The Total Environment, 838,156019, https://doi.org/10.1016/j.scitotenv.2022.156019

Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Hauck, J., Olsen, A. et al. (2020). Global Carbon Budget 2020. Earth System Science Data 12(4), 3269-3340. https://essd.copernicus.org/articles/12/3269/2020/

Fuentealba, M., Bahamóndez, C., Sarricolea, P., Meseguer-Ruiz, O. and Latorre, C. (2021). The 2010–2020 'megadrought' drives reduction in lake surface area in the Andes of central Chile (32º - 36ºS). Journal of Hydrology: Regional Studies 38, 100952. https://doi.org/10.1016/j.ejrh.2021.100952

Fuller, R., Landrigan, P.J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M. et al. (2022). Pollution and health: A progress update. Lancet Planet Health 6(6), e535-e547. https://doi.org/10.1016/S2542-5196(22)00090-0

Fundación Xavier Albó; Centro de Investigación y Promoción del Campesinado (CIPCA). (2017). Agricultura sostenible en el municipio de Anzaldo: beneficios de la agroecología en Bolivia. La Paz: Fundación Xavier Albó - CIPCA; 2017. Disponible en: https://alianzaagroecologia.redelivre.org.br/files/2017/06/Estudio-de-Caso-2.-Agricultura-sostenible-en-Anzaldo.pdf

Gamble, J.L., Balbus, J., M. Berger., K. Bouye, V. Campbell, K. Chief et al. (2016). Populations of concern. In The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. Washington, DC: U.S. Global Change Research Program. chapter 9. 247–286. http://dx.doi.org/10.7930/J0Q81B0T

Garcia, L.C., Szabo, J.K., de Oliveira Roque, F., de Matos Martins Pereira, A., Nunes da Cunha, C., Damasceno-Júnior, G.A. et al. (2021). Record-breaking wildfires in the world's largest continuous tropical wetland: Integrative fire management is urgently needed for both biodiversity and humans. Journal of Environmental Management 293, 112870. https://doi.org/10.1016/j.jenvman.2021.112870

Gasparrini, A., Guo, Y., Sera, F., Vicedo-Cabrera, A.M., Huber, V., Tong, S. et al. (2017). Projections of temperature-related excess mortality under climate change scenarios. Lancet Planet Health 1(9), e360-e367. https://doi.org/10.1016/S2542-5196(17)30156-0

GBD 2019 Diabetes and Air Pollution Collaborators (2022). Estimates, trends, and drivers of the global burden of type 2 diabetes attributable to $PM_{(2.5)}$ air pollution, 1990-2019: An analysis of data from the Global Burden of Disease Study 2019. Lancet Planet Health 6(7), e586-e600. https://doi.org/10.1016/S2542-5196(22)00122-X

GBD 2021 Risk Factors Collaborators (2024). Global burden and strength of evidence for 88 risk factors in 204 countries and 811 subnational locations, 1990-2021: A systematic analysis for the Global Burden of Disease Study 2021. Lancet 403(10440), 2162-2203. https://doi.org/10.1016/s0140-6736(24)00933-4

Gettelman, A., Christensen, M.W., Diamond, M.S., Gryspeerdt, E., Manshausen, P., Stier, P. et al. (2024). Has reducing ship emissions brought forward global warming? Geophysical Research Letters 51(15), e2024GL109077. https://doi.org/10.1029/2024GL109077

Global Framework on Chemicals (2025). https://www.chemicalsframework.org/ Accessed: 12 July 2025

Global Science-Policy Panel on Chemicals, Waste, and Pollution (2025). https://www.unep.org/ietc/news/story/countries-establish-new-global-science-policy-panel-chemicals-waste-and-pollution Accessed: 12 July 2025

Government, P. (2022). Proportion of population using solid fuels for cooking, broken down by area. National Statistics Institute https://estadisticasambientales.ine.gov.py/detalle.php?id=113 Accessed: 3 April 2025)

Government of India (2024). Economic Survey 2023-24. Ministry of Finance. Government of India. New Delhi. https://www.thehinducentre.com/resources/68435569-Economic-Survey-Complete-PDF_compressed.pdf

Griffiths, S.D., Entwistle, J.A., Kelly, F.J. and Deary, M.E. (2022). Characterising the ground level concentrations of harmful organic and inorganic substances released during major industrial fires, and implications for human health. Environment International 162, 107152. https://doi.org/10.1016/j.envint.2022.107152

Grillakis, M., Voulgarakis, A., Rovithakis, A., Seiradakis, K.D., Koutroulis, A., Field, R.D. et al. (2022). Climate drivers of global wildfire burned area. Environmental Research Letters 17(4), 045021. https://dx.doi.org/10.1088/1748-9326/ac5fa1

Grogan, L.F., Humphries, J.E., Robert, J., Lanctôt, C.M., Nock, C.J., Newell, D.A. et al. (2020). Immunological Aspects of Chytridiomycosis. Journal of Fungi (Basel) 6(4). https://pubmed.ncbi.nlm.nih.gov/32288342/

Hamid, M., khuroo, A.A., Charles, B., Ahmad, R., Singh, C.P. and Aravind, N.A. (2018). Impact of climate change on the distribution range and niche dynamics of Himalayan birch, a typical treeline species in Himalayas. Biodiversity Conservation(8–9), 2345–2370. https://www.springerprofessional.de/en/impact-of-climate-change-on-the-distribution-range-and-niche-dyn/16163198

Han, Q., Sun, S., Liu, Z., Xu, W. and Shi, P. (2022). Accelerated exacerbation of global extreme heatwaves under warming scenarios. International Journal of Climatology 42(11), 5430-5441. https://doi.org/10.1002/joc.7541

Handa, I.T., Aerts, R., Berendse, F., Berg, M.P., Bruder, A., Butenschoen, O. et al. (2014). Consequences of biodiversity loss for litter decomposition across biomes. Nature 509(7499), 218-221. https://doi.org/10.1038/nature13247

Hansen, J.E., Sato, M., Simons, L., Nazarenko, L.S., Sangha, I., Kharecha, P. et al. (2023). Global warming in the pipeline. Oxford Open Climate Change 3(1), kgad008. https://doi.org/10.1093/oxfclm/kgad008

Hansen, J.E., Kharecha, P., Sato, M., Tselioudis, G., Kelly, J., Bauer, S.E. et al. (2025). Global warming has accelerated: Are the United Nations and the public well-informed? Environment: Science and Policy for Sustainable Development 67(1), 6-44. https://doi.org/10.1080/00139157.2025.2434494

Harrison, S., Franklin, J., Hernandez, R.R., Ikegami, M., Safford, H.D. and Thorne, J.H. (2024). Climate change and California's terrestrial biodiversity. Proceedings of the National Academy of Sciences 121(32), e2310074121. https://doi.org/10.1073/pnas.2310074121

He, T., Ding, W., Cheng, X., Cai, Y., Zhang, Y., Xia, H. et al. (2024). Meta-analysis shows the impacts of ecological restoration on greenhouse gas emissions. Nature Communications 15(1), 2668. https://doi.org/10.1038/s41467-024-46991-5

Health Effects Institute (2024). State of Global Air 2024: A Special Report on Global Exposure to Air Pollution and its Health Impacts, with a Focus on Children's Health. Special Report. Boston, MA: Health Effects Institute. https://www.healthdata.org/sites/default/files/2024-06/soga-2024-report.pdf

Heaviside, C., Macintyre, H. and Vardoulakis, S. (2017). The urban heat island: Implications for health in a changing environment. Current Environmental Health Reports 4(3), 296-305. https://doi.org/10.1007/s40572-017-0150-3.

Hoffmann, B., Boogaard, H., de Nazelle, A., Andersen, Z.J., Abramson, M., Brauer, M. et al. (2021). WHO Air Quality Guidelines 2021-Aiming for Healthier Air for all: A Joint Statement by Medical, Public Health, Scientific Societies and Patient Representative Organisations. International Journal of Public Health 66, 1604465. https://doi.org/10.3389/ijph.2021.1604465

Holm, S.M., Miller, M.D. and Balmes, J.R. (2021). Health effects of wildfire smoke in children and public health tools: A narrative review. Journal of Exposure Science & Environmental Epidemiology 31(1), 1-20. https://doi.org/10.1038/s41370-020-00267-4

Houghton, R.A. (2012). Carbon emissions and the drivers of deforestation and forest degradation in the tropics. Current opinion in environmental sustainability 4(6), 597-603. https://doi.org/10.1016/j.cosust.2012.06.006

Hu, X., Yao, B. and Fang, X. (2022). Anthropogenic emissions of ozone-depleting substance CH_3Cl during 2000–2020 in China. Environmental Pollution 310, 119903. https://doi.org/10.1016/j.envpol.2022.119903

Huang, H., Rodriguez-Iturbe, I. and Calabrese, S. (2024). Widespread temporal and spatial variability in net ecosystem productivity under climate change. One Earth 7(3), 473-482. https://doi.org/10.1016/j.oneear.2024.01.008

Hubau, W., Lewis, S.L., Phillips, O.L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A. et al. (2020). Asynchronous carbon sink saturation in African and Amazonian tropical forests. Nature 579(7797), 80-87. https://doi.org/10.1038/s41586-020-2035-0

Hugelius, G., Ramage, J., Burke, E., Chatterjee, A., Smallman, T.L., Aalto, T. et al. (2024). Permafrost region greenhouse gas budgets suggest a weak CO_2 sink and CH_4 and N_2O sources, but magnitudes differ between top-down and bottom-up methods. Global Biogeochemical Cycles 38(10), e2023GB007969. https://doi.org/10.1029/2023GB007969

Hughes, K.A. and Convey, P. (2022). Non-native Species in Antarctic Terrestrial Environments: How Climate Change and Increasing Human Activity Are Compounding the Threat of Invasion. CABI, 95–118. https://doi.org/10.1079/9781800621459.0006

Humphrey, G.J., Gillson, L. and Ziervogel, G. (2021). How changing fire management policies affect fire seasonality and livelihoods. Ambio 50(2), 475-491. https://doi.org/10.1007/s13280-020-01351-7

Intergovernmental Panel on Climate Change (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (eds.). Cambridge. https://dx.doi.org/10.1017/9781009157896

Intergovernmental Panel on Climate Change (2022). Summary for Policymakers. In Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Pörtner, H.O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A. et al. (eds.). Cambridge: Cambridge University Press. 3–33. https://doi.org/10.1017/9781009325844.001

Intergovernmental Panel on Climate Change (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. H. Lee and J. Romero (eds.). Geneva. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf

International Energy Agency (2022). Global Energy Review: CO_2 Emissions in 2021. Paris. https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2

Jones, M.E., LaCroix, R.E., Zeigler, J., Ying, S.C., Nico, P.S. and Keiluweit, M. (2020). Enzymes, Manganese, or Iron? Drivers of oxidative organic matter decomposition in soils. Environmental Science & Technology 54(21), 14114-14123. https://doi.org/10.1021/acs.est.0c04212

Jones, M.W., Veraverbeke, S., Andela, N., Doerr, S.H., Kolden, C., Mataveli, G. et al. (2024). Global rise in forest fire emissions linked to climate change in the extratropics. Science 386(6719), eadl5889. https://doi.org/10.1126/science.adl5889

Joos, F., Lienert, S. and Zaehle, S. (2024). No increase is detected and modeled for the seasonal cycle amplitude of δ13C of atmospheric carbon dioxide. EGUsphere 2024, 1-33. https://egusphere.copernicus.org/preprints/2024/egusphere-2024-1972/

Kamurasi, I., Bartlett, K., Holyk, T., Rathburn, B., Moecke, D.P., Winter, A. et al. (2024). Prevalence of indoor air pollutants from First Nation homes in North Central British Columbia, Canada. International Journal of Circumpolar Health 83(1), 2389612. https://doi.org/10.1080/22423982.2024.2389612

Karlsson, M., Alfredsson Eva. and and Westling, N. (2020). Climate policy co-benefits: A review. Climate Policy 20(3), 292-316. https://doi.org/10.1080/14693062.2020.1724070

Ke, P., Ciais, P., Sitch, S., Li, W., Bastos, A., Liu, Z. et al. (2024). Low latency carbon budget analysis reveals a large decline of the land carbon sink in 2023. National Science Review 11(12). https://doi.org/10.1093/nsr/nwae367

Keenan, T.F., Hollinger, D.Y., Bohrer, G., Dragoni, D., Munger, J.W., Schmid, H.P. et al. (2013). Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise. Nature 499(7458), 324-327. https://doi.org/10.1038/nature12291

Khavari, B., Ramirez, C., Jeuland, M. and Fuso Nerini, F. (2023). A geospatial approach to understanding clean cooking challenges in sub-Saharan Africa. Nature Sustainability 6(4), 447-457. https://doi.org/10.1038/s41893-022-01039-8

Kinnunen, A., Hautamäki, R., Junnila, J.B., Jalkanen, J., Järvi, L., Kulmala, L., Lampinen, J., Havu, M., Junnila, S. and Raymond, C. (2025) Assessing the implications of EU Nature Restoration Law targets from carbon sequestration and biodiversity perspectives in a high-green urban environment. npj Urban Sustainability, 5(1), p.20.

Kipp, A., Cunsolo, A., Vodden, K., King, N., Manners, S. and Harper, S.L. (2019). At-a-glance - Climate change impacts on health and wellbeing in rural and remote regions across Canada: a synthesis of the literature. Health Promotion and Chronic Disease Prevention in Canada 39(4), 122-126. https://pmc.ncbi.nlm.nih.gov/articles/PMC6553582/

Knibb-Lamouche, J. (2013). Leveraging Culture to Address Health Inequalities: Examples from Native Communities: Workshop Summary. United States National Academies Press https://www.ncbi.nlm.nih.gov/books/NBK201298/ Accessed: 04 February 2024

Kobziar, L.N., Vuono, D., Moore, R., Christner, B.C., Dean, T., Betancourt, D. et al. (2022). Wildland fire smoke alters the composition, diversity, and potential atmospheric function of microbial life in the aerobiome. ISME Communications 2(1), 8. https://doi.org/10.1038/s43705-022-00089-5

Kramer, R.J., He, H., Soden, B.J., Oreopoulos, L., Myhre, G., Forster, P.M. et al. (2021). Observational evidence of increasing global radiative forcing. Geophysical Research Letters 48(7), e2020GL091585. https://doi.org/10.1029/2020GL091585

Krecl, P. et al. (2020) Open waste burning causes fast and sharp changes in particulate concentrations in peripheral neighborhoods. The Science of the Total Environment, 765, p. 142736. https://doi.org/10.1016/j.scitotenv.2020.142736

Kreider, M.R., Higuera, P.E., Parks, S.A., Rice, W.L., White, N. and Larson, A.J. (2024). Fire suppression makes wildfires more severe and accentuates impacts of climate change and fuel accumulation. Nature Communications 15(1), 2412. https://doi.org/10.1038/s41467-024-46702-0

Kumar, S.S., Ananta, G.M. and Ashutosh, C.P. (2020). Mitigation of climate change through approached agriculture-soil carbon sequestration (A Review). Current Journal of Applied Science and Technology 39(33), 47-64. https://doi.org/10.9734/cjast/2020/v39i3331017

Ladstädter, F., Steiner, A.K. and Gleisner, H. (2023). Resolving the 21st century temperature trends of the upper troposphere–lower stratosphere with satellite observations. Scientific Reports 13(1), 1306. https://doi.org/10.1038/s41598-023-28222-x

Lan, X., K.W. Thoning and E.J. Dlugokencky (2022). Trends in globally-averaged CH_4, N_2O, and SF6 Determined from NOAA Global Monitoring Laboratory Measurements. https://doi.org/10.15138/P8XG-AA10

Lee, H. and Jaffe, D.A. (2024). Wildfire impacts on $O(_3)$ in the continental United States using $PM(_{2.5})$ and a generalized additive model (2018-2023). Environmental Science & Technology 58(33), 14764-14774. https://doi.org/10.1021/acs.est.4c05870

Lee, K.K., Bing, R., Kiang, J., Bashir, S., Spath, N., Stelzle, D. et al. (2020). Adverse health effects associated with household air pollution: A systematic review, meta-analysis, and burden estimation study. Lancet Global Health 8(11), e1427-e1434. https://doi.org/10.1016/S2214-109X(20)30343-0

Leihy, R.I., Peake, L., Clarke, D.A., Chown, S.L. and McGeoch, M.A. (2023). Introduced and invasive alien species of Antarctica and the Southern Ocean Islands. Scientific Data 10(1), 200. https://doi.org/10.1038/s41597-023-02113-2

Leite-Filho, A.T., de Sousa Pontes, V.Y. and Costa, M.H. (2019). Effects of deforestation on the onset of the rainy season and the duration of dry spells in Southern Amazonia. Journal of Geophysical Research: Atmospheres 124(10), 5268-5281. https://doi.org/10.1029/2018JD029537

Li, J., Carlson, B.E., Yung, Y.L., Lv, D., Hansen, J., Penner, J.E. et al. (2022). Scattering and absorbing aerosols in the climate system. Nature Reviews Earth & Environment 3(6), 363-379. https://doi.org/10.1038/s43017-022-00296-7

Li, K. and Chen, Y. (2023). Characterizing the indicator-based, day-and-night, and climate-based variations in response of surface urban heat island during heat wave across global 561 cities. Sustainable Cities and Society 99, 104877. https://doi.org/10.1016/j.scs.2023.104877

Li, T., Cohen, A.J., Krzyzanowski, M., Zhang, C., Gumy, S., Mudu, P. et al. (2025). Sand and dust storms: A growing global health threat calls for international health studies to support policy action. The Lancet Planetary Health 9(1), e34-e40. https://doi.org/10.1016/S2542-5196(24)00308-5

Li, W., Shao, L., Wang, W., Li, H., Wang, X., Li, Y. et al. (2020). Air quality improvement in response to intensified control strategies in Beijing during 2013–2019. Science of The Total Environment 744, 140776. https://doi.org/10.1016/j.scitotenv.2020.140776

Li , Y., Tang, Y., Wang, S., Toumi, R., Song, X. and Wang, Q. (2023). Recent increases in tropical cyclone rapid intensification events in global offshore regions. Nature Communications 14(1), 5167. https://doi.org/10.1038/s41467-023-40605-2

Libonati, R., DaCamara, C.C., Peres, L.F., de Carvalho, L.A.S. and Garcia, L.C. (2020). Rescue Brazil's burning Pantanal wetlands. Nature 588, 217-219. https://doi.org/10.1038/d41586-020-03464-1

Lickley, M., Fletcher, S., Rigby, M. and Solomon, S. (2021). Joint inference of CFC lifetimes and banks suggests previously unidentified emissions. Nature Communications 12(1), 2920. https://doi.org/10.1038/s41467-021-23229-2

Lickley, M., Solomon, S., Fletcher, S., Velders, G.J.M., Daniel, J., Rigby, M. et al. (2020). Quantifying contributions of chlorofluorocarbon banks to emissions and impacts on the ozone layer and climate. Nature Communications 11(1), 1380. https://doi.org/10.1038/s41467-020-15162-7

Lima, J.S., Lenoir, J. and Hylander, K. (2024). Potential migration pathways of broadleaved trees across the receding boreal biome under future climate change. Global Change Biology 30(8), e17471. https://doi.org/10.1111/gcb.17471

Liu, J., Varghese, B.M., Hansen, A., Xiang, J., Zhang, Y., Dear, K. et al. (2021). Is there an association between hot weather and poor mental health outcomes? A systematic review and meta-analysis. Environment International 153, 106533. https://doi.org/10.1016/j.envint.2021.106533

Liu, Z., Rogers, B.M., Keppel-Aleks, G., Helbig, M., Ballantyne, A.P., Kimball, J.S. et al. (2024). Seasonal CO_2 amplitude in northern high latitudes. Nature Reviews Earth & Environment 5(11), 802-817. https://doi.org/10.1038/s43017-024-00600-7

Lodh, A. and Haldar, S. (2024). Investigating the impact of tropical deforestation on Indian monsoon hydro-climate: a novel study using a regional climate model. Natural Hazards 120, 11399–11431. https://doi.org/10.1007/s11069-024-06615-z

Loring, P.A. and Gerlach, S.C. (2015). Searching for progress on food security in the North American North: A research synthesis and meta-analysis of the peer-reviewed literature. Arctic 68(3), 380-392. http://www.jstor.org/stable/43872256

Luo, Z., Luo, Y., Wang, G., Xia, J. and Peng, C. (2020). Warming-induced global soil carbon loss attenuated by downward carbon movement. Global Change Biology 26(12), 7242-7254. https://doi.org/10.1111/gcb.15370

Lüthi, S., Fairless, C., Fischer, E.M., Scovronick, N., Ben, A., Coelho, M.D.S.Z.S. et al. (2023). Rapid increase in the risk of heat-related mortality. Nature Communications 14(1), 4894. https://doi.org/10.1038/s41467-023-40599-x

Lwin, K.S., Tobias, A., Chua, P.L., Yuan, L., Thawonmas, R., Ith, S. et al. (2023). Effects of desert dust and sandstorms on human health: A scoping review. Geohealth 7(3), e2022GH000728. https://doi.org/10.1029/2022GH000728

MacVicar, S., Berrang-Ford, L., Harper, S., Huang, Y., Namanya Bambaiha, D. and Yang, S. (2017). Whether weather matters: Evidence of association between in utero meteorological exposures and foetal growth among Indigenous and non-Indigenous mothers in rural Uganda. PLoS One 12(6), e0179010. https://doi.org/10.1371/journal.pone.0179010

Maes, J., Bruzón, A.G., Barredo, J.I., Vallecillo, S., Vogt, P., Rivero, I.M. et al. (2023). Accounting for forest condition in Europe based on an international statistical standard. Nature Communications 14(1), 3723. https://doi.org/10.1038/s41467-023-39434-0

Maji, K.J., Namdeo, A., Bell, M., Goodman, P., Nagendra, S.M.S., Barnes, J.H. et al. (2021). Unprecedented reduction in air pollution and corresponding short-term premature mortality associated with COVID-19 lockdown in Delhi, India. Journal of the Air & Waste Management Association 71(9), 1085-1101. https://pubmed.ncbi.nlm.nih.gov/33764280/

Malashock, D.A., Delang, M.N., Becker, J.S., Serre, M.L., West, J.J., Chang, K.L. et al. (2022). Global trends in ozone concentration and attributable mortality for urban, peri-urban, and rural areas between 2000 and 2019: A modelling study. Lancet Planet Health 6(12), e958-e967. https://doi.org/10.1016/s2542-5196(22)00260-1

Malhi, Y., Swingland, I.R., Bettelheim, E.C., Grace, J., Prance, G.T., Saunders, L.S. et al. (2002). Forests, carbon and global climate. Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences 360(1797), 1567-1591. https://doi.org/10.1098/rsta.2002.1020

Mani, S., Agrawal, S., Jain, A. and Ganesan, K. (2021). State of Clean Cooking Energy Access in India: Insights from the India Residential Energy Survey (IRES) 2020. https://www.ceew.in/sites/default/files/ires-report-on-state-of-clean-cooking-energy-access-in-india.pdf

Manisalidis, I., Stavropoulou, E., Stavropoulos, A. and Bezirtzoglou, E. (2020). Environmental and health impacts of air pollution: A review. Frontiers in Public Health 8, 14. https://doi.org/10.3389/fpubh.2020.00014

Marengo, J.A., Cunha, A.P., Cuartas, L.A., Deusdará Leal, K.R., Broedel, E., Seluchi, M.E. et al. (2021). Extreme Drought in the Brazilian Pantanal in 2019–2020: Characterization, Causes, and Impacts. Frontiers in Water 3. https://doi.org/10.3389/frwa.2021.639204

Mataveli, G.A.V., de Oliveira, G., Seixas, H.T., Pereira, G., Stark, S.C., Gatti, L.V. et al. (2021). Relationship between biomass burning emissions and deforestation in Amazonia over the last two decades. Forests 12(9), 1217. https://doi.org/10.3390/f12091217

Matthews, V., Vine, K., Atkinson, A.-R., Longman, J., Lee, G.W., Vardoulakis, S. et al. (2023). Justice, culture, and relationships: Australian Indigenous prescription for planetary health. Science 381(6658), 636-641. https://doi.org/10.1126/science.adh9949

Mattila, T.J. (2024). The role of peatlands in carbon footprints of countries and products. Science of The Total Environment 947, 174552. https://doi.org/10.1016/j.scitotenv.2024.174552

Mbow, C., C. Rosenzweig, L.G. Barioni, T.G. Benton, M. Herrero, M. Krishnapillai et al. (2019). Food Security. In Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Intergovernmental Panel on Climate Change. chapter 5. https://www.ipcc.ch/srccl/chapter/chapter-5/

Mbuzi, V., Fulbrook, P. and Jessup, M. (2017). Indigenous Peoples' experiences and perceptions of hospitalisation for acute care: A metasynthesis of qualitative studies. International Journal of Nursing Studies 71, 39-49. https://doi.org/10.1016/j.ijnurstu.2017.03.003

McArdle, C.E., Dowling, T.C., Carey, K., DeVies, J., Johns, D., Gates, A.L. et al. (2023). Asthma-associated emergency department visits during the Canadian wildfire smoke episodes - United States, April- August 2023. Morbidity and Mortality Weekly Report 72(34), 926-932. http://dx.doi.org/10.15585/mmwr.mm7234a5

McKemey, M., Ens, E., Rangers, Y.M., Costello, O. and Reid, N. (2020). Indigenous Knowledge and seasonal calendar inform adaptive savanna burning in northern Australia. Sustainability 12(3), 995. https://www.mdpi.com/2071-1050/12/3/995

McKemey, M.B., Banbai Rangers., Ens, E.J., Hunter, J.T., Ridges, M., Costello, O. et al. (2021). Co-producing a fire and seasons calendar to support renewed Indigenous cultural fire management. Austral Ecology 46(7), 1011-1029. https://doi.org/10.1111/aec.13034

McNamara, K.E., Westoby, R. and Chandra, A. (2021). Exploring climate-driven non-economic loss and damage in the Pacific Islands. Current opinion in environmental sustainability 50, 1-11. https://doi.org/10.1016/j.cosust.2020.07.004

Meng, L., Liu, J., Tarasick, D.W., Randel, W.J., Steiner, A.K., Wilhelmsen, H. et al. (2021). Continuous rise of the tropopause in the Northern Hemisphere over 1980–2020. Science Advances 7(45), eabi8065. https://doi.org/doi:10.1126/sciadv.abi8065

Meng, X., Lu, B., Liu, C., Zhang, Z., Chen, J., Herrmann, H. et al. (2023). Abrupt exacerbation in air quality over Europe after the outbreak of Russia-Ukraine war. Environment International 178, 108120. https://doi.org/10.1016/j.envint.2023.108120

Miao, L., Li, S., Zhang, F., Chen, T., Shan, Y. and Zhang, Y. (2020). Future drought in the dry Lands of Asia Under the 1.5 and 2.0 °C warming scenarios. Earth's Future 8(6), e2019EF001337. https://doi.org/10.1029/2019EF001337

Middleton, J., Cunsolo, A., Jones-Bitton, A., Wright, C.J. and Harper, S.L. (2020). Indigenous mental health in a changing climate: A systematic scoping review of the global literature. Environmental Research Letters 15(5), 053001. https://dx.doi.org/10.1088/1748-9326/ab68a9

Miner, K.R., Turetsky, M.R., Malina, E., Bartsch, A., Tamminen, J., McGuire, A.D. et al. (2022). Permafrost carbon emissions in a changing Arctic. Nature Reviews Earth & Environment 3(1), 55-67. https://doi.org/10.1038/s43017-021-00230-3

Ministry of Environment Forest and Climate Change Government of the People's Republic of Bangladesh and GIZ (2018). Nationwide Climate Vulnerability Assessment in Bangladesh. https://moef.portal.gov.bd/sites/default/files/files/moef.portal.gov.bd/notices/d31d60fd_df55_4d75_bc22_1b0142fd9d3f/Draft%20NCVA.pdf

Mirón, I.J., Linares, C. and Díaz, J. (2023). The influence of climate change on food production and food safety. Environmental Research 216, 114674. https://doi.org/10.1016/j.envres.2022.114674

Mirzabaev, A., J. Wu, J. Evans, F. García-Oliva, I.A.G. Hussein, M.H. Iqbal et al. (2019). Desertification. In Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts et al. (eds.). chapter 3. 249-343. https://www.ipcc.ch/site/assets/uploads/sites/4/2019/11/06_Chapter-3.pdf

Molina, L.T., Retama, A. and Zavala, M. (2023). Diagnosis of Current Knowledge of the Scientific Bases for Air Quality Management in the Megalopolis. Boston; MA: Molina Center for Strategic Studies in Energy and the Environment https://www.gob.mx/cms/uploads/attachment/file/869816/Diagnostic_Report__full_version_.pdf

Monteleone, B., Borzí, I., Bonaccorso, B. and Martina, M. (2023). Quantifying crop vulnerability to weather-related extreme events and climate change through vulnerability curves. Natural Hazards 116(3), 2761-2796. https://doi.org/10.1007/s11069-022-05791-0

Morawska, L., Allen, J., Bahnfleth, W., Bennett, B., Bluyssen, P.M., Boerstra, A. et al. (2024). Mandating indoor air quality for public buildings. Science 383(6690), 1418-1420. https://doi.org/10.1126/science.adl0677

Mousavi, H., Moshir Panahi, D. and Kalantari, Z. (2024). Dust and climate interactions in the Middle East: Spatio-temporal analysis of aerosol optical depth and climatic variables. Science of The Total Environment 927, 172176. https://pubmed.ncbi.nlm.nih.gov/38575026/

Murphy, D.M., Abou-Ghanem, M., Cziczo, D.J., Froyd, K.D., Jacquot, J., Lawler, M.J. et al. (2023). Metals from spacecraft reentry in stratospheric aerosol particles. Proceedings of the National Academy of Sciences 120(43), e2313374120. https://doi.org/10.1073/pnas.2313374120

Natali, S.M., Holdren, J.P., Rogers, B.M., Treharne, R., Duffy, P.B., Pomerance, R. et al. (2021). Permafrost carbon feedbacks threaten global climate goals. Proceedings of the National Academy of Sciences of the United States of America 118(21). https://doi.org/10.1073/pnas.2100163118

National Aeronautics and Space Administration (2021). NASA helps map impact of COVID-19 lockdowns on harmful air pollution. https://www.nasa.gov/missions/aqua/nasa-helps-map-impact-of-covid-19-lockdowns-on-harmful-air-pollution/ Accessed: 25 October 2024

National Park Service (2018). Where does air pollution come from? National Park Service, https://www.nps.gov/subjects/air/sources.htm Accessed: 25 October 2024

Ndehedehe, C.E., Ferreira, V.G., Adeyeri, O.E., Correa, F.M., Usman, M., Oussou, F.E. et al. (2023). Global assessment of drought characteristics in the Anthropocene. Resources, Environment and Sustainability 12, 100105. https://doi.org/10.1016/j.resenv.2022.100105

Neale, R.E., Barnes, P.W., Robson, T.M., Neale, P.J., Williamson, C.E., Zepp, R.G. et al. (2021). Environmental effects of stratospheric ozone depletion, UV radiation, and interactions with climate change: UNEP Environmental Effects Assessment Panel, Update 2020. Photochemical & Photobiological Sciences 20(1), 1-67. https://doi.org/10.1007/s43630-020-00001-x

Neale, P.J., Williamson, C.E., Banaszak, A.T., Häder, D.P., Hylander, S., Ossola, R. et al. (2023). The response of aquatic ecosystems to the interactive effects of stratospheric ozone depletion, UV radiation, and climate change. Photochemical & Photobiological Sciences 22(5), 1093-1127. https://doi.org/10.1007/s43630-023-00370-z

Nedoluha, G.E., Gomez, R.M., Boyd, I., Neal, H., Allen, D.R., Lambert, A. et al. (2023). Mesospheric Water Vapor in 2022. Journal of Geophysical Research: Atmospheres 128(18), e2023JD039196. https://doi.org/10.1029/2023JD039196

Neimark, B., Otu-Larbi, F., Bigger, P. and Larbi, R. (2024). A Multitemporal Snapshot of Greenhouse Gas Emissions from the Israel-Gaza Conflict. http://dx.doi.org/10.2139/ssrn.4684768

Nikolakis, W., Roberts, E., Hotte, N. and Ross, R.M. (2020). Goal setting and Indigenous fire management: A holistic perspective. International Journal of Wildland Fire 29(11), 974-982. https://doi.org/10.1071/WF20007

Nikolakis, W.D. and Roberts, E. (2020). Indigenous fire management: A conceptual model from literature. Ecology and Society 25(4). https://www.ecologyandsociety.org/vol25/iss4/art11/

Nitzbon, J., Schneider von Deimling, T., Aliyeva, M., Chadburn, S.E., Grosse, G., Laboor, S. et al. (2024). No respite from permafrost-thaw impacts in the absence of a global tipping point. Nature Climate Change 14(6), 573-585. https://doi.org/10.1038/s41558-024-02011-4

Niu, Z., Habre, R., Chavez, T.A., Yang, T., Grubbs, B.H., Eckel, S.P. et al. (2022). Association between ambient air pollution and birth weight by maternal individual- and neighborhood-level stressors. JAMA Network Open 5(10), e2238174. https://doi.org/10.1001/jamanetworkopen.2022.38174

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F. and Erasmi, S. (2016). Greenhouse gas emissions from soils—A review. Geochemistry 76(3), 327-352. https://doi.org/10.1016/j.chemer.2016.04.002

Oki, T. and Kanae, S. (2006). Global hydrological cycles and world water resources. Science 313(5790), 1068-1072. https://doi.org/10.1126/science.1128845

O'Sharkey, K., Xu, Y., Cabison, J., Rosales, M., Yang, T., Chavez, T. et al. (2023). Effects of in-utero personal exposure to $PM_{2.5}$ sources and components on birthweight. Scientific Reports 13(1), 21987. https://doi.org/10.1038/s41598-023-48920-w

Oliveira, M.R., Ferreira, B.H.S., Souza, E.B., Lopes, A.A., Bolzan, F.P., Roque, F.O. et al. (2022). Indigenous brigades change the spatial patterns of wildfires, and the influence of climate on fire regimes. Journal of Applied Ecology 59(5), 1279-1290. https://doi.org/10.1111/1365-2664.14139

Oliveira, U., Soares-Filho, B., Rodrigues, H., Figueira, D., Gomes, L., Leles, W. et al. (2023). A near real-time web-system for predicting fire spread across the Cerrado biome. Scientific Reports 13(1), 4829. https://doi.org/10.1038/s41598-023-30560-9

Olson, D.M. and Metz, G.A.S. (2020). Climate change is a major stressor causing poor pregnancy outcomes and child development. F1000Res 9. https://doi.org/10.12688/f1000research.27157.1

Osman, A.I., Chen, L., Yang, M., Msigwa, G., Farghali, M., Fawzy, S. et al. (2023). Cost, environmental impact, and resilience of renewable energy under a changing climate: A review. Environmental Chemistry Letters 21(2), 741-764. https://doi.org/10.1007/s10311-022-01532-8

Oster, R.T., Grier, A., Lightning, R., Mayan, M.J. and Toth, E.L. (2014). Cultural continuity, traditional Indigenous language, and diabetes in Alberta First Nations: A mixed methods study. International Journal for Equity in Health 13, 92. https://doi.org/10.1186/s12939-014-0092-4

Pai, S.J., Carter, T.S., Heald, C.L. and Kroll, J.H. (2022). Updated World Health Organization air quality guidelines highlight the importance of non-anthropogenic PM ($_{2.5}$). Environmental Science & Technology Letters 9(6), 501-506. https://doi.org/10.1021/acs.estlett.2c00203

Pan, Y., Liu, X., Zhou, Z., et al. (2024) Carbon neutrality and clean air acts can enable China to meet the Minamata Convention goals with substantial cost savings. One Earth 7(3), 483-496. https://doi.org/10.1016/j.oneear.2024.02.006

Pande, C.B., Moharir, K.N., Varade, A.M., Abdo, H.G., Mulla, S. and Yaseen, Z.M. (2023). Intertwined impacts of urbanization and land cover change on urban climate and agriculture in Aurangabad city (MS), India using google earth engine platform. Journal of Cleaner Production 422, 138541. https://doi.org/10.1016/j.jclepro.2023.138541

Panzavolta, T., Bracalini, M., Benigno, A. and Moricca, S. (2021). Alien Invasive Pathogens and Pests Harming Trees, Forests, and Plantations: Pathways, Global Consequences and Management. Forests 12(10), 1364. https://doi.org/doi:10.3390/f12101364

Papadogeorgou, G., Kioumourtzoglou, M.-A., Braun, D. and Zanobetti, A. (2019). Low levels of air pollution and health: Effect estimates, methodological challenges, and future directions. Current Environmental Health Reports 6(3), 105-115. https://doi.org/10.1007/s40572-019-00235-7

Parker, E.R. (2021). The influence of climate change on skin cancer incidence - A review of the evidence. International Journal of Women's Dermatology 7(1), 17-27. https://doi.org/10.1016/j.ijwd.2020.07.003

Parkinson, S. and Cottrell, L. (2022). Estimating the Military's Global Greenhouse Gas Emissions. West Yorkshire, UK: Scientists for Global Responsibility (SGR). https://ceobs.org/wp-content/uploads/2022/11/SGR-CEOBS_Estimating_Global_MIlitary_GHG_Emissions.pdf

Parr, C.L., te Beest, M. and Stevens, N. (2024). Conflation of reforestation with restoration is widespread. Science 383(6684), 698-701. https://doi.org/10.1126/science.adj0899

Pasiecznik N. and Goldammer JG. (2022). Towards fire-smart landscapes. Tropical forest Issues 61. N., P. and JG., G. (eds.). Ede: Tropenbos International. https://doi.org/10.55515/DVRK2501

Pathak, G.S. et al. (2023) Plastic pollution and the open burning of plastic wastes. Global Environmental Change, 80, p. 102648. https://doi.org/10.1016/j.gloenvcha.2023.102648

Peralta, O., Ortínez-Alvarez, A., Torres-Jardón, R., Suárez-Lastra, M., Castro, T. and Ruíz-Suárez, L.G. (2021). Ozone over Mexico City during the COVID-19 pandemic. Science of The Total Environment 761, 143183. https://doi.org/10.1016/j.scitotenv.2020.143183

Peries, S.D., Sewwandi, M., Sandanayake, S., Kwon, H.-H. and Vithanage, M. (2024). Airborne transboundary microplastics–A Swirl around the globe. Environmental Pollution 353, 124080. https://doi.org/10.1016/j.envpol.2024.124080

Perkins-Kirkpatrick, S.E., Lewis, S.C. (2020) Increasing trends in regional heatwaves. Nat Commun 11, 3357. https://doi.org/10.1038/s41467-020-16970-7

Peters, G.P., Andrew, R.M., Canadell, J.G., Fuss, S., Jackson, R.B., Korsbakken, Jan I. et al. (2017). Key indicators to track current progress and future ambition of the Paris Agreement. Nature Climate Change 7(2), 118-122. https://doi.org/10.1038/nclimate3202

Phillips, O.L., Brienen, R.J.W. and the Rainfor Collaboration (2017). Carbon uptake by mature Amazon forests has mitigated Amazon nations' carbon emissions. Carbon Balance and Management 12(1), 1. https://doi.org/10.1186/s13021-016-0069-2

Popkin, B.M,, Adair, L.S,, Ng, S.W (2012). Global nutrition transition and the pandemic of obesity in developing countries. Nutrition Reviews 70(1), 3-21. https://doi.org/10.1111/j.1753-4887.2011.00456.x

Pörtner, H.-O., Scholes, R.J., Agard, J., Archer, E., Bai, X., Barnes, D. et al. (2021). IPBES-IPCC Co-sponsored Workshop Report on Biodiversity and Climate Change. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.5281/zenodo.4920414

Pratap, V., Saha, U., Kumar, A. and Singh, A.K. (2021). Analysis of air pollution in the atmosphere due to firecrackers in the Diwali period over an urban Indian region. Advances in Space Research 68(8), 3327-3341. https://doi.org/10.1016/j.asr.2021.06.031

Qian, C., Ye, Y., Jiang, J., Zhong, Y., Zhang, Y., Pinto, I. et al. (2024). Rapid attribution of the record-breaking heatwave event in North China in June 2023 and future risks. Environmental Research Letters 19(1), 014028. https://dx.doi.org/10.1088/1748-9326/ad0dd9

Rakovec, O., Samaniego, L., Hari, V., Markonis, Y., Moravec, V., Thober, S. et al. (2022). The 2018–2020 multi-year drought sets a new benchmark in Europe. Earth's Future 10(3), e2021EF002394. https://doi.org/10.1029/2021EF002394

Rantanen, M., Karpechko, A.Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K. et al. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment 3(1), 168. https://doi.org/10.1038/s43247-022-00498-3

Redvers, N., Aubrey, P., Celidwen, Y. and Hill, K. (2023). Indigenous Peoples: Traditional knowledges, climate change, and health. PLOS Global Public Health 3(10), e0002474. https://doi.org/10.1371/journal.pgph.0002474

Reid, C.E. and Maestas, M.M. (2019). Wildfire smoke exposure under climate change: impact on respiratory health of affected communities. Current Opinion in Pulmonary Medicine 25(2), 179-187. https://doi.org/10.1097/mcp.0000000000000552

Retama, A., Neria-Hernández, A., Jaimes-Palomera, M., Rivera-Hernández, O., Sánchez-Rodríguez, M., López-Medina, A. et al. (2019). Fireworks: A major source of inorganic and organic aerosols during Christmas and New Year in Mexico City. Atmospheric Environment: X 2, 100013. https://doi.org/10.1016/j.aeaoa.2019.100013

Reyes-García, V., García-Del-Amo, D., Porcuna-Ferrer, A., Schlingmann, A., Abazeri, M., Attoh, E.M.N.A.N. et al. (2024a). Local studies provide a global perspective of the impacts of climate change on Indigenous Peoples and local communities. Sustainable Earth Reviews 7(1), 1. https://doi.org/10.1186/s42055-023-00063-6

Reyes-García, V., García-del-Amo, D., Álvarez-Fernández, S., Benyei, P., Calvet-Mir, L., Junqueira, A.B. et al. (2024b). Indigenous Peoples and local communities report ongoing and widespread climate change impacts on local social-ecological systems. Communications Earth & Environment 5(1), 29. https://doi.org/10.1038/s43247-023-01164-y

Robinson, S.A., Revell, L.E., Mackenzie, R. and Ossola, R. (2024). Extended ozone depletion and reduced snow and ice cover—Consequences for Antarctic biota. Global Change Biology 30(4), e17283. https://doi.org/10.1111/gcb.17283

Robson, T.M. and Aphalo, P.J. (2019). Transmission of ultraviolet, visible and near-infrared solar radiation to plants within a seasonal snow pack. Photochemical & Photobiological Sciences 18(8), 1963-1971. https://doi.org/10.1039/c9pp00197b

Rodrigues, U., Lullfitz, A., Coyne, L., Dean, A., Eades, A., Flowers, E. et al. (2022). Indigenous Knowledge, aspiration, and potential application in contemporary fire mitigation in southwest Australia. Human Ecology 50(5), 963-980. https://doi.org/10.1007/s10745-022-00359-9

Rodríguez, I., Inturias, M., Masay, E. and Peña, A. (2023). Decolonizing wildfire risk management: Indigenous responses to fire criminalization policies and increasingly flammable forest landscapes in Lomerío, Bolivia. Environmental Science & Policy 147, 103-115. https://doi.org/10.1016/j.envsci.2023.06.005

Rolleston, A.K., Cassim, S., Kidd, J., Lawrenson, R., Keenan, R. and Hokowhitu, B. (2020). Seeing the unseen: Evidence of kaupapa Māori health interventions. AlterNative: An International Journal of Indigenous Peoples 16(2), 129-136. https://doi.org/10.1177/1177180120919166

Romanello, M., Di Napoli, C., Drummond, P., Green, C., Kennard, H., Lampard, P. et al. (2022). The 2022 report of the Lancet Countdown on health and climate change: Health at the mercy of fossil fuels. Lancet 400(10363), 1619-1654. https://doi.org/10.1016/S0140-6736(22)01540-9

Romanello, M., Napoli, C.D., Green, C., Kennard, H., Lampard, P., Scamman, D. et al. (2023). The 2023 report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. Lancet 402(10419), 2346-2394. https://doi.org/10.1016/s0140-6736(23)01859-7

Romanello, M., Walawender, M., Hsu, S.-C., Moskeland, A., Palmeiro-Silva, Y., Scamman, D. et al. (2024). The 2024 report of the Lancet Countdown on health and climate change: Facing record-breaking threats from delayed action. The Lancet 404(10465), 1847-1896. https://doi.org/10.1016/S0140-6736(24)01822-1

Rosentreter, J.A., Laruelle, G.G., Bange, H.W., Bianchi, T.S., Busecke, J.J.M., Cai, W.-J. et al. (2023). Coastal vegetation and estuaries are collectively a greenhouse gas sink. Nature Climate Change 13(6), 579-587. https://doi.org/10.1038/s41558-023-01682-9

Ross J. Salawitch, David W. Fahey, Michaela I. Hegglin, Laura A. McBride, Walter R. Tribett and Sarah J. Doherty (2019). Twenty questions and answers about the ozone Layer: 2018 update, scientific assessment of ozone depletion. 2018. Geneva: World Meteorological Organization. https://csl.noaa.gov/assessments/ozone/2018/downloads/twentyquestions.pdf

Rotterdam Convention on the prior informed consent procedure for certain hazardous chemicals and pesticides in international trade (2025). https://www.pic.int/ Accessed: 12 July 2025

Roychoudhury, C., He, C., Kumar, R., McKinnon, J.M. and Arellano, A.F., Jr., (2022). On the relevance of aerosols to snow cover variability over high mountain Asia. Geophysical Research Letters. http://hdl.handle.net/10150/666898

Russell-Smith, J., Yates, C., Vernooij, R., Eames, T., van der Werf, G., Ribeiro, N. et al. (2021). Opportunities and challenges for savanna burning emissions abatement in southern Africa. Journal of Environmental Management 288, 112414. https://doi.org/10.1016/j.jenvman.2021.112414

Sahu, M., Chattopadhyay, B., Das, R. and Chaturvedi, S. (2023). Measuring impact of climate change on Indigenous health in the background of multiple disadvantages: A scoping review for equitable public health policy formulation. Journal of Prevention 44(4), 421-456. https://doi.org/10.1007/s10935-022-00718-8

Salisbury, J., Hu, X., Speed, J.D.M., Iordan, C.M., Austrheim, G. and Cherubini, F. (2023). Net climate effects of Moose browsing in early successional Boreal Forests by integrating carbon and albedo dynamics. Journal of Geophysical Research: Biogeosciences 128(3), e2022JG007279. https://doi.org/10.1029/2022JG007279

Salmond, J.A., Vardoulakis, S., Kinney, P. and Green, D. (2022). Editorial: Cities in lockdown: Implications of COVID-19 for air quality and urban environmental health. Frontiers in Sustainable Cities 4. https://doi.org/10.3389/frsc.2022.913629

Saunois, M., Martinez, A., Poulter, B., Zhang, Z., Raymond, P., Regnier, P. et al. (2024). Global Methane Budget 2000-2020. Earth System Science Data 2024, 1-147. https://doi.org/10.5194/essd-2024-115

Savo, V., Lepofsky, D., Benner, J.P., Kohfeld, K.E., Bailey, J. and Lertzman, K. (2016). Observations of climate change among subsistence-oriented communities around the world. Nature Climate Change 6(5), 462-473. https://doi.org/10.1038/nclimate2958

Scharlemann, J.P.W., Tanner Edmund V. J., Hiederer Roland. and and Kapos, V. (2014). Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Management 5(1), 81-91. https://doi.org/10.4155/cmt.13.77

Schoeberl, M.R., Wang, Y., Ueyama, R., Dessler, A., Taha, G. and Yu, W. (2023). The Estimated Climate Impact of the Hunga Tonga-Hunga Ha'apai Eruption Plume. Geophysical Research Letters 50(18), e2023GL104634. https://doi.org/10.1029/2023GL104634

Schramm, P.J., Brown, C.L., Saha, S., Conlon, K.C., Manangan, A.P., Bell, J.E. et al. (2021). A systematic review of the effects of temperature and precipitation on pollen concentrations and season timing, and implications for human health. International Journal of Biometeorology 65(10), 1615-1628. https://doi.org/10.1007/s00484-021-02128-7

Schweizer, D., van Kuijk, M. and Ghazoul, J. (2021). Perceptions from non-governmental actors on forest and landscape restoration, challenges and strategies for successful implementation across Asia, Africa and Latin America. Journal of Environmental Management 286, 112251. https://doi.org/10.1016/j.jenvman.2021.112251

Schucht, S., Tognet, F., Létinois, L. (2024), Wheat and potato yield loss in 2022 in Europe due to ozone exposure (Eionet Report – ETC HE 2024/9). European Topic Centre on Human Health and the Environment. https://www.eionet.europa.eu/etcs/etc-he/products/etc-he-products/etc-he-reports/etc-he-report-2024-9-wheat-and-potato-yield-loss-in-2022-in-europe-due-to-ozone-exposure#:~:text=The%20study%20quantified%20losses%20in,be%20due%20to%20error%20compensation

Sciusco, P., Chen, J., Abraha, M., Lei, C., Robertson, G.P., Lafortezza, R. et al. (2020). Spatiotemporal variations of albedo in managed agricultural landscapes: Inferences to global warming impacts (GWI). Landscape Ecology 35(6), 1385-1402. https://doi.org/10.1007/s10980-020-01022-8

Scovronick, N., Budolfson, M., Dennig, F., Errickson, F., Fleurbaey, M., Peng, W. et al. (2019). The impact of human health co-benefits on evaluations of global climate policy. Nature Communications 10(1), 2095. https://doi.org/10.1038/s41467-019-09499-x

Secretariat of the Stockholm Convention (2019). Monitoring Reports. Stockholm Convention. https://chm.pops.int/implementation/globalmonitoringplan/monitoringreports/tabid/525/default.aspx Accessed: 04 February 2024

Semenza, J.C., Rocklöv, J. and Ebi, K.L. (2022). Climate change and cascading risks from infectious disease. Infectious Diseases and Therapy 11(4), 1371-1390. https://doi.org/10.1007/s40121-022-00647-3

Senande-Rivera, M., Insua-Costa, D. and Miguez-Macho, G. (2022). Spatial and temporal expansion of global wildland fire activity in response to climate change. Nature Communications 13(1), 1208. https://doi.org/10.1038/s41467-022-28835-2

Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A. et al. (2021). Weather and climate extreme events in a changing climate In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (eds.). Cambridge: Cambridge University Press. chapter 11. 1513-1766. https://doi.org/10.1017/9781009157896.013

Shindell, D. and Smith, C.J. (2019). Climate and air-quality benefits of a realistic phase-out of fossil fuels. Nature 573(7774), 408-411. https://doi.org/10.1038/s41586-019-1554-z

Shiraishi, T. and Hirata, R. (2021). Estimation of carbon dioxide emissions from the megafires of Australia in 2019–2020. Scientific Reports 11(1), 8267. https://doi.org/10.1038/s41598-021-87721-x

Silva, C.A., Santilli, G., Sano, E.E. and Laneve, G. (2021). Fire occurrences and greenhouse gas emissions from deforestation in the Brazilian Amazon. Remote Sensing, 3. https://doi.org/10.3390/rs13030376

Slatyer, R.A., Umbers, K.D.L. and Arnold, P.A. (2022). Ecological responses to variation in seasonal snow cover. Conservation Biology 36(1), e13727. https://doi.org/10.1111/cobi.13727

Smirnova, N., Shaver, A.C., Mehta, A.J., Philipsborn, R. and Scovronick, N. (2023). Climate Change, Air Quality, and Pulmonary Health Disparities. Clinics in Chest Medicine 44(3), 489-499. https://doi.org/10.1016/j.ccm.2023.03.005

Sokhi, R.S., Singh, V., Querol, X., Finardi, S., Targino, A.C., Andrade, M.d.F. et al. (2021). A global observational analysis to understand changes in air quality during exceptionally low anthropogenic emission conditions. Environment International 157, 106818. https://doi.org/10.1016/j.envint.2021.106818

Solomon, N., Birhane, E., Gordon, C., Haile, M., Taheri, F., Azadi, H. et al. (2018). Environmental impacts and causes of conflict in the Horn of Africa: A review. Earth-Science Reviews 177, 284-290. https://doi.org/10.1016/j.earscirev.2017.11.016

Song, J., Wang, Y., Zhang, Q., Qin, W., Pan, R., Yi, W. et al. (2023). Premature mortality attributable to NO_2 exposure in cities and the role of built environment: A global analysis. Science of The Total Environment 866, 161395. https://doi.org/10.1016/j.scitotenv.2023.161395

Sonwani, S., Hussain, S. and Saxena, P. (2022). Air pollution and climate change impact on forest ecosystems in Asian region – a review. Ecosystem Health and Sustainability 8(1), 2090448. https://doi.org/10.1080/20964129.2022.2090448

Southerland, V.A., Brauer, M., Mohegh, A., Hammer, M.S., van Donkelaar, A., Martin, R.V. et al. (2022). Global urban temporal trends in fine particulate matter ($PM_{2.5}$) and attributable health burdens: estimates from global datasets. The Lancet Planetary Health 6(2), e139-e146. https://doi.org/10.1016/S2542-5196(21)00350-8

Sridharan, S., Kumar, M., Singh, L., Bolan, N.S. and Saha, M. (2021). Microplastics as an emerging source of particulate air pollution: A critical review. Journal of Hazardous Materials 418, 126245. https://doi.org/10.1016/j.jhazmat.2021.126245

Stafoggia, M., Oftedal, B., Chen, J., Rodopoulou, S., Renzi, M., Atkinson, R.W. et al. (2022). Long-term exposure to low ambient air pollution concentrations and mortality among 28 million people: Results from seven large European cohorts within the ELAPSE project. Lancet Planet Health 6(1), e9-e18. https://doi.org/10.1016/S2542-5196(21)00277-1

Stern, G.A., Macdonald, R.W., Outridge, P.M., Wilson, S., Chételat, J., Cole, A. et al. (2012). How does climate change influence Arctic mercury? Science of The Total Environment 414, 22-42. https://doi.org/10.1016/j.scitotenv.2011.10.039

Szopa, S., V. Naik, B. Adhikary, P. Artaxo, T. Berntsen, W.D. Collins et al. (2021). Short-lived climate forcers. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger et al. (eds.). Cambridge: Cambridge University Press. chapter 6. 817–922. https://doi.org/10.1017/9781009157896.008

Tang, X., Yang, T., Yu, D., Xiong, H. and Zhang, S. (2024). Current insights and future perspectives of ultraviolet radiation (UV) exposure: Friends and foes to the skin and beyond the skin. Environment International 185, 108535. https://doi.org/10.1016/j.envint.2024.108535

Tear, T.H., Wolff, N.H., Lipsett-Moore, G.J., Ritchie, M.E., Ribeiro, N.S., Petracca, L.S. et al. (2021). Savanna fire management can generate enough carbon revenue to help restore Africa's rangelands and fill protected area funding gaps. One Earth 4(12), 1776-1791. https://doi.org/10.1016/j.oneear.2021.11.013

Telwala, Y., Brook, B.W., Manish, K. and Pandit, M.K. (2013). Climate-induced elevational range shifts and increase in plant species richness in a Himalayan biodiversity epicentre. PLoS One 8(2), e57103. https://doi.org/10.1371/journal.pone.0057103

The Acid Deposition Monitoring Network in East Asia (2019). Fourth Report for Policy Makers: —towards Clean Air for a Sustainable Future in East Asia through Collaborative Activities. Bangkok: United Nations Environment Programme Asia and the Pacific Office. https://www.eanet.asia/wp-content/uploads/2020/03/EANET-RPM4_2019.pdf

Thompson, R., Lawrance, E.L., Roberts, L.F., Grailey, K., Ashrafian, H., Maheswaran, H. et al. (2023). Ambient temperature and mental health: A systematic review and meta-analysis. The Lancet Planetary Health 7(7), e580-e589. https://doi.org/10.1016/S2542-5196(23)00104-3

Tirado, M.C., Clarke, R., Jaykus, L.A., McQuatters-Gollop, A. and Frank, J.M. (2010). Climate change and food safety: A review. Food Research International 43(7), 1745-1765. https://doi.org/10.1016/j.foodres.2010.07.003

Tong, D., Geng, G., Zhang, Q., Cheng, J., Qin, X., Hong, C. et al. (2021). Health co-benefits of climate change mitigation depend on strategic power plant retirements and pollution controls. Nature Climate Change 11(12), 1077-1083. https://doi.org/10.1038/s41558-021-01216-1

Touré, N.E., Kaudia, A., Hicks, K., Mbandi, A., Khomzi, K., Garland, R. et al. (2024). Briefing Note: Combating Air Pollution to Control Desertification and Improve Food Security in Africa. https://www.preventionweb.net/media/99284/download?startDownload=20250401

Trisos, C.H., Merow, C. and Pigot, A.L. (2020). The projected timing of abrupt ecological disruption from climate change. Nature 580(7804), 496-501. https://doi.org/10.1038/s41586-020-2189-9

Tschakert, P., Coomes, O.T. and Potvin, C. (2007). Indigenous livelihoods, slash-and-burn agriculture, and carbon stocks in Eastern Panama. Ecological Economics 60(4), 807-820. https://doi.org/10.1016/j.ecolecon.2006.02.001

United Nations Convention to Combat Desertification (2022). Sand and Dust Storms Compendium: Information and Guidance on Assessing and Addressing the Risks. Bonn: Secretariat of the United Nations Convention to Combat Desertification (UNCCD). https://www.unccd.int/sites/default/files/2022-05/1871_Book_SDS_%20Compendium_V1.pdf

United Nations Economic Commission for Europe (UNECE) (2025). The Air Convention and Its Protocols. https://unece.org/environmental-policy-1/air Accessed: 12 July 2025

United Nations Environment Programme (2018). Technical Background Report (TBR) to the Global Mercury Assessment. Nairobi. https://www.unep.org/globalmercurypartnership/resources/report/technical-background-report-global-mercury-assessment-2018

United Nations Environment Programme (2019), ed. Global Environment Outlook – GEO-6: Healthy Planet, Healthy People. Cambridge University Press.

United Nations Environment Programme (2019a). Air Pollution in Asia and the Pacific: Science-based Solutions 2019. Geneva. https://www.ccacoalition.org/resources/air-pollution-asia-and-pacific-science-based-solutions-summary-full-report

United Nations Environment Programme (2019b). Global Mercury Assessment 2018. Geneva. https://minamataconvention.org/sites/default/files/2021-06/GMA2018.pdf

United Nations Environment Programme (2021). Pakistan's ten billion tree tsunami. https://www.unep.org/news-and-stories/story/pakistans-ten-billion-tree-tsunami Accessed: 23 March 2025

United Nations Environment Programme (2022). Spreading like Wildfire – The Rising Threat of Extraordinary Landscape Fires. A UNEP Rapid Response Assessment. Nairobi. https://www.grida.no/publications/769

United Nations Environment Programme (2023a). Third Global Monitoring Report. https://chm.pops.int/Portals/0/download.aspx?d=UNEP-POPS-COP.11-INF-38.English.pdf

United Nations Environment Programme (2023b). Integrated Assessment of Air Pollution and Climate Change for Sustainable Development in Africa. Nairobi. https://www.ccacoalition.org/sites/default/files/resources/files/Introduction_Integrated%20Assessment%20of%20Air%20Pollution%20and%20Climate%20Change%20for%20Sustainable%20Development%20in%20Africa.pdf

United Nations Environment Programme (2024a). Environmental Impact of the Conflict in Gaza: Preliminary Assessment of Environmental Impacts. Nairobi. https://www.un.org/unispal/wpcontent/uploads/2024/06/environmental_impact_conflict_Gaza.pdf

United Nations Environment Programme (2024b). Second Indigenous Knowledge and Local Knowledge Dialogue (GEO-7). Oaxaca, México.

United Nations Environment Programme (2024c). Report of the first part of the third session of the ad hoc open-ended working group on a science-policy panel to further contribute to the sound management of chemicals and waste and to prevent pollution. Geneva. https://www.unep.org/events/conference/oewg-31-science-policy-panel-contribute-further-sound-management-chemicals-and

United Nations Environment Programme (2024d). Emissions Gap Report 2024: No More Hot Air … Please! With A Massive ap Between Rhetoric and Reality, Countries Draft New Climate Commitments. Nairobi. https://wedocs.unep.org/handle/20.500.11822/46404

United Nations Environment Programme and Climate and Clean Air Coalition (2021). Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. Nairobi: United Nations Environment Programme. https://www.ccacoalition.org/sites/default/files/resources//2021_Global-Methane_Assessment_full_0.pdf

United Nations Framework Convention on Climate (2025). Global Stocktake. https://unfccc.int/topics/global-stocktake Accessed: 4 April 2025

United Nations Framework Convention on Climate Change (2023). 2023 NDC Synthesis Report. UNFCCC. https://unfccc.int/ndc-synthesis-report-2023#Projected-GHG-Emission-levels

Valdivia-Gago, A., Zavaleta-Cortijo, C., Carcamo, C., Berrang-Ford, L., Lancha, G., Pizango, P. et al. (2023). The seasonality of nutrition status in Shawi Indigenous children in the Peruvian Amazon. PLOS Climate 2(9), e0000284. https://doi.org/10.1371/journal.pclm.0000284

van der Esch, S., Sewell, A., Bakkenes, M., Berkhout, E., Doelman, J.C., Stehfest, E. et al. (2022). The global potential for land restoration: Scenarios for the Global Land Outlook 2. The Hague: PBL Netherlands Environmental Assessment Agency. https://www.pbl.nl/en/publications/the-global-potential-for-land-restoration-scenarios-for-the-global-land-outlook-2

van Huissteden, J. (2020). Thawing Permafrost: Permafrost Carbon in a Warming Arctic. 1st edn. Switzerland: Springer International Publishing. https://doi.org/10.1007/978-3-030-31379-1

van Steen, Y., Ntarladima, A.M., Grobbee, R., Karssenberg, D. and Vaartjes, I. (2019). Sex differences in mortality after heat waves: Are elderly women at higher risk? International Archives of Occupational and Environmental Health 92(1), 37-48. https://doi.org/10.1007/s00420-018-1360-1

van Wees, D., van der Werf, G.R., Randerson, J.T., Rogers, B.M., Chen, Y., Veraverbeke, S. et al. (2022). Global biomass burning fuel consumption and emissions at 500 m spatial resolution based on the Global Fire Emissions Database (GFED). Geosci. Model Dev. 15(22), 8411-8437. https://gmd.copernicus.org/articles/15/8411/2022/

Vardoulakis, S., Giagloglou, E., Steinle, S., Davis, A., Sleeuwenhoek, A., Galea, K.S. et al. (2020a). Indoor Exposure to Selected Air Pollutants in the Home Environment: A Systematic Review. International Journal of Environmental Research and Public Health 17(23). https://doi.org/10.3390/ijerph17238972

Vardoulakis, S., Jalaludin, B.B., Morgan, G.G., Hanigan, I.C. and Johnston, F.H. (2020b). Bushfire smoke: Urgent need for a national health protection strategy. Medical Journal of Australia 212(8), 349-353.e341. https://doi.org/10.5694/mja2.50511

Vardoulakis, S., Kettle, R., Cosford, P., Lincoln, P., Holgate, S., Grigg, J. et al. (2018). Local action on outdoor air pollution to improve public health. International Journal of Public Health 63(5), 557-565. https://doi.org/10.1007/s00038-018-1104-8

Vecchio, E.A., Dickson, M. and Zhang, Y. (2022). Indigenous mental health and climate change: A systematic literature review. The Journal of Climate Change and Health 6, 100121. https://doi.org/10.1016/j.joclim.2022.100121

Velasco, E. and Retama, A. (2017). Ozone's threat hits back Mexico City. Sustainable Cities and Society 31, 260-263. https://doi.org/10.1016/j.scs.2016.12.015

Velders, G.J.M., Daniel, J.S., Montzka, S.A., Vimont, I., Rigby, M., Krummel, P.B. et al. (2022). Projections of hydrofluorocarbon (HFC) emissions and the resulting global warming based on recent trends in observed abundances and current policies. Atmos. Chem. Phys. 22(9), 6087-6101. https://acp.copernicus.org/articles/22/6087/2022/

Velis, C.A. and Cook, E. (2021). Mismanagement of plastic waste through open burning with emphasis on the global south: A systematic review of risks to occupational and public health. Environmental Science & Technology 55(11), 7186-7207. https://doi.org/10.1021/acs.est.0c08536

Vidal-Cuellar, C.L., Chicmana-Zapata, V., Arotoma-Rojas, I., Meza, G., Ford, J.D., Rodríguez Ferruchi, H. et al. (2024). Pathways to strengthen the climate resilience of health systems in the Peruvian Amazon by working with Indigenous leaders, communities and health officers. BMJ Glob Health 8(Suppl 3). https://doi.org/10.1136/bmjgh-2023-014391

Villat, J. and Nicholas, K.A. (2024). Quantifying soil carbon sequestration from regenerative agricultural practices in crops and vineyards. Frontiers in Sustainable Food Systems 7. https://doi.org/10.3389/fsufs.2023.1234108

von Schneidemesser, E., Driscoll, C., Rieder, H.E. and Schiferl, L.D. (2020). How will air quality effects on human health, crops and ecosystems change in the future? Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 378(2183), 20190330. https://doi.org/10.1098/rsta.2019.0330

Wang, R., Goll, D., Balkanski, Y., Hauglustaine, D., Boucher, O., Ciais, P. et al. (2017). Global forest carbon uptake due to nitrogen and phosphorus deposition from 1850 to 2100. Global Change Biology 23(11), 4854-4872. https://doi.org/10.1111/gcb.13766

Wang, H., Huang, C., Tao, W., Gao, Y., Wang, S., Jing, S. et al. (2022). Seasonality and reduced nitric oxide titration dominated ozone increase during COVID-19 lockdown in eastern China. npj Climate and Atmospheric Science 5(1), 24. https://doi.org/10.1038/s41612-022-00249-3

Wang, P., Solomon, S. and Stone, K. (2023). Stratospheric chlorine processing after the 2020 Australian wildfires derived from satellite data. Proceedings of the National Academy of Sciences 120(11), e2213910120. https://doi.org/10.1073/pnas.2213910120

Wang, S. and Toumi, R. (2022). More tropical cyclones are striking coasts with major intensities at landfall. Scientific Reports 12(1), 5236. https://doi.org/10.1038/s41598-022-09287-6

Wang, X., Xu, Z., Su, H., Ho, H.C., Song, Y., Zheng, H. et al. (2021). Ambient particulate matter (PM_1, $PM_{2.5}$, PM_{10}) and childhood pneumonia: The smaller particle, the greater short-term impact? Science of The Total Environment 772, 145509. https://doi.org/10.1016/j.scitotenv.2021.145509

Weber, S.E., Diez, J.M., Andrews, L.V., Goulden, M.L., Aronson, E.L. and Allen, M.F. (2019). Responses of arbuscular mycorrhizal fungi to multiple coinciding global change drivers. Fungal Ecology 40, 62-71. https://doi.org/10.1016/j.funeco.2018.11.008

Weidinmyer, C., Yokelson, R. J. and Gullett, B. K. (2014) Global Emissions of Trace Gases, Particulate Matter, and Hazardous Air Pollutants from Open Burning of Domestic Waste. Environmental Science & Technology, 48 (16). 10.1021/es502250z

White, A.R. (2024). The firestorm within: A narrative review of extreme heat and wildfire smoke effects on brain health. Science of The Total Environment 922, 171239. https://doi.org/10.1016/j.scitotenv.2024.171239

Woolley, K.E., Dickinson-Craig, E., Lawson, H.L., Sheikh, J., Day, R., Pope, F.D. et al. (2022). Effectiveness of interventions to reduce household air pollution from solid biomass fuels and improve maternal and child health outcomes in low- and middle-income countries: A systematic review and meta-analysis. Indoor Air 32(1), e12958. https://doi.org/10.1111/ina.12958

World Health Organization (2010). WHO guidelines for indoor air quality: Selected pollutants. https://www.who.int/publications/i/item/9789289002134 (Accessed: 25 August 2024)

World Health Organization (2021). What are the WHO air quality guidelines? Improving health by reducing air pollution. https://www.who.int/news-room/feature-stories/detail/what-are-the-who-air-quality-guidelines (Accessed: 14 August 2023)

World Health Organization (2024). Household air pollution. https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health Accessed: August 25 2024

World Meteorological Organization (2022). Scientific Assessment of Ozone Depletion: 2022. Geneva. https://ozone.unep.org/system/files/documents/Scientific-Assessment-of-Ozone-Depletion-2022.pdf

World Meteorological Organization (2023a). WMO greenhouse gas bulletin:The state of greenhouse gases in the atmosphere based on global observations through 2022. https://library.wmo.int/records/item/68532-no-19-15-november-2023?offset=30 Accessed: 22 March 2025

World Meteorological Organization (2024a). Significant weather and climate events 2023. Geneva. https://wmo.int/files/significant-weather-climate-events-2023

World Meteorological Organization (2024b). WMO global annual to decadal climate update. Target years: 2024 and 2024-2028. https://library.wmo.int/idurl/4/68910 Accessed: 03 April 2025

World Meteorological Organization (2024c). Vicious circle of climate change, wildfires and air pollution has major impacts 5 September 2024 https://wmo.int/news/media-centre/vicious-circle-of-climate-change-wildfires-and-air-pollution-has-major-impacts#:~:text=A%20vicious%20cycle%20of%20climate,World%20Meteorological%20Organization%20(WMO).&text=The%20WMO%20Air%20Quality%20and,a%20special%20

World Meteorological Organization (2025a). WMO confirms 2024 as warmest year on record at about 1.55°C above pre-industrial level. https://wmo.int/news/media-centre/wmo-confirms-2024-warmest-year-record-about-155degc-above-pre-industrial-level (Accessed: 22 March 2025 2025)

Wu, S., Lin, X., Bian, Z., Lipson, M., Lafortezza, R., Liu, Q. et al. (2024). Satellite observations reveal a decreasing albedo trend of global cities over the past 35 years. Remote Sensing of Environment 303(114003). https://doi.org/10.1016/j.rse.2024.114003

Wu, X., Lu, Y., Zhou, S., Chen, L. and Xu, B. (2016). Impact of climate change on human infectious diseases: Empirical evidence and human adaptation. Environment International 86, 14-23. https://doi.org/10.1016/j.envint.2015.09.007

Wu, Y., Wen, B., Li, S. and Guo, Y. (2021). Sand and dust storms in Asia: a call for global cooperation on climate change. Lancet Planet Health 5(6), e329-e330. https://doi.org/10.1016/S2542-5196(21)00082-6

Xie, Y., Lin, M., Decharme, B., Delire, C., Horowitz, L.W., Lawrence, D.M. et al. (2022). Tripling of western US particulate pollution from wildfires in a warming climate. Proceedings of the National Academy of Sciences 119(14), e2111372119. https://doi.org/doi:10.1073/pnas.2111372119

Xu, R., Ye, T., Yue, X., Yang, Z., Yu, W., Zhang, Y. et al. (2023). Global population exposure to landscape fire air pollution from 2000 to 2019. Nature 621(7979), 521-529. https://doi.org/10.1038/s41586-023-06398-6

Xu, R., Yu, P., Abramson, M.J., Johnston, F.H., Samet, J.M., Bell, M.L. et al. (2020). Wildfires, global climate change, and human health. New England Journal of Medicine 383(22), 2173-2181. https://www.nejm.org/doi/full/10.1056/NEJMsr2028985

Xu, Y., Kobayashi, K. and Feng, Z. (2024). Wheat yield response to elevated O_3 concentrations differs between the world's major producing regions. Science of The Total Environment 907, 168103. https://doi.org/10.1016/j.scitotenv.2023.168103

Yadav, S.K., Mishra, R.K. and Gurjar, B.R. (2022). Fireworks induced quasi-ultrafine particle number concentration and size-resolved elemental distribution in megacity Delhi. Arabian Journal of Geosciences 15(1), 102. https://doi.org/10.1007/s12517-021-09385-1

Yang, J., Kang, S., Chen, D., Zhao, L., Ji, Z., Duan, K. et al. (2022). South Asian black carbon is threatening the water sustainability of the Asian Water Tower. Nature Communications 13(1), 7360. https://doi.org/10.1038/s41467-022-35128-1

Yang, R. and Zhong, C. (2022). Analysis on spatio-temporal evolution and influencing factors of Air Quality Index (AQI) in China. Toxics 10(12), 712. https://doi.org/10.3390/toxics10120712

Yao Wang, M. F., Ziyang, L., Hongping, H., Yuliang, G. X. P., Yijie, W., Ke, Y. et al. (2024) Methane emissions from landfills differentially underestimated worldwide. Nat Sustain 7, 496–507. https://doi.org/10.1038/s41893-024-01307-9

Yoshioka, M., Grosvenor, D.P., Booth, B.B.B., Morice, C.P. and Carslaw, K.S. (2024). Warming effects of reduced sulfur emissions from shipping. Atmospheric Chemistry and Physics 24(23), 13681-13692. https://doi.org/10.5194/acp-24-13681-2024

Yu, M., Zhang, S., Ning, H., Li, Z. and Zhang, K. (2024). Assessing the 2023 Canadian wildfire smoke impact in Northeastern US: Air quality, exposure and environmental justice. Science of The Total Environment 926, 171853. https://doi.org/10.1016/j.scitotenv.2024.171853

Yu, W., Weintraub, S.R. and Hall, S.J. (2021). Climatic and Geochemical Controls on Soil Carbon at the Continental Scale: Interactions and Thresholds. Global Biogeochemical Cycles 35(3), e2020GB006781. https://doi.org/10.1029/2020GB006781

Yu, Z., Ciais, P., Piao, S., Houghton, R.A., Lu, C., Tian, H. et al. (2022). Forest expansion dominates China's land carbon sink since 1980. Nature Communications 13(1), 5374. https://doi.org/10.1038/s41467-022-32961-2

Yuan, T., Song, H., Oreopoulos, L., Wood, R., Bian, H., Breen, K. et al. (2024). Abrupt reduction in shipping emissions as an inadvertent geoengineering termination shock produces substantial radiative warming. Communications Earth & Environment 5(1), 281. https://doi.org/10.1038/s43247-024-01442-3

Yue, H., He, C., Huang, Q. et al. (2024) Substantially reducing global PM2.5-related deaths under SDG3.9 requires better air pollution control and healthcare. Nat Commun 15, 2729 (2024). https://doi.org/10.1038/s41467-024-46969-3

Zandalinas, S.I., Fritschi, F.B. and Mittler, R. (2021). Global Warming, Climate Change, and Environmental Pollution: Recipe for a Multifactorial Stress Combination Disaster. Trends in Plant Science 26(6), 588-599. https://doi.org/10.1016/j.tplants.2021.02.011

Zelinka, M.D., Smith, C.J., Qin, Y. and Taylor, K.E. (2023). Aerosol Effective Radiative Forcings in CMIP Models. EGUsphere. https://doi.org/10.5194/egusphere-2023-689

Zerefos, C., Fountoulakis, I., Eleftheratos, K. and Kazantzidis, A. (2023). Long-term variability of human health-related solar ultraviolet-B radiation doses for the 1980s to the end of the 21st century. Physiological Reviews 103(3), 1789-1826. https://doi.org/10.1152/physrev.00031.2022

Zhang, J., Wei, Y. and Fang, Z. (2019). Ozone pollution: A major health hazard worldwide. Frontiers in Immunology 10. https://doi.org/10.3389/fimmu.2019.02518

Zhang, P., Jeong, J.-H., Yoon, J.-H., Kim, H., Wang, S.-Y.S., Linderholm, H.W. et al. (2020). Abrupt shift to hotter and drier climate over inner East Asia beyond the tipping point. Science 370(6520), 1095-1099. https://www.science.org/doi/abs/10.1126/science.abb3368

Zhang, L., Li, J., Jiang, Z., Dong, Y., Ying, T. and Zhang, Z. (2022). Clear-sky direct aerosol radiative forcing uncertainty associated with aerosol vertical distribution based on CMIP6 models. Journal of Climate 35(10), 3021-3035. https://doi.org/10.1175/JCLI-D-21-0480.1

Zhang, W., Gou, X., Zhang, F., Liu, W., Zhang, Y. and Gao, L. (2023a). Divergent responses of Qinghai spruce (Picea crassifolia) to recent warming along elevational gradients in the central Qilian Mountains, Northwest China. Journal of Geographical Sciences 33(1), 151-168. https://doi.org/10.1007/s11442-023-2077-y

Zhang, J., Liu, K., He, X., Li, W., Zhang, M. and Cai, Q. (2023b). Evaluation of heavy metal contamination of soil and the health risks in four potato-producing areas. Frontiers in Environmental Science 11. https://doi.org/10.3389/fenvs.2023.1071353

Zhao, K. and Jackson, R.B. (2014). Biophysical forcings of land-use changes from potential forestry activities in North America. Ecological Monographs 84(2), 329-353. https://doi.org/10.1890/12-1705.1

Zhao, Q., Guo, Y., Ye, T., Gasparrini, A., Tong, S., Overcenco, A. et al. (2021). Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study. The Lancet Planetary Health 5(7), e415-e425. https://doi.org/10.1016/S2542-5196(21)00081-4

Zhou, H., Tao, F., Chen, Y., Yin, L., Li, Y., Wang, Y. et al. (2024a). Paddy rice methane emissions, controlling factors, and mitigation potentials across Monsoon Asia. Science of The Total Environment 935, 173441. https://doi.org/10.1016/j.scitotenv.2024.173441

Zhou, B., Chen, G., Yu, H., Zhao, J. and Yin, Y. (2024b) Revealing the Nonlinear Impact of Human Activities and Climate Change on Ecosystem Services in the Karst Region of Southeastern Yunnan Using the XGBoost–SHAP Model. Forests, 15(8), p.1420.

Ziska, L.H., Makra, L., Harry, S.K., Bruffaerts, N., Hendrickx, M., Coates, F. et al. (2019). Temperature-related changes in airborne allergenic pollen abundance and seasonality across the northern hemisphere: A retrospective data analysis. Lancet Planet Health 3(3), e124-e131. https://doi.org/10.1016/S2542-5196(19)30015-4

Zurba, M. and Papadopoulos, A. (2023). Indigenous participation and the incorporation of Indigenous Knowledge and Perspectives in global environmental governance forums: A systematic review. Environmental Management 72(1), 84-99. https://doi.org/10.1007/s00267-021-01566-8.

04 Land and Soils

Coordinating Lead Authors: Pandi Zdruli (International Centre for Advanced Mediterranean Agronomic Studies (CIHEAM) Mediterranean Agronomic Institute of Bari, Andrei Kirilenko (University of Florida), Xiyan Xu (Chinese Academy of Sciences)

Lead Authors: Lydie-Stella Koutika (Soil Care and Environmental Studies (SCES), Pointe-Noire, Republic of the Congo), Jyotsna Krishnakumar (Keystone Foundation), Ravendra (Ravi) Naidu (Global Centre for Environmental Remediation, the University of Newcastle and crc for Contamination Assessment and Remediation of the Environment)

Coordinating Authors: Bhabananda Biswas (Global Centre for Environmental Remediation, the University of Newcastle and crc for Contamination Assessment and Remediation of the Environment), Jonathan Davies (University of British Columbia), Leisa Perch (SAEDI Consulting (Barbados) Inc), Le Yu (Tsinghua University)

Fellows: Zoe Barr (Yale School of the Environment)

GEO Secretariat support: Hilary Allison

Credit: iviphoto93/Envato

Chapter summary

Credit: Mumemories/Envato

Globally, about 20-40 per cent of Earth's land area is degraded, jeopardizing the livelihoods of about 40 per cent of the world population, disproportionally affecting women and older people (*well established*). According to the United Nations Convention to Combat Desertification, we are losing the equivalent of four football fields to land degradation every second, amounting to over 4 million km^2 of degraded land each year. At the same time, desertification threatens a third of the world's land surface. {4.1, 4.3.2}

Human pressures on land and soil resources are rising sharply, with over 70 per cent of the Earth's land area already transformed by human activity (*well established*). Competition for land is high, and resources are finite. As competition for land intensifies, the projections suggest that by 2050, only about 10 per cent of land will remain in a near-natural state. Deforestation continues to be the leading driver of land use change. {4.1, 4.2}

Terrestrial biodiversity continues to decline in abundance and richness, primarily due to changing land cover and land use. Some estimates suggest that 200,000 species may have become extinct during the 20th century (*established but incomplete*). One million species are estimated to be at risk if current trends continue. {4.3.4} Biodiversity decline, across terrestrial biomes, including grasslands, forests, deserts, tundra, and taiga, still continues (well established). {4.2, 4.3.4.1}

An estimated 95 per cent of the world's food and feed supplies are produced in soils that also play a crucial role in climate change mitigation by storing more carbon than the biosphere and atmosphere combined (*well established*). Yet, global soils are degrading at alarming rates, with predictions that almost 95 per cent could be degraded by 2050, an increase from one-third today. Each year, more than 24 billion tonnes of soil are lost to erosion, amounting to 3.4 tonnes of soil lost annually for every person on the planet. {4.3.2}

The global environmental crises, the crisis of climate change, the crisis of biodiversity loss, land degradation and desertification, and the crisis of pollution and waste, have already caused extensive harm to land and soil resources (*well established*). Without urgent

action, the damage will intensify. Soils act as both sources and sinks of carbon, making their management crucial in determining whether soils help mitigate or accelerate climate change. {4.3.1.7, 4.3.2}

Chemical pollution, including greenhouse gas (GHG) emissions, represents some of the largest human impacts on the planet. Non-GHG chemical pollution is estimated to be five times greater in scale than GHG emissions (*established but incomplete*). These gases and chemicals now circulate the planet, contaminating the atmosphere, soil, fresh water, oceans, and global food supply, profoundly affecting all life forms. International conventions have failed to curb this unsustainable growth or even keep track of new chemical releases. The living environment's health deteriorates as the population and global economy expand. {4.3.1, 4.4, 4.5.3}

While there are many point sources of chemical contamination of land and soil, the contaminants released through economic activities are of major concern (*established but incomplete*). Globally, chemical contamination is primarily driven by industrial activity, such as mining, farming, manufacturing, energy production and the displacement of topsoil for development. At the same time, novel pollutants with largely unknown toxic effects, such as micro and nanoplastics, nanochemicals, and "forever chemicals", are also being released into the environment. {4.3.1.1, 4.3.1.2, 4.3.1.3, 4.3.1.5}

By 2050, global annual waste generation is projected to increase by 70 per cent, contributing to nearly a million deaths annually (*established but incomplete*). With municipal solid waste exceeding 2 billion tonnes annually, land, water, and soil contamination is severe. Dumping of waste has significant implications for natural resources, particularly affecting marginalized and Indigenous Communities and undermining efforts towards circularity in material use. {4.3.1.6}

Climate-related extreme events have become more frequent, prolonged and severe, causing more wildfires, droughts and permafrost thawing (*established but incomplete*). Shifts in air temperature, precipitation patterns, warm season length, and heat waves drive these changes. As a result, soil carbon is being released into the atmosphere at a higher rate, disrupting nutrient cycles. Climate change and its associated extremes are predicted to become major drivers of terrestrial biodiversity decline, with far-reaching political, economic, and ecological consequences. {4.3.3.3, 4.3.3.4, 4.3.3.5, 4.3.3.6}

Rising carbon dioxide emissions from forest loss, soil erosion, climate extremes, and permafrost degradation are compromising the role of soil as a carbon dioxide sink in mitigating climate change (*established but incomplete*). Despite that, land still absorbs 29-30 per cent of the total carbon dioxide emissions. However, the role of this carbon sink is increasingly compromised by higher contributions of other GHGs, namely methane and nitrous oxide from fertilized fields, manures, livestock, and other agricultural sources. {4.3.2.2, 4.3.3.2, 4.3.3.3}

The loss of terrestrial aboveground genetic diversity is a major concern, particularly pronounced on islands, where it significantly impacts the local population (*established but incomplete*). Large agribusiness and international corporations promoting intensive agriculture, monoculture, synthetic fertilizers and pesticides have accelerated the loss of genetic and agrogenetic diversity. Land and soil degradation, habitat destruction, and human activities have contributed to the deterioration of genetic variability in recent decades. {4.3.4.3}

Soil biodiversity is crucial for maintaining healthy ecosystems (*well established*). Hosting more than 50 per cent of life on Earth, from microbes to mammals, soils are the most biodiverse habitat. However, despite its importance, only 1 per cent of soil biodiversity is known to the scientific community. {4.3.4.4}

Changes in the physical environment are already affecting natural and human systems, which are closely interconnected (*well established*). Land use change, land degradation, intensive agriculture, livestock expansion, urban sprawl, and habitat loss are accelerating biodiversity loss. The ongoing extinction of terrestrial species is evident in the widespread decline of insects and overall species richness, in both number and diversity {4.3.4.2}. Permafrost thawing drives ecosystem changes, affecting the freshwater cycle, destroying infrastructure and releasing GHGs {4.3.3.3}. Meanwhile, droughts and wildfires are negatively impacting agriculture and forestry, even though these effects may be partially offset by increased productivity in colder climates due to longer growing

period and improved vegetation cover due to the "carbon fertilization" effect. {4.3.3.1, 4.3.3.5}

Essential provisioning, regulating, supporting, and cultural ecosystem services are under increased stress from the interconnected impacts of natural resource overexploitation, conventional and emergent pollutants, land use change, intensive and unsustainable farming, deforestation, climate change, and biodiversity loss. Meanwhile, these ecosystem services are essential for human health, food security, and the regulation of water and nutrient cycles. {4.4.1, 4.4.2}

Marginalized, vulnerable, nature-dependent communities, including Indigenous Peoples, experience the effects of changes in the natural environment most acutely. Land degradation and biodiversity loss directly impact livelihoods, sociocultural traditions, economies and overall well-being of Indigenous Peoples and local communities (*well established*). {4.3.2.4 and 4.3.1.2} Integrated sustainable land, soil and water management practices, rooted in Indigenous Knowledge systems, offer some of the best available solutions to overcome the impacts of land degradation and biodiversity loss. {4.6} Furthermore, through a combined conservation in crop, livestock, and forestry sectors, Indigenous practices offer valuable entry points to climate change adaptation (well established). {4.3.3.5} Numerous studies demonstrate that Indigenous soil conservation and management methods are embedded within cultural belief systems and continue to be practiced today. Additionally, Indigenous Knowledge holders and scholars highlight the importance of Indigenous governance in the stewardship of land and other natural resources, including biodiversity. However, the lack of sufficient international climate financing to support these efforts remains a key barrier. {4.6}

The world is not on track to meet the international targets for land quality, biodiversity and soil health (*well established*). Progress monitoring of land degradation neutrality goals for 2030 reveals deteriorating trends in land productivity, declining land cover quality, and a slower pace of soil organic carbon stocks replenishment – all of which are linked with severe environmental damage. {4.5.1}

Furthermore, the goals of the Paris Agreement to limit global temperature increase to well below 2 degrees Celsius, while pursuing efforts to limit the increase to 1.5 degrees, are unlikely to be met. This shortfall will further accelerate land surface temperatures, which are rising faster than the ocean and global mean temperatures. {4.3.3.1, 4.5.2}

In addition, none of the 20 Aichi Biodiversity Targets for terrestrial biodiversity, agreed in 2010, were fully achieved by 2020. While good progress was made on the components in four out of 20 targets, including protected area coverage and preparation of national biodiversity strategies and action plans, the progress on the other six targets was slow. Overall, 12 out of 16 indicators used for reporting showed significantly worsening trends. The Kunming-Montreal Global Biodiversity Framework, endorsed at the 15th Conference of the Parties of the Convention on Biological Diversity in 2022, has a set of indicators that are presently being operationalized. {4.5.4} **Efforts under internationally agreed conventions to tackle soil pollution and contamination have shown severe implementation challenges.** {4.5.3}.

4.1 Introduction

Is the world running out of productive land? How much is left for food, biodiversity, housing, infrastructure, and leisure? What is the effect of land grabbing on land availability? Land grabbing can drive land use changes, biodiversity loss, and carbon sequestration and lead to conversion from smallholder to commercial use, impacting Indigenous as well as local communities (Gilbert 2017; Wilkinson 2017).

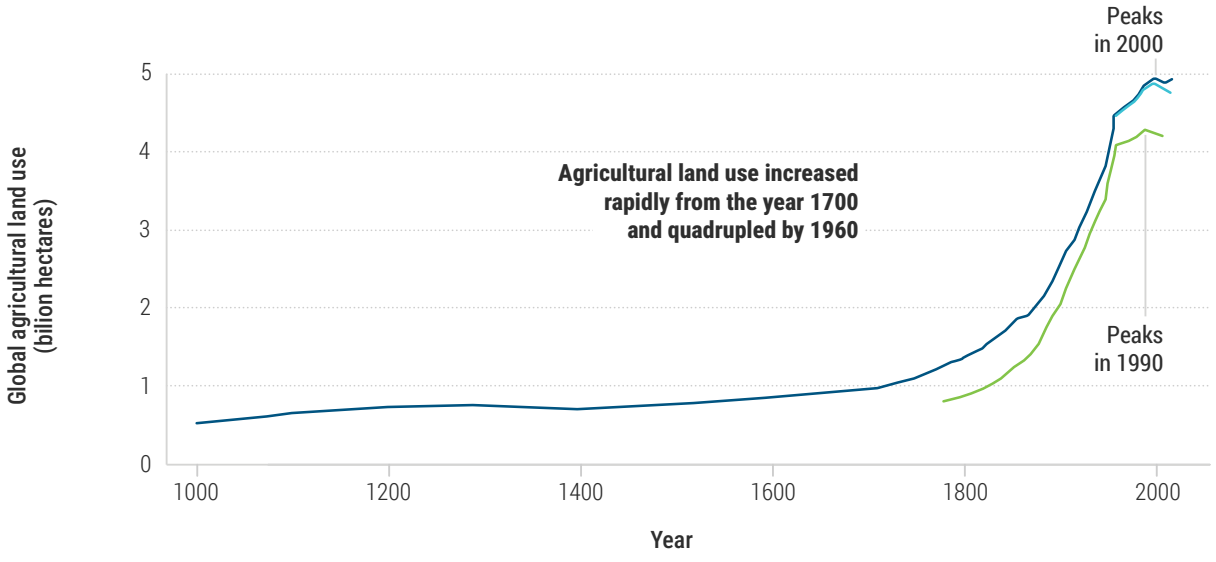
In 2019, the urban population exceeded the rural population (McNabb 2019), and by 2050, 68 per cent of the global population will reside in urban areas (Schug et al. 2023; Tang et al. 2024), occupying some of the most fertile soils on the planet. The rapid expansion of built-up areas can lead to environmental pressures worldwide (Yan et al. 2022). For instance, since the mid-1950s, the total surface area of cities in Europe increased by 78 per cent (Build Europe 2022), contributing significantly to soil sealing and its adverse effects on biodiversity loss, flooding, contamination (Espinoza-Tofalos et al. 2025) and water scarcity.

These effects can have major impacts on food security, regional weather patterns, climate change, hydrology, biodiversity and livelihoods (Hang et al. 2020; Wang et al. 2022) as the world continues to experience rapid environmental degradation (Diaz et al. 2019). Humans have substantially changed the Earth's surface, especially over the last two centuries (Wiedenhofer et al. 2021; Potapov et al. 2022), causing dramatic impacts on ecosystems **(Figure 4.1).**

Globally, between 20 per cent and 40 per cent of Earth's land area – more than 2 billion hectares – is degraded, jeopardizing the livelihoods of more than 3.5 billion people (mostly women and older people), about 40 per cent of the world population (UNCCD 2022; Chinweze 2023). According to the United Nations Convention to Combat Desertification (UNCCD), we are losing the equivalent of four football fields to land degradation every second.

A full 71 per cent of the Earth's surface is covered by water, and only half of the remaining 29 per cent of land is suitable for biomass production. The United Nations

Figure 4.1: Historical trends in global agricultural land use including croplands and pasture for livestock



- HYDE 3.2 database
  - Measured from national census data, combined with gridded data of population density and land modelling.
  - Global agricultural land use peaked around 2000 (Goldewijk et al. 2017).
- FAO (2024)
  - Measured from national census data, country reports and expert estimates.
  - Global agricultural land use peaked around 2000.
- Taylor and Rising (2021)
  - Measured from national census data, combined with gridded data of population density and land modelling.
  - Global agricultural land use peaked in the 1990s.

Source: Adapted from OurWorldinData.org/land-use

Food and Agriculture Organization (FAO) estimates that food production should increase by 60-70 per cent (FAO 2022b; van Dijk et al. 2021) to meet the needs of a population projected to reach almost 10 billion by 2050. Meanwhile, about 30 per cent of global food produced is still being wasted (Jaglo et al. 2021; United Nations Environment Programme (UNEP 2024c). In Italy alone, yearly food waste costs €15.6 billion (International Observatory on Food and Sustainability, 2024). According to the Food System Economics Commission, food systems have an enormous impact on the environment, as one-third of greenhouse gas emissions worldwide and 70-80 per cent of global biodiversity losses are related to food systems, suggesting a radical overhaul of how food is produced, distributed and consumed. Changing tax incentives and human diets could create US$10 trillion of yearly benefits through reduced carbon emissions, pollution, biodiversity loss, and positive impacts on human health (Ruggeri Laderchi et al. 2024).

Soil provides 95 per cent of our food needs (Kopittke et al. 2019). However, the world has used much of the available arable lands **(Figure 4.2)**, while converting forests, grasslands, and natural areas into cropland poses significant risks to biodiversity and the release of carbon. Furthermore, land abandonment can also have consequences on biodiversity (Crawford 2024). At the same time, millions of hectares of unproductive land could be converted into conservation zones that enhance biodiversity and soil carbon sequestration (Xie et al. 2019; Folberth et al. 2020) or used for renewable energy production (Muscat et al. 2020).

Data from FAO shows an increase in forest surface area between 2015 and 2019, from 39 to 40 million km^2, and shrubland, from 12 to 17 million km^2, while agricultural land shrank by 3 million km^2, largely due to urban sprawl (Bren d'Amour et al. 2016; Xie et al. 2023; Canadians for a Sustainable Society, 2023). Most agricultural land is used for livestock, about 77 per cent or 37 million km^2. In comparison, only 23 per cent or 11 million km2 is used for crops (**Figure 4.2**). Small farms, those smaller than 2 hectares, make up 84 per cent of all farms globally but operate only about 12 per cent of the world's farmland, whereas the largest 1 per cent of farms in the world control more than 70 per cent of the world's farmland (FAO 2019). Organic agriculture accounted for 75 million hectares globally, just 1.6 per cent of total global agricultural land (FAO 2024b).

Land and soils deliver vital ecosystem services beyond their provisioning role in agricultural production. Notably, soils play a crucial role in sustainable development as both sinks and sources of carbon. Soil holds more carbon than aboveground vegetation and the atmosphere combined (Lehmann and Kleber 2015), but whether this carbon remains stored depends on how soil is managed.

The amount of carbon stored in soils is roughly 300 times greater than that released annually from burning fossil fuels. Emissions from land use change due to loss of biomass and soil organic matter are estimated to contribute 25 per cent of atmospheric carbon dioxide (CO_2) (Le Quéré et al. 2015; Intergovernmental Panel on Climate Change [IPCC] 2019). Over the past 12,000 years, the global expansion of arable farmland has released approximately 110 billion metric tonnes of carbon from topsoil (Sanderman et al. 2017), roughly equivalent to 80 years of current US emissions (US EIA 2020).

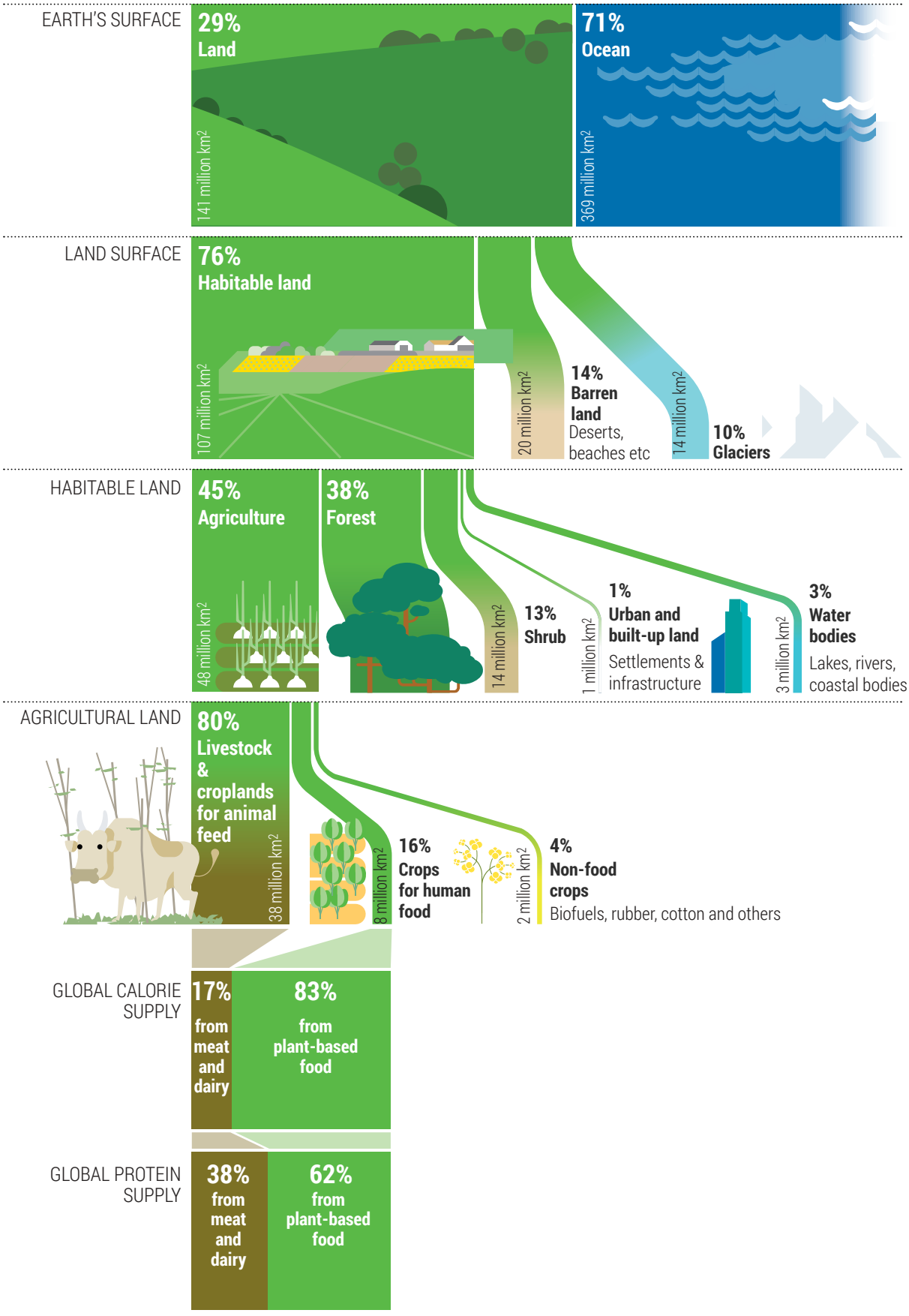
Land and soil only caught the attention of decision makers in the context of climate change in the past two decades, even as the world continues to face land degradation and resource depletion. **Box 4.1** reports new findings from global assessments since GEO-6 (UNEP 2019).

4.2 Pressures on land and soils

The latest global land use data reveals a diverse picture with contrasting trends and intense competition for land resources, especially between forests and cropland. From 2000 to 2020, cropland mainly increased in Sub-Saharan Africa (Masolele et al. 2024), South East Asia, and Latin America, but declined in North America, Europe, and East Asia. While deforestation is decreasing in some regions, it is increasing rapidly in others.

South America exhibits the most prominent transition from forest to cropland. Deforestation in the region amounts to 75.70 Mha or 11 per cent of the total global land use change with conversion of natural vegetation, particularly forests, into croplands (Zabel et al. 2019; Armenteras et al. 2017; Móstiga et al. 2024). Colombia hosts unique ecosystems for biodiversity, such as páramos that hold vast amounts of water, but 57 per cent of these ecosystems have been lost (Moran Cortes et al. 2022). Those converted to agriculture have lost their biodiversity and vegetation and become compacted from the excessive use of agricultural machinery, resulting in significant degradation.

Figure 4.2: **Global land use for food production in 2019**



Source: Adapted from UNEP (2023)

Box 4.1: Key findings on land and soils from assessments published since GEO-6

Humans have transformed over 70 per cent of the global land cover, and up to 40 per cent of the planet's land is degraded (UNCCD 2022). Erosion remains severe, exceeding 10 to over 100 times the rate of soil formation (IPCC 2019, IPCC 2023a). As well, 40 per cent of the world's agricultural land is already damaged, and more than three-quarters is experiencing drier conditions (UNCCD 2022). The most significant sources of carbon emissions from land use change are tropical deforestation and peatland burning and draining (IPCC 2022a). Peatlands alone emit 1,941.2 megatonnes of CO_2 equivalents annually (UNEP 2022).

Despite the declining rate of global deforestation, 10 million ha of forests per year were lost between 2015 and 2020 (FAO 2022a). As of 2020, the total carbon stock in forests was estimated to be 662 Gt, an average of 163 tonnes/ha (FAO 2020). However, efforts in reforestation and improved forest management are paying back; between 2011 and 2020, forests absorbed more carbon than they emitted (FAO 2022a).

A forest restoration project by CIFOR-ICRAF using a 'Nelder wheel' design to support ecological restoration and reforestation efforts in Kisangani in the Democratic Republic of Congo. Credit: Fiston Wasanga/CIFOR

Of the world's 823 terrestrial regions, 42.4 per cent have at least 17 per cent of their area protected (Secretariat of the Convention on Biological Diversity [CBD] 2020). In addition to protected areas, Indigenous lands help maintain higher biodiversity and species abundance (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES] 2019). However, terrestrial biodiversity continues to be negatively impacted by habitat loss, invasion, pollution, overexploitation, and climate change. Local species populations have declined in around 50 per cent of observed terrestrial plant and animal species, often due to extreme climate events (IPCC 2022a). Approximately 9 per cent of the world's estimated 5.9 million terrestrial species are at risk of extinction in the coming decades due to insufficient habitat for long-term survival (IPBES 2019).

Forest area is expanding in Europe, North America, and certain parts of Asia, where notable strides have been made in forest conservation, restoration, and rejuvenation efforts (Du et al. 2023). The area planted with forest in Central Asia has been rising at rates of 3.68 MHa/year and 4.62 MHa/year for 1990-2000 and 2000-2010, respectively (Potapov et al. 2022). However, after 2010, planted forest expansion slowed to a rate of 2.78 MHa/year.

Satellite data for land-use change patterns between 1992 and 2020 show that the most prevalent land use transitions occurred between cropland and forest and vice versa. Global changes from forest to cropland represented 129.89 Mha, while changes from cropland to forest were only 85.70 Mha. Urban encroachment expanded from 1992 till 2020 primarily at the expanse of cropland, accounting for 46.14 Mha, or 67 per cent of the urban-related land use changes, representing a worrying trend that may have consequences on food supply and food security (Nuissl and Siedentop 2021). Urbanization occurred primarily in Europe, India, China (Li et al. 2024), and Latin America (Giobellina and Vitale 2022), coinciding with the conversion of croplands and natural habitats.

Terrestrial ecosystems include a variety of biomes, including tundra, taiga, temperate deciduous forest, tropical rainforest, mangroves, grassland, permafrost, deserts, Mediterranean scrub, and coniferous forests. Each of them has unique ecosystem functions and services. Rangelands cover 54 per cent of the Earth's land and sustain 69 per cent of agricultural areas for animal production (International Livestock Research Institute et al. 2021). The northern permafrost region that covers approximately 15 per cent of the Earth's land area, extending from the Arctic Ocean's coastline through much of Alaska, northern Canada, and North Eurasia, contains roughly one-third of all soil carbon in its frozen soils, equivalent to more carbon than humans have ever released (Patzner et al. 2020). The global climate would be significantly affected if those carbon stores were released due to permafrost thawing. Other important ecosystems are karst landscapes that occupy approximately 20 per cent of terrestrial ice-free areas globally and are major geomorphological features in North America, Europe, the Middle East, Asia and Australia (Goldscheider et al. 2020; Zhang et al. 2023).

Terrestrial ecosystems are under pressure from anthropogenic factors and climate change. Tropical forests are affected by deforestation, many grasslands are overgrazed, while large deciduous forest areas were severely damaged by forest fires, as in Canada in 2023 (National Aeronautics and Space Administration 2023). With over 75 per cent of the Earth's land already degraded, and over 90 per cent that could become degraded by 2050 (Hill et al. 2018), humanity has reached the point where, without action, the situation will further degrade with severe consequences and irreparable damage and reach a point of no return. Moreover, forest degradation emits the same or more carbon than deforestation, and it can cause a disruption in the hydrological cycle and cause further biodiversity loss (Lapola et al. 2023).

One third of the world's land surface is threatened by desertification, and over 4 million km^2 of land is being degraded yearly, while one-third of global soils are already degraded (UNCCD 2022). Land degradation, particularly soil erosion, combined with climate change, is estimated to reduce global crop yields by about 10 per cent by 2050. The greatest impacts are expected in India, China and Sub-Saharan Africa, where land degradation could halve crop production, mainly due to the prevalence of monoculture farming systems (The World Counts 2023).

The pressures on land and soils described in Chapter 2.3 and section 4.2 above each contribute to a varying degree to the global environmental crises of climate change, biodiversity loss, land degradation and desertification, and pollution and waste. Section 4.3 below shows how the global environmental crises interconnect with the natural system of land and soils.

4.3 State and trends of the land

4.3.1 Land and soil pollution

Chemical pollution is currently the most serious environmental threat to humanity. With approximately 220 billion tonnes of chemical substances emitted yearly, chemical pollution is five times greater than climate emissions (Cribb 2023). According to the World Health Organization (WHO 2016), every year 13.7 million deaths, or 24 per cent of deaths globally, and 600 million disabilities are linked to chemical pollutants. Despite its severity, the global understanding of chemical pollution remains fragmented (Naidu et al. 2021).

Chemical pollution has point or non-point sources in soil, water and air (Naidu et al. 2021). Point-source pollution refers to industry effluent containing toxic chemicals (e.g. heavy metal(loid)s or hydrocarbons), the source of which can be easily identified. Non-point sources are challenging to locate as they could come from various sources. As a sink for many chemical pollutants, soil is a major source of chemical exposure to humans and other organisms (Rodríguez-Eugenio et al. 2018).

Soil pollution is driven by multiple factors, including inadequate legislation in many countries to prevent, manage or remediate contaminated sites, resulting in continued chemical pollution. Significant gaps remain in identifying the location of highly contaminated sites and their environmental consequences and understanding the effects of the contamination caused by chemical dispersal (FAO and UNEP 2021). Industries, such as mining, mineral processing, farming, and construction, discharge trillions of tonnes of chemically active material into the environment each year (Cribb 2021). Global chemical inventories suggest that there are over 350,000 chemicals registered for production and use (Wang et al. 2020), many of which could be toxic even in small doses, whether alone or in combination with other pollutants or as breakdown products following release in the environment. This chapter focuses on pollution drivers primarily associated with chemicals of concern and chemicals that receive less attention. These are detailed in 4.3.1.1 to 4.3.1.6.

4.3.1.1 Pollutants associated with mining

Mining has long been the primary source of earth materials such as coal and iron ore. Although advances in recycling technologies have reduced dependence on mining for some resources, overall mining activity continues to rise due to growing demand for such materials as copper, lithium, and other rare earth oxide materials. Mining waste contains harmful heavy metals, including cadmium, lead, zinc, arsenic, and mercury, which pose significant risks to biodiversity and human health. Mining activities release these metals into the atmosphere, from where they settle in the soil, contaminating water through direct infiltration, surface runoff, accumulation and precipitation, or absorption by plants (Moghimi Dehkordi et al. 2024). Rare earth oxide material production reportedly reached nearly 300,000 metric tonnes in 2022, a dramatic increase compared to the previous decade (Statista 2023). Mining rare earth minerals results in significant emissions (Golroudbary et al. 2021), disrupting the soil nutrient cycle and generating large quantities of waste during extraction, with waste comprising often more than 90 per cent of the total volume of mined materials.

Mining operations in many countries remain one of the largest polluting sectors, accelerated by increasing economic growth and the industrialization of lower-income agrarian economies (FAO and UNEP 2021). Significant sources of contaminants are the tailings (leftover extractants and residues stored in mining sites), acid drainage, dust generation and deposition, and hydrogeological alterations caused by mining **(Figure 4.3)**.

Chen et al. (2022) analyzed metadata from reports on 102 copper mine sites worldwide. Contamination levels from exposure to copper and cadmium were recorded as moderate to alarming at sites in Oman, China, Australia, and the United Kingdom of Great Britain and Northern Ireland. Associated metalloids, such as arsenic, were also found to be toxic to the ecological receptors in the mines or their surroundings.

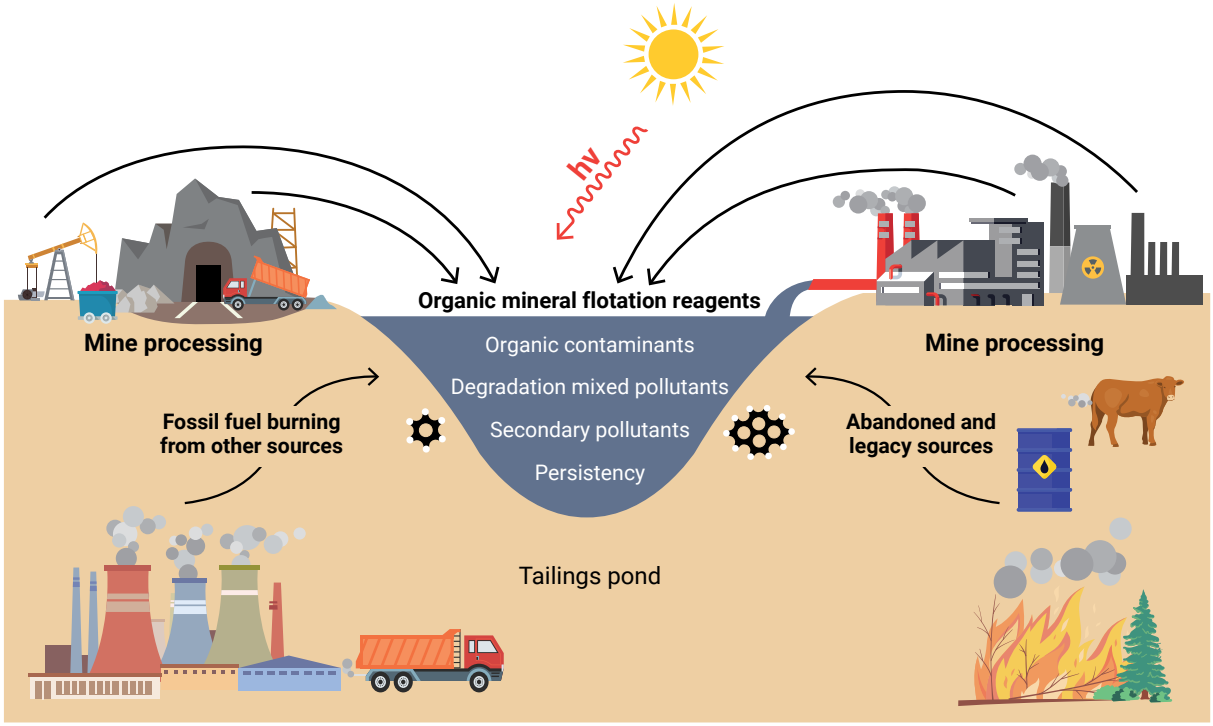
The Minamata Convention on Mercury mandates reducing or eliminating mercury in mining and artisanal activities (Chapter 3.5.5).

4.3.1.2 Chemical pollution from the application of agrochemicals

Agrochemicals, including fertilizers, pesticides, insecticides, and herbicides, are major contributors to diffuse pollution. For example, cadmium linked to phosphate, nitrogen and phosphorus fertilizers, or pesticide migration through the soil layers can cause diffuse pollution of rivers, coastal areas, lakes, and other waterbodies. The extent and severity of contamination often correlate with the country's economic development level. A significant concern is the export of prohibited chemicals from affluent countries (e.g., within the European Union) to lower-income nations. This practice, sometimes referred to as "chemical colonization," has resulted in widespread contamination in regions such as South America, Africa, and Asia, where regulatory frameworks are often weak due to political and economic pressures from wealthier producer countries (Bombardi 2019).

Pollution caused by agrochemicals has complex, far-reaching impacts. Soil is the initial repository where

Figure 4.3: Organic pollutants' source and transport linking to mining operations



Source: Modified from Zhang et al. (2020)

these chemicals accumulate or migrate (Foster and Chilton 2021). The United Nations Environment Programme's global partnership on nutrient management states "an excess of nutrients in the environment because of industrial and agricultural activity has profound impacts, from the pollution of water supplies and hence eutrophication to the undermining of important ecosystems and the services and livelihoods they support." (UNEP 2023a).

Despite its strong links with agriculture and cities, diffuse pollution is yet to be recognized in most countries. Even in low concentrations (ranging from microgram/g to ng/g), agrochemicals can pose potential risks to human and environmental health due to their bioaccumulation in the food chain and their potential to disrupt ecosystems and human biological processes. While diffuse pollution is linked to agriculture, no specific policies currently exist to regulate it. Furthermore, current monitoring systems are limited to detecting conventional pollutants, leaving recently emerged and emerging pollutants largely undetected.

4.3.1.3 Recently emerged and emerging pollutants

Contaminants of emerging concern (CECs) are recently identified chemicals, materials, and biological agents whose environmental and human health impacts are not yet fully understood. Growing concerns surround CECs, such as per- and polyfluoroalkyl substances (PFAS), microplastics, pharmaceuticals, and antimicrobial resistance, all of which raise concerns for land and soil health (Knapp et al. 2021; Pagaling et al. 2023; Wang et al. 2024). Along with these, contamination by radioactive materials originating from uranium mining and nuclear accidents, such as caesium-137 in Chernobyl, and their persistence in soils are yet to be thoroughly investigated and understood.

Aqueous film-forming foams that contain PFAS, commonly known as "forever chemicals" and used to extinguish fuel-based fires in training and fire suppression activities, have resulted in numerous contaminated sites (Das et al. 2013), including airports, defence facilities, mineral and petroleum industrial sites, firefighting training facilities and oil refineries. Wide ranges of consumer products incorporate PFAS, including textile, water-resistant fabrics, cleaning products, grease-resistant paper, non-stick cookware, refrigerants, building materials. More than 10,000 PFAS exist, but only a fraction is routinely monitored by most laboratories. These chemically stable, toxic compounds represent a serious global problem for environmental regulators, practitioners, and owners of the affected sites.

Plastic pollution has gained significant attention in recent decades. In agricultural settings, plastic mulch is a major source of small plastic particles in soil. More broadly, large quantities of plastics are dumped in landfills, rivers and oceans, representing a significant source of pollution (Chapter 5.2.2.1). An estimated 70-80 per cent of ocean plastics originates from land-based sources, transported via rivers and coastal run-off. Previous studies suggested that a small number of rivers contribute disproportionally to this pollution: (Li et al. 2016), one study estimated that the top ten rivers were responsible for 50-60 per cent; another study put the figure at over 90 per cent (Lebreton et al. 2018). Of the roughly 9.2 billion tonnes of plastic produced during 1950-2017, nearly 76 per cent has ended up as waste, carried through rivers (UNEP 2024a). Over time, plastics break down into micro- and nanoplastics that are ubiquitous due to their small size and interactions with organic matter, affecting both terrestrial and aquatic ecosystems (Lang et al. 2024; Sobhani et al. 2022). As the efforts to manage plastic pollution are increasing, the emerging risks associated with micro- and nanoplastics are gaining attention, driven by increasing research efforts to understand their environmental effects (Udovicki et al. 2022; Cheng et al. 2024).

Microplastic and nanoplastic pollution disrupts ecosystems and may pose serious risk to human health. (Yang et al. 2021; Nature Medicine 2024). MacLeod et al. (2021) highlighted the potential of plastic pollution to affect nutrient cycles and biodiversity, while Masson et al. (2023) suggested that nanoplastics can modify soil properties, release contaminants and harm soil biota.

Along with microplastics, growing concerns are linked to emerging contaminants (Persson et al. 2022) associated with pharmaceuticals, pesticide metabolites and thousands of synthetic chemicals released into the environment every year. Despite their widespread use, less than 20 per cent of these chemicals are assessed for potential environmental and human health risks, mainly due to gaps in global policies on synthetic chemicals. Contaminants from soils can accumulate in plants and animals, threatening food quality.

4.3.1.4 Aerosol deposition

Aerosols are liquid or solid particles suspended in the atmosphere with complex chemical compositions originating from various sources, such as burning biomass, transport cooking, volcanic ash, and sandstorms. When aerosols carry chemical pollutants such as sulfates, nitrates, heavy metals, hydrocarbons, microplastics, and mineral dust, they pose an environmental risk.

Soil pollution from aerosol deposition can occur in several pathways (Tong et al. 2023). Pollutants settle on surfaces from precipitation, climatic events, or the movement of aerosol contaminants in the air, increasing human exposure risk. Aerosol pollutants migrate globally through airborne particles, gases and aerosols, water-borne suspended particles, and dissolved pollutants (Naidu et al. 2021).

4.3.1.5 Persistent Organic Pollutants

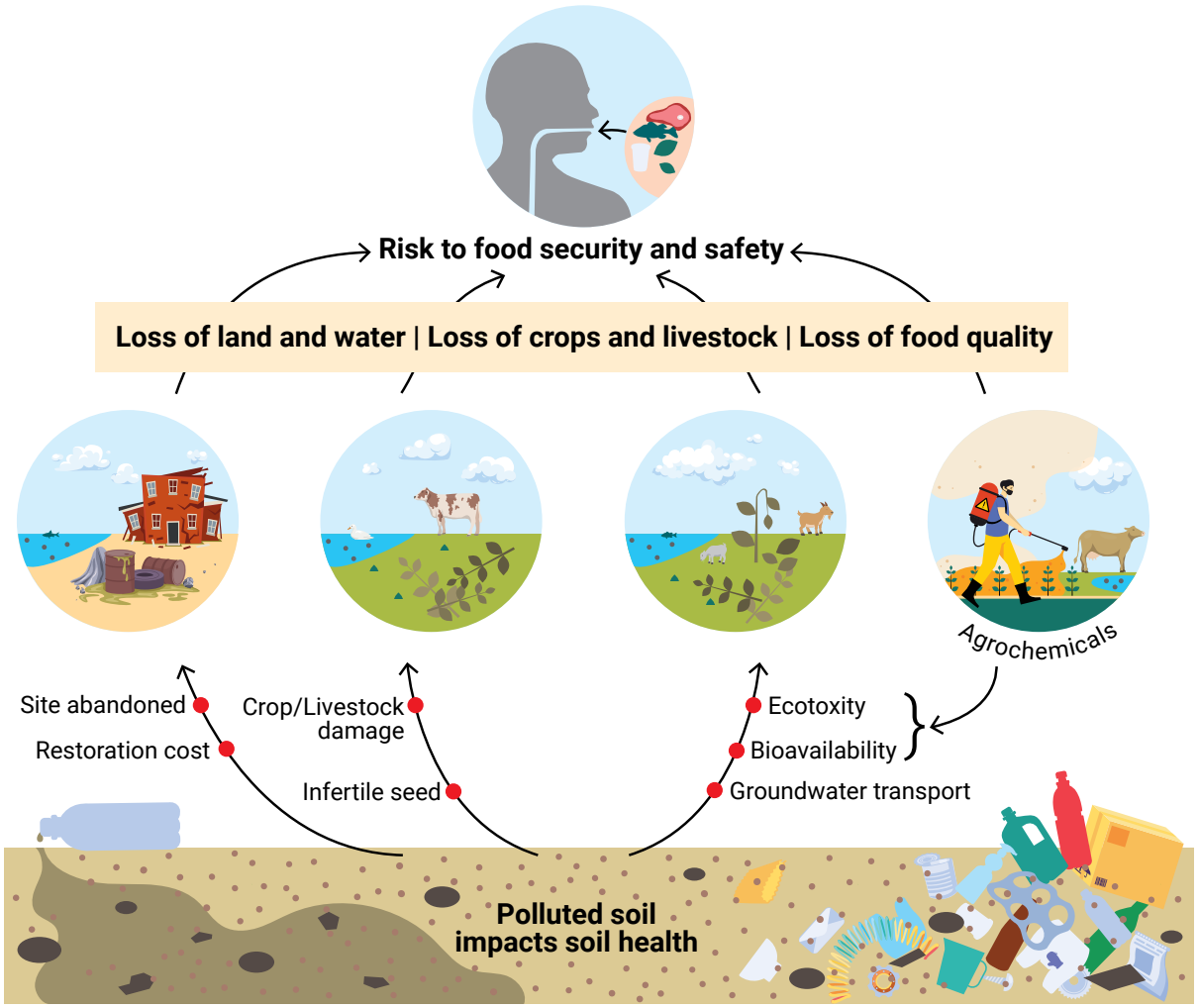
Climate change's critical yet highly uncertain effect is its impact on harmful pollutants, such as PFAS, DDT, and dioxins, that resist degradation, travel long distances through the atmosphere and hydrosphere, and enter food chains, affecting animals and humans. While the potential impacts are significant, they remain under-researched. Key concerns include changes in UV radiation, re-mobilization of persistent organic pollutants due to melting ice, extreme events, and the resulting effects on human health (Nadal et al. 2015) and crop production (Zandalinas et al. 2021).

4.3.1.6 Waste

Globally, the annual volume of municipal solid waste amounts to 2.1 billion tonnes (UNEP 2024) and is projected to increase to 3.8 billion tonnes by 2050 (Alves 2023; UNEP 2024). This trend becomes even more pronounced when hazardous wastes are included. For example, in 2023 alone, the medical, industrial, electronic, mining and agricultural sectors in the United States of America generated over 350 million tons of hazardous waste (Hazardous Waste Haulers Environmental 2023).

Worldwide, irrespective of country or production lifecycles, industrial waste is often stockpiled and dumped, frequently on Indigenous lands (Paul and Caplins 2020), or ineffectively recycled. This mismanagement has negative environmental and human health consequences, lost land productivity and high material management costs.

Figure 4.4: The effect of chemical pollutants on food security and food safety



Source: Naidu et al. (2021)

While multiple conventions address waste management, the mandate differs from country to country. In high-income nations, the concept of waste circularity is more widely recognized and implemented, while in low-income countries, a lack of financial investment and regulation hinders progress. As waste continues to pose significant environmental challenges, advancing an integrated, circular economy-driven waste management is a critical priority at national, regional, and global scales. Notably, many Indigenous Communities practise principles of circularity, offering alternative solutions (Beamer et al. 2023; Siragusa and Arzyutov 2020).

4.3.1.7 Impacts on carbon/nutrient cycle, ecosystems and biodiversity

Contaminants know no boundaries; they can be found anywhere and, by definition, pose a risk to human health and ecosystems (Fuller et al. 2022). Globally, around 10 million potentially contaminated sites have been recorded (Li et al. 2024), though the actual number is likely much higher. Compounding this issue is the emergence of new chemicals that humanity has yet to assess for their environmental impact, which may pose a greater risk to ecosystems as exposure increases.

Contaminants may enter the food chain and bioaccumulate, undermining food quality and ultimately food security and safety **(Figure 4.4)**. Wildlife, fish, and humans are exposed to persistent organic pollutants, heavy metals, pesticides, radioactive nucleotides, and substances from the persistent bioaccumulative and toxic and persistent mobile and toxic hazard classes, which are all detrimental to food safety and pose serious health risks (Kelly et al. 2007; WHO 2022a; Johnson et al. 2020).

Credit: irestock/Envato

Pollution affects agricultural productivity, resulting in lower yields or loss of cropland (Biswas et al. 2018; Naidu et al. 2021). Excessive use of agrochemicals and chemical pollution from other sources damages soil quality, leaving it more vulnerable to the effects of climate change and associated aridity that contributes to soil salinity (Okur and Örçen 2020). In addition to soil pollution, air pollution – including black carbon, hydrofluorocarbons, and tropospheric ozone – also significantly reduces crop yields, with potential losses of up to a 50 per cent decrease in expected production (Burney and Ramanathan 2014; Liu and Desai 2021).

4.3.2 Land and soil degradation

Land degradation results from a combination of drivers and pressures such as population growth, poor land management, unsustainable agriculture, pollution, land use conversion, bush encroachment, and deforestation (UNCCD 2022a). These pressures have severe consequences on food security and migration. Key land degradation processes in arable land include aridity, vegetation decline, soil erosion by water and wind, soil salinization, and soil organic carbon decline (Prăvălie et al. 2021). Other processes include soil contamination, compaction, soil sealing and landslides. Aridity affects 40 per cent of arable lands, and erosion affects 20 per cent of land globally (Prăvălie et al. 2021). These two factors represent the most significant pressures, singly and in combination, on land resource degradation. Some estimates predict that up to 95 per cent of the Earth's soils could be degraded by 2050 (Save Soil 2024).

In 2022, the UNCCD estimated that 20-40 per cent of the world's land area was degraded to various degrees (UNCCD 2022), a significant increase from just under 20 per cent in 2017 (UNCCD 2019; United Nations Economic and Social Council 2019). The rise is attributed mainly to unsustainable land use and management practices. In the European Union, 60-70 per cent of soils are considered unhealthy, and more than 2.8 million

potentially contaminated sites have been identified (European Commission 2020).

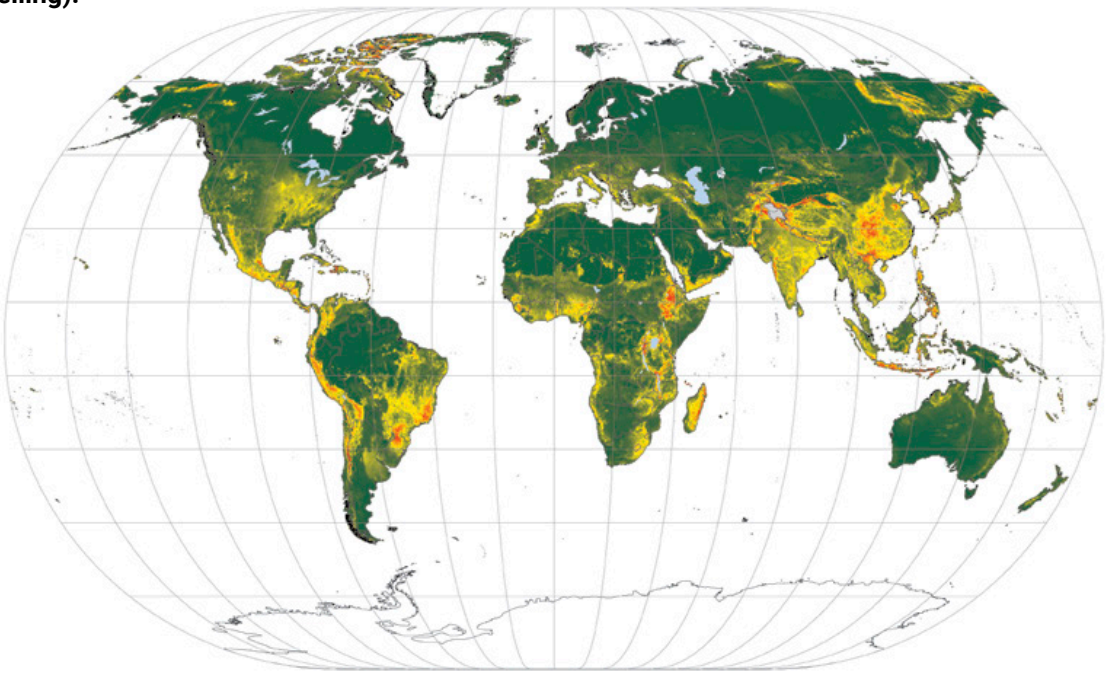
Unsustainable agricultural practices – including continuous cultivation of arable lands, tillage practices such as up and down slope cultivation, degradation of vegetation cover, and a lack of intercropping, diversification and crop rotations – intensify soil erosion. Such practices cause an estimated loss of 24 billion tonnes of fertile soil every year, the equivalent of 3.4 tonnes for every person on the planet (International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), 2009) (**Image 4.1**; **Figure 4.5**). Erosion depletes soil nutrients, diminishes soil productivity and soil organic carbon, and deteriorates ecosystem services. Often, the off-site damage from erosion, such as flooding and sedimentation, is far more severe than on-site (Boardman et al. 2019). Panagos et al. (2024) estimated that removing 1 billion m^3 of sediments due to erosion in the European Union costs €5-8 billion annually.

Coastal erosion remains a significant issue. The economic toll of coastal erosion and associated coastal defences is substantial, particularly in Africa, Europe, the Caribbean, Australia and the the United States of America (Heger and Vashold 2021; European Environment Agency 2006; Ellis and Bajracharya 2023). Arctic coastlines are especially vulnerable, with erosion rates reaching up to 10 m per year. Arctic coastal erosion is predicted to become increasingly sensitive as global temperatures rise, reaching 0.4–0.8 metres per year for every 1°C of warming and releasing 2.3–4.2 teragrams of carbon annually per degree of warming by the end of the century (Nielsen et al. 2022).

4.3.2.1 Drought

Land degradation driven by drought can severely affect local populations (Hill et al.2018; Walker and Van Loon 2023; European Commission Joint Research Centre and UNCCD 2024), particularly affecting women, older people and children. There are four types of droughts: meteorological, hydrological, agricultural, and socioeconomic. While the first three focus on physical processes, socioeconomic drought reflects broader impacts of water shortages on supply, demand, and socioeconomic systems

Figure 4.5: Soil erosion estimates predicted through the GloSEM platform (Global Soil Erosion Modelling).



The map illustrates the soil erosion rates divided into seven classes according to the European Soil Bureau classification

Source: Borrelli et al. (2020)

Image 4.1: Agricultural practices such as up and down slope cultivation can exacerbate soil erosion. Credit: Garakta-Studio/Envato

(Wilhite and Glantz 1985; Lee et al. 2022) (Chapter 3.2.3, Chapter 6.3.2.1). Agricultural drought can lead to crop failure, food insecurity and forced migration (**Image 4.2**). Droughts are considered the second most difficult to cope with after hurricanes (National Geographic, 2023), severely impacting local populations. (McDowell et al. 2022).

Since 2000, the frequency of droughts has increased globally by nearly 30 per cent (IPCC 2022a; UNCCD 2022; United Nations Office for Disaster Risk Reduction 2022), posing a significant threat to agricultural systems and resulting in billions of global economic losses. Droughts can take the form of flash droughts or dry spells with intensified severity due to climate change and devastating impact. Europe, North Africa, North, Central and East Asia, the Sahel and the west coast of South America are particularly vulnerable to drought and climate change (Chiang et al. 2021). However, attributing these trends on a global and continental scale remains challenging due to high uncertainty (Rojas 2020).

In Central Asia, almost a third of the population, 75 million people, lack access to reliable water sources

Image 4.2: A family relocating to another town 70 kilometres away due to drought episodes in Bale Goba, Ethiopia in 2022. Credit: © UNICEF Ethiopia/Nahom Tesfaye

(Yuan et al. 2023). In China the number of hot days is rising, while the average number of rainy days is decreasing (Wang et al. 2023). Eastern China experienced an extreme drought in July–August 2022, affecting 38.3 million people in 21 provinces, including Sichuan and Chongqing, destroying more than 4.1 million hectares of crops with direct economic losses exceeding 32.8 billion yuan (Cao et al. 2024).

Observations indicate increased frequency, duration, and severity of droughts worldwide (Spinoni et al. 2014; Chapter 3.2.3), especially in the Mediterranean (Dittus et al. 2024). Shifting drought regimes are reducing the productivity of natural ecosystems (Feng et al. 2021) and accelerating the severity of heatwaves and wildfires (Vicente-Serrano et al. 2024).

4.3.2.2 Carbon emissions and storage in terrestrial ecosystems

Global CO_2 emissions from land use, land use change, and forestry averaged 1.2 ± 0.7 GtC per year (4.5 ± 2.6 $GtCO_2$ per year) for the 2012–2021 period with a preliminary projection of 1.1 ± 0.7 GtCper year (3.9 ± 2.6 $GtCO_2$ per year) for 2022 (Friedlingstein et al. 2022). Among the tropical forests, the Congo basin has the highest carbon sink (-0.61 Gt CO_2 per year), followed by the Amazonian basin (-0.10 Gt CO_2 per year). In comparison, forests in South East Amazonia have become net emitters (+0.49 Gt CO_2 per year) (Hubau et al. 2020). The highest carbon emitters during 2012–2021 in descending order were Brazil, Indonesia, and the Democratic Republic of the Congo, together accounting for more than half of the global land-use emissions, primarily due to higher deforestation rates (Friedlingstein et al. 2022).

Image 4.3: Aerial view of a palm oil plantation in Sentabai Village, West Kalimantan, Indonesia. Credit: © Nanang Sujana/ CIFOR

Over the past two centuries, net CO_2 emissions from soils have increased by 8 per cent due to land conversion and unsustainable management (Wang et al. 2021). While native grasslands store a significant amount of carbon, drylands, covering more than 40 per cent of the total land area, while supporting 3.2 billion people (Prăvălie et al. 2016) and hosting 50 per cent of global livestock, also play a crucial role. Though drylands store less organic carbon per hectare than humid regions, the vast surface area they cover makes them a significant global carbon sink with high inorganic carbon stocks. Black soils (chernozems) are crucial, holding vast amounts of organic carbon. So are peatlands that cover only 3-4 per cent of the Earth's surface but contain around one-third of the world's soil carbon, double the amount of the world's forests (UNEP 2022). Despite their importance, only 17 per cent of peatlands fall within a protected area. Coastal wetlands also have exceptional carbon storage capacity, storing three to five times more carbon per unit area than tropical rainforests (Teng 2025).

Tropical rainforests store 25 per cent-40 per cent of global soil carbon, despite only covering 7 per cent of Earth's land area (Cusack et al. 2023). Tropical rainforest ecosystems store massive amounts of aboveground carbon and harbour rich biodiversity (Fischer et al. 2023). Unfortunately, tropical forests have experienced the most significant carbon losses due to land use change. Deforestation **(Image 4.3)**, second only to fossil fuels use in terms of greenhouse gas emissions, remains a major driver, with the Brazilian Amazon being the world's deforestation hotspot (Levy et al. 2023). Although deforestation rates in the Brazilian Amazon have recently declined, the region still lost 5,000 square kilometres of rainforest in 2023, an area three times the size of Greater London (Stafford 2024).

Other riparian countries in the Amazon region, such as Bolivia, Peru and Colombia, also face rapid deforestation. For instance, Bolivia lost more than 3.3 million hectares of humid primary forest between 2002 and 2021, with annual deforestation rates exceeding 5.5 per cent yearly (Global Forest Watch 2023). This is especially concerning because primary forests store significantly more carbon than younger regrowth forests (Hong et al. 2025). In Brazil, cattle ranching and increased soybean production for trade with China and Europe continue to drive deforestation (da Silva et al. 2023).

Globally, about 10 million hectares of forest are lost each year, an area the size of Portugal. 95 per cent of deforestation happens in the tropics (Heinrich et al. 2023). Only half of this deforestation is compensated for by forest regrowth. In 2024 alone, Indonesia lost 261,575 ha of primary and secondary forests, more than 4,000 ha (AFP 2024).

Tropical soils are expected to be the first to respond to climate change, with significant carbon losses due to higher mineralization and carbon release. To achieve global conservation and sustainability goals, at least 79 per cent of the world's remaining vegetation must be retained (Simmonds et al. 2023). However, accurately measuring carbon stocks is challenging due to limited field data in many countries; therefore, models are used, but the results of these assessments should be interpreted with caution.

If adequately managed, soils could help mitigate the effects of climate change (IPCC 2019, Harvey 2023). The Coalition for Soil Health (2023) estimates that widespread adoption of sustainable soil management practices could sequester up to 1.8 GtC annually by 2030. Addressing land degradation with sustainable land and soil management could add US$75.6 trillion to world income annually (Economics of Land Degradation Initiative 2019).

The voluntary action plan 4 per 1000: Soils for Food Security and Climate, adopted in Paris in 2015 (Lal 2015), aims to boost global agricultural soil carbon stocks by 4 per 1000 each year to help mitigate climate change and improve food security. This improvement could compensate for all greenhouse gas emissions associated with agriculture while ensuring soil health. Another major effort is the Bonn Challenge, which seeks to restore 350 million hectares of degraded forest landscapes by 2030.

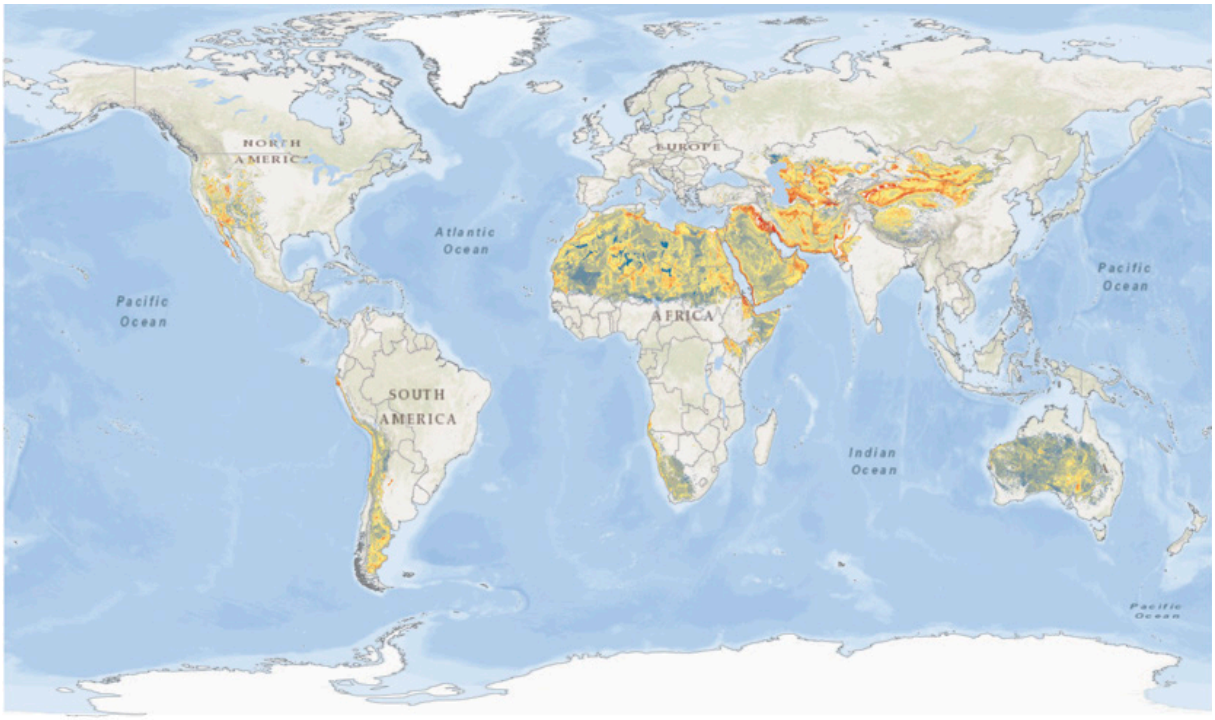
Proven sustainable land management practices (World Overview of Conservation Approaches and Technologies 2025), such as conservation, no tillage (Wang et al. 2025), cover cropping, and crop rotation, demonstrate that reversing land and soil degradation is possible when the right policies are implemented and local communities are meaningfully involved. Healthy land and soils are essential for achieving more than half of the Sustainable Development Goals (SDGs), including climate change mitigation, adaptation, and biodiversity (Lal et al. 2021).

4.3.2.3 Sand and dust storms, and soil erosion

Sand and dust storms can have significant transboundary impacts on the environment, climate, health, livelihoods, agriculture, food security and the well-being of millions of people **(Image 4.4)** affecting 151 countries in Africa, Asia, North and South America, and Oceania, sand and dust storm events can severely impact economic development **(Figure 4.6)**. A single sand and dust storm event can cause economic losses amounting to hundreds of millions of dollars. For instance, a major dust storm in Mongolia in March 2021 killed 200,000 livestock and destroyed 121 animal shelters (FAO 2023c).

Image 4.4: Afghan citizens in Uzbekistan and vulnerable people from host communities engaged in afforestation efforts to combat desertification and dust storms in Surkhandarya region of Uzbekistan, bordering Afghanistan. Credit: © UNHCR/ Elyor Nemat

Figure 4.6: Global distribution of sand and dust storms



SDS Annual Index

1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0

Source: UNCCD (2024a)

Saharan dust frequently reaches southern Europe and the Americas, carrying bacterial and fungal pathogens (Das et al. 2023). It also contributes to soil and ocean fertilization, adding phosphorus, iron and other nutrients through deposition (Ohnemus et al. 2025). Massive dust storms in the Gulf of Alaska can last for days, releasing tonnes of fine sediment into the atmosphere and influencing the global climate system (Barr et al. 2023).

Soil erosion by water is a severe degradation process, affecting soil quality, water resources, biodiversity, carbon cycling, land productivity, and socioeconomic conditions. Studies (e.g. Borrelli et al. 2023) suggest that cropland expansion can potentially accelerate global soil erosion, with the highest increase in Sub-Saharan Africa at 3.51 Mg per hectare per year, South America at 3.53 Mg per hectare per year and South East Asia at 3.47 Mg per hectare per year. Despite considerable research on arable agriculture, almost half of global soil erosion by water occurs in semi-natural ecosystems (Borelli et al. 2017).

Topsoil loss by water or wind erosion is the most significant cause of soil material displacement, with water erosion affecting about 56 per cent of the total land area subject to human-induced soil degradation, and wind erosion affecting a further 38 per cent of that. Chemical and physical soil deterioration affects about 12 per cent and 4 per cent, respectively (UNCCD 2024b).

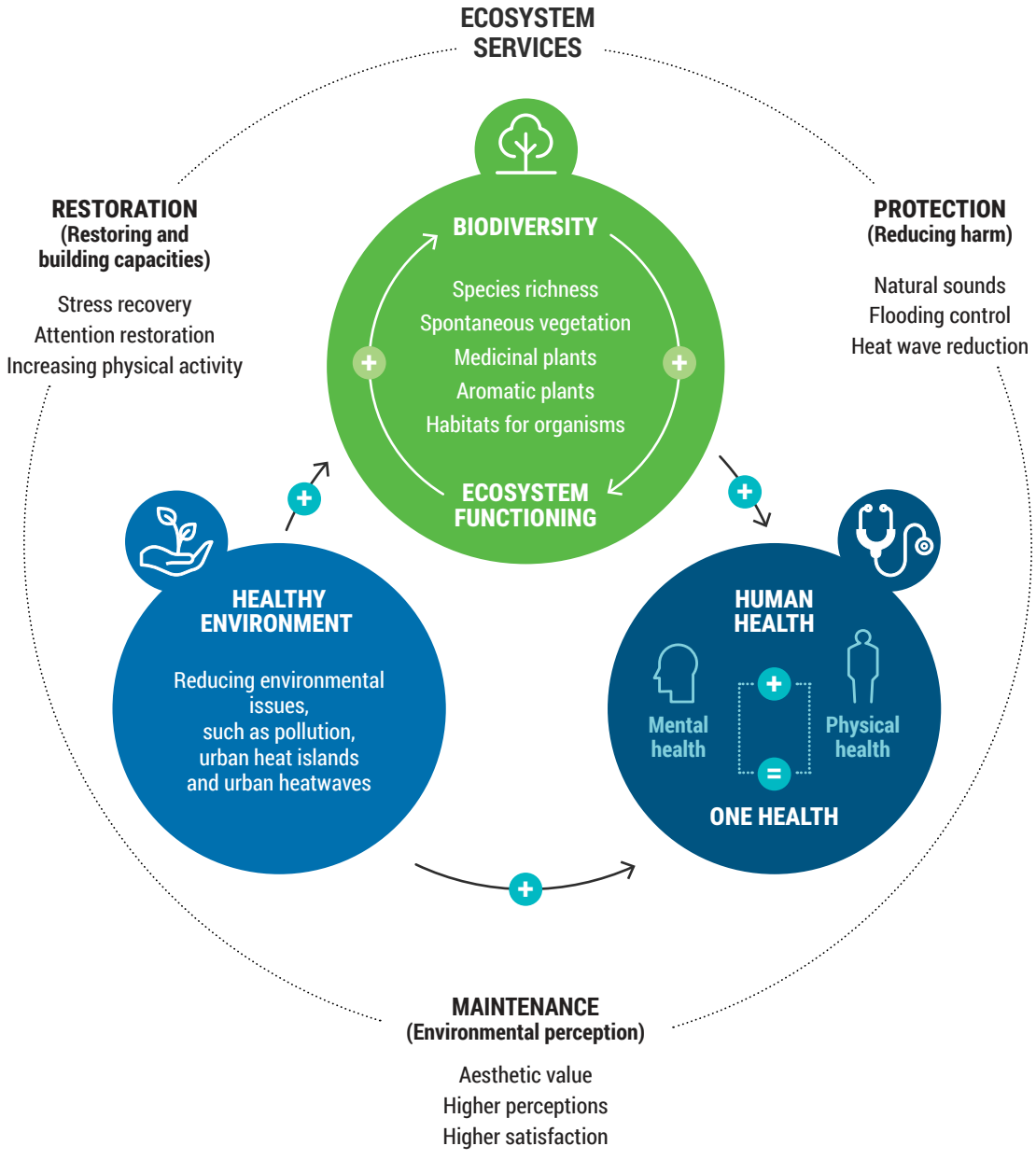
Due to limited data availability, global soil erosion estimates often rely on coarse-scale models. As a result, semi-empirical approaches are used in physical models and to inform policy. (Borrelli et al. 2020) **(Figure 4.6)**. Conservation agriculture, agroecology (Bezner Kerr et al. 2023) and regenerative agriculture –based on minimal soil disturbance, crop rotations and cover cropping – now cover an estimated 11 to 14 per cent of agricultural land globally, or ~1.42 billion hectares (FAO 2022b). These practices could reduce global soil erosion by 7.1 per cent (Borrelli et al. 2017), while maintaining biological soil crusts can reduce erosion and mitigate sandstorms (Zucca et al. 2022).

4.3.2.4 Land degradation, climate change and pollution impact on biodiversity

Land use changes drive biodiversity loss and diminish ecosystem functions and services, with significant consequences on human well-being, especially that of Indigenous Peoples (Isbell et al. 2017; 2023; Tsuji et al. 2023; Brubacher et al. 2024). These impacts vary depending on geographic location and sociological, economic, and political context (Bruley et al. 2021; Folkard-Tapp et al. 2021; DeClerck et al. 2023).

The conceptual framework **(Figure 4.7)** illustrates the link between biodiversity, ecosystem functioning and services, and human well-being, highlighting the crucial role of biodiversity. Restoration, protection and maintenance maintain balance across ecosystems, including urban areas (Zhang et al. 2022). Land degradation, global warming and pollution contribute to the decline of terrestrial biodiversity (Malhi et al. 2020; Ekka et al. 2023) and the ability of ecosystems to provide their services (IPBES 2019; Santini et al. 2022; Petrosillo et al. 2023). Habitat degradation,

Figure 4.7: Conceptual framework showing the interdependence of biodiversity, healthy environment and human health regulated by ecosystem services (protection, maintenance, and restoration)



Source: Zhang et al. (2022)

extensive use of alien species, and overexploitation of bioresources, together with climate change and air pollution, further exacerbate the damage to terrestrial biodiversity and ecosystems (Shivanna et al. 2022; Kanakidou et al. 2022).

4.3.3 Climate change and changes on land

4.3.3.1. Land changes in a warming world

Globally, land has warmed by 1.6°C (IPCC, 2023); if this trend continues, the temperatures would breach the "preferred maximum" threshold described in the Paris Agreement (United Nations Framework Convention on Climate Change, 2016) and raise concerns about crossing the "point of no return" (Hansen et al. 2025). Over 20 per cent of humanity already experiences a warming of 1.5°C during at least one season of the year (Jones 2023). Future climate trends are discussed in Chapter 10.4.1.

The changes related to land warming, such as air temperature, seasonality, precipitation patterns, heatwave incidents, and droughts will affect natural and human systems. Fire weather conditions have intensified in length and severity over the past 40 years globally, counteracting the effects of landscape fragmentation and forest clearing on fuel build-up and fire propagation (Jones et al. 2022). Increases in the frequency, duration, and severity of droughts (Spinoni et al. 2014) are undermining agricultural productivity.

Permafrost thawing drives ecosystem changes, affecting the freshwater cycle, and destroying infrastructure. Climate change-driven shifts in environmental conditions force species to shift their ranges (Chen et al. 2011; Pecl et al. 2017; Davidson et al. 2020; Feeley et al. 2023), threatening ecosystem composition. Land warming also alters phenological events, such as flowering, migration, and hibernation, affecting many species (Inouye 2022; Piao et al. 2019).

4.3.3.2. Changes in terrestrial carbon storage and nutrient cycles

The net land CO_2 flux reflects carbon sequestration through photosynthesis in plant and microbial biomass and soils. In contrast, the release of carbon to the atmosphere is driven by deforestation, shifting cultivation, and land degradation. Land use change generates a carbon pulse of 1.1±0.7GtC/yr, accounting for roughly 10 per cent of anthropogenic CO_2 emissions (Friedlingstein et al. 2022), while the soil carbon sink of 3.1±0.6GtC/yr offsets about 30 per cent of the total CO_2 emissions.

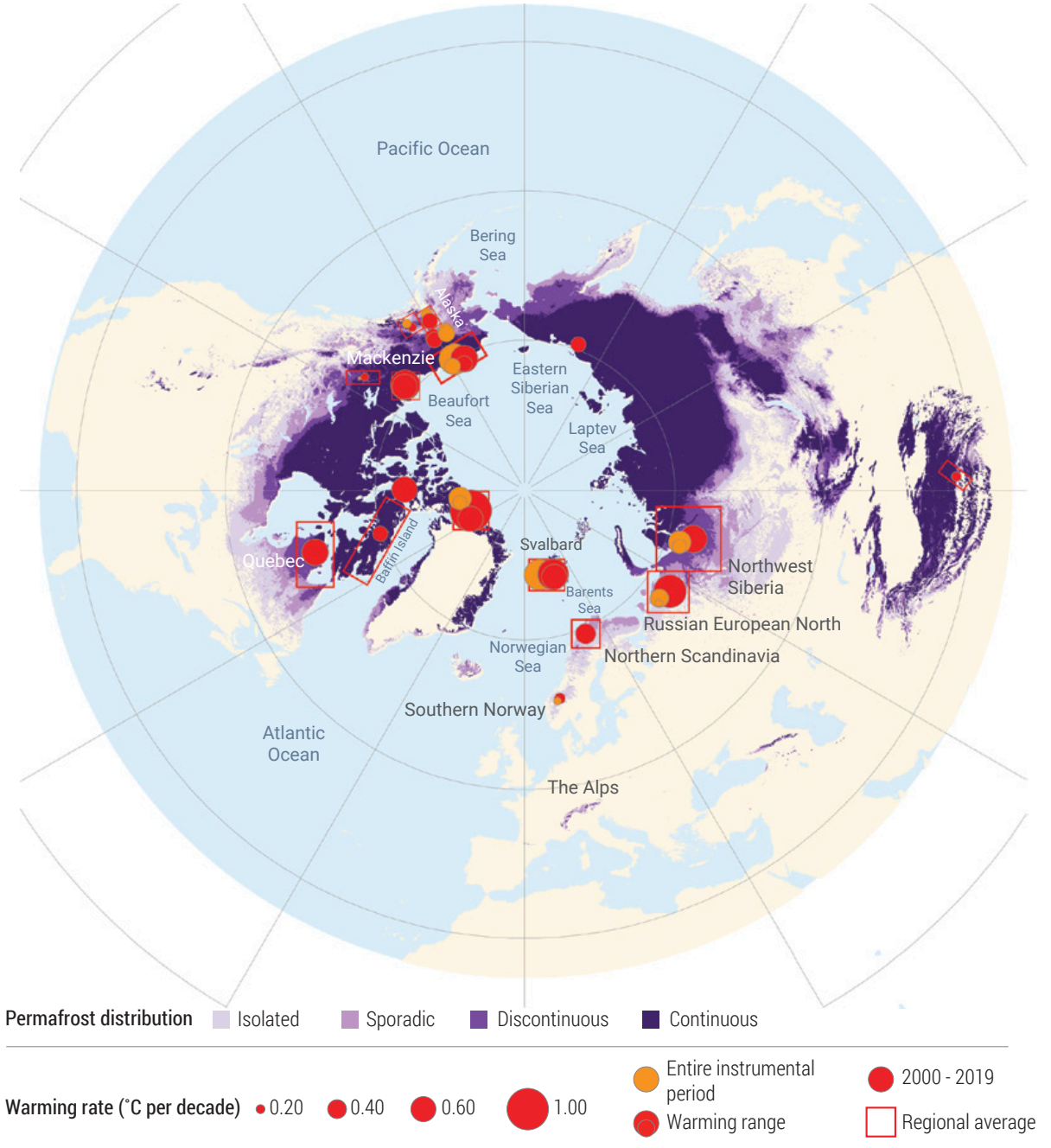
The increase in terrestrial carbon sink is primarily driven by rising atmospheric CO_2, anthropogenic nitrogen input, and the effects of climate change, such as lengthened growing seasons and enhanced productivity in boreal forests and collectively known as "the CO_2 fertilization effect" (Friedlingstein et al. 2022). Elevated temperatures, frequent droughts, heatwaves, and other climate change impacts can counteract these gains. Nutrient availability can constrain the CO_2 fertilization effect (Reich and Hobbie 2013; Wang et al. 2020) as the lack of nitrogen and phosphorus limit productivity on 18 per cent and 43 per cent of land, respectively (Du et al. 2020). Due to deforestation, tropical forests are shifting from carbon sinks to carbon-neutral systems or even carbon emitters (Tagesson et al. 2020; Wigneron et al. 2020; McFarlane et al. 2024). By the end of the century, the land carbon sink will likely stop growing or reach saturation (Shi et al. 2021).

Anthropogenic nitrous oxide emissions increased 30 per cent over the past four decades (Tian et al. 2020) and is responsible for 6.2 per cent of global warming, undermining environmental health, and modifying global biogeochemical cycles. At least 60 per cent of nitrous oxide emissions are from agriculture (Grecequet et al. 2022).

4.3.3.3. Permafrost thaw

Permafrost soil, found beneath a quarter of the northern Hemisphere, is warming. Climate change accelerates permafrost thawing, triggering microbial breakdown of soil carbon, releasing CO_2 and methane to the atmosphere (Schuur et al. 2015; Canadell et al. 2021). Permafrost warming is faster at higher elevations and latitudes, reaching up to 1°C/decade, as compared to <0.3°C/decade in sub-Arctic latitudes (Smith et al. 2022), with a mean of 0.4°C/decade (Gudmundsson et al. 2022); abrupt thaw can release large amounts of CO_2 and methane within time frames of days to years (**Figure 4.8**).

Figure 4.8: Permafrost warming trends



Source: Smith et al. (2022)

Permafrost thawing disrupts biogeochemical cycles, modifies hydrology, and restricts ecosystems' ability to cope with climatic changes (Volkova et al. 2021; Namsaraev et al. 2023; Baltzer et al. 2014; Jin et al. 2021). It also triggers secondary environmental impacts, such as transforming forests into shrublands, wetlands, and lakes, further accelerating thawing (Jin et al. 2021) and affecting future water availability (Chapter 6.2.2). Permafrost thawing damages infrastructure, restricts transportation, increases landslide risks, and raises construction costs (Hjort et al. 2022; Debortoli et al. 2023).

In the Russian Federation, permafrost thaw-related damages affect 10 per cent of buildings in Yakutsk and Norilsk, and 80 per cent in Vorkuta (Hjort et al. 2022). Additionally, thawing releases contaminants previously stored in frozen soils, which can enter the food chain, impairing human health (Ray 2024).

4.3.3.4. Climate change, terrestrial ecosystems and biodiversity

While climate change is shifting species' ranges (Anderegg et al. 2019; Román-Palacios and Wiens

2020), land use change, agriculture, habitat loss and fragmentation are increasing stress on biodiversity. Compound effects from intensive agriculture and climate change can reduce insect abundance and species richness by 50 per cent and 27 per cent, respectively. (Outhwaite et al. 2022; Muller et al. 2023). Notably, some species adapt to a warmer climate, triggering outbreaks of agricultural and forest pests (Jactel et al. 2019), such as locusts in East Africa (Salih et al. 2020). The ongoing biodiversity loss is similar in terms of scope to the previous five mass extinctions (Halam and Wignall 1997; Cowie et al. 2022), yet is occurring more abruptly (Ceballos et al. 2015, Ceballos and Ehrlich 2018).

Warmer temperatures can also disrupt phenological relationships. Since the 1980s, leaf unfolding began to occur earlier, shifting by 3-4.2 days per decade in Europe and 5.5 days per decade in China (Piao et al. 2019). Before the 1980s, little change was observed (Vitasse 2022). This change disrupts plant-animal interaction, such as pollination and seed dispersal (Teixido et al. 2022), weakening the ability of ecosystems to deliver essential services (Mooney et al. 2009). Protected areas provide habitats and maintain microclimate conditions crucial for biodiversity under global warming (Xu et al. 2022). For instance, large-scale reforestation in China has increased forest connectivity by bridging isolated patches and creating extensive core forests. Forests larger than 100 km^2 provide more than twice the cooling capacity than areas ≤ 10 km^2 (Huang et al. 2022).

4.3.3.5. Impacts of climate change on agricultural productivity

The effect of climate change on agriculture varies by region (Jägermeyr et al. 2021), generally increasing yields in colder regions and decreasing yields in warmer areas (IPCC 2022a). In addition to temperature change and shifts in precipitation, increasing incidents of extreme events, such as agricultural droughts and wildfires, are increasingly harming forestry (Chapter 2.3.1) and agriculture. Meanwhile, productivity gains in colder climates might also be attributed to technology advancements (Kirilenko and Dronin 2022). For example, prior to the war in Ukraine, Ukraine and the Russian Federation had become the second and third leading world wheat exporters (FAO 2021), even though the yield models have projected a drop in productivity related to climate change (Pavlova et al. 2019; Lobell et al. 2011).

Atmospheric carbon enrichment influences crop yields through the "carbon fertilization" effect (Canadell et al. 2021). Free Air Carbon Enrichment experiments and crop model simulations show that higher levels of CO_2 can increase crop yields and improve water use efficiency, depending on the crops. However, this may decrease crop quality (Toreti et al. 2020), especially regarding nutritional value (Soares et al. 2019).

Total factor productivity, which accounts for labour and capital input, is a more appropriate measure of agricultural performance than raw yields (Organisation for Economic Cooperation and Development 2001). Econometric models show that climate change has reduced the agricultural total factor productivity by about 21 per cent since 1961, with adverse effects generally observed across the Global South (Ortiz-Bobea et al. 2021). Unfavourable weather in conjunction with conflicts and other drivers increase food insecurity, especially in Africa at 40 per cent **(Figure 4.9)** and Asia at 23 per cent (Cardell et al. 2024).

In response, agriculture and forestry are adapting to climate change. Multiple surveys (World Overview of Conservation Approaches and Technologies 2025) have demonstrated that most farmers across different regions are aware of the effects of climate change on crop production, including shifting precipitation patterns, drought and flood risks, and hotter temperatures. Common adaptation strategies include shifting planting dates to earlier in the year to avoid heatwaves, switching to more profitable climate-suitable crops, introducing improved crop varieties and animal breeds, planting trees in pastures andfields for shade, switching to an integrated agroforestry approach **(Image 4.5)**, crop diversification, using mixed crop-livestock systems, improving irrigation

Image 4.5: Silvopasture is an agroforestry practice that deliberately integrates trees, pasture and grazing livestock on the same land. Trees provide shade and shelter to livestock, vegetation provides high quality forage, and animal waste provides nutrients to grass and trees. This practice can also increase wildlife diversity and improve soil and water quality. Credit: Mack Evans/National Agroforestry Center (CC-BY-2.0)

and increasing the number of ponds (Aguliera et al. 2020, Nkuba et al. 2020a). In India, farmers responded to hotter summers and more frequent droughts by planting trees surrounding fields, switching to lower water requirement crops, and increasing irrigation (Singh 2020). In Uganda, pastoralists and arable farmers use Indigenous forecasting (Nkuba et al. 2023), and smallholder farmers are adopting drought-resistant cultivars and fallowing (Atube et al. 2021). In Ethiopia, farmers adapt through crop diversification, planting date adjustment, water management improvements, crops with livestock integration, and tree planting for shade (Belay et al. 2017).

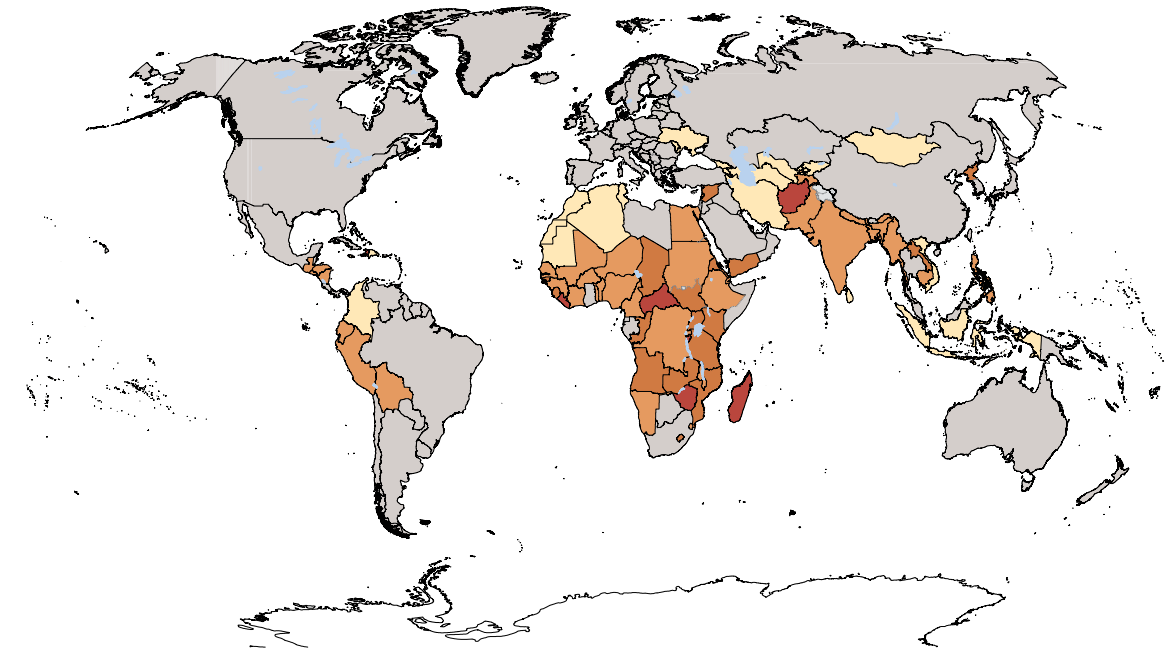
A recent study suggests that even accounting for adaptation, global food production declines 120 kcal per person per day, 4.4 per cent of recommended consumption, per 1°C warming (Hultgren et al. 2025). Adaptation options are limited for smaller, poorer households due to restricted access to knowledge, funds, and credit and to insecure tenure (Khan et al. 2020), compounded by soil degradation. While autonomous adaptation is widely studied, most research focuses on Africa (Oladele et al. 2024) and South East Asia, with fewer studies from Latin America (Fierros-González and López-Feldman 2021) and countries in the northern hemisphere (Soubry 2020). In addition, the social dimension of adaptation to climate change remains underexplored (Davidson 2016).

In the forestry sector, the examples of adaptation outside of carbon management are scarce. Interventions focused solely on carbon sequestration frequently result in monocultures rather than restoring forest biodiversity (World Overview of Conservation Approaches and Technologies 2025). As a critical supplier of provisioning services, forestry is highly vulnerable to land use change (Keenan 2015), affecting the livelihoods of millions of people in forest-dependent communities and many others. The Intergovernmental Panel on Climate Change (IPCC) (2022a) outlined multiple adaptation options, primarily for tropical regions, but warns that, under high-impact scenarios, dieback of some forests in Sub-Saharan Africa and South Asia may be unavoidable. Certain risks, such as heatwaves, loss of pollinators, invasive species and diseases, can only be addressed through large-scale interventions beyond the capacity of the forest sector alone (IPCC 2022a).

4.3.3.6. Extreme events

Climate change has likely increased the frequency and intensity of extreme events, including heatwaves, droughts, storms, and floods (Seneviratne et al.

Figure 4.9: Food insecurity in Sub-Saharan Africa



Note: IFSA = International Food Security Assessment

Source: Cardell et al (2024)

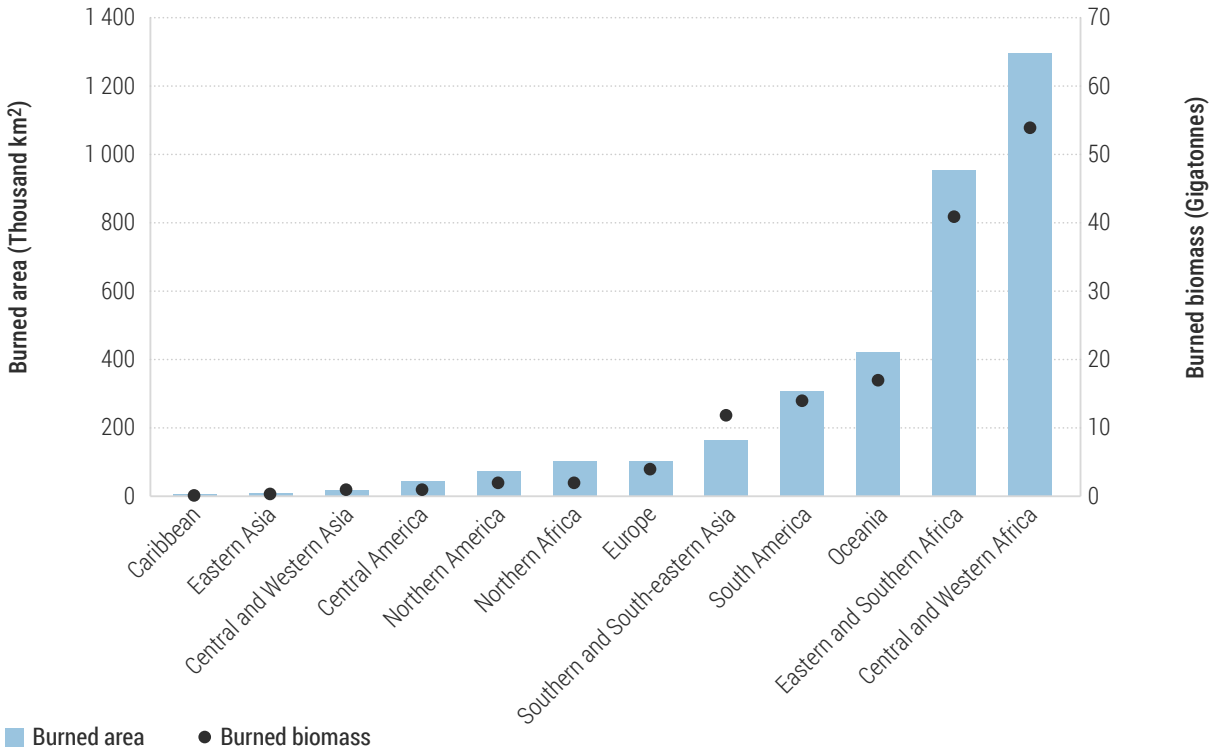
2021). Examples include compound heatwave-drought events in Europe in 2003 and 2022 (Ciais et al. 2003; Tripathy et al. 2023), the Russian Federation in 2010 (Sedlmeier et al. 2018), and California and South America in 2020 (Marengo et al. 2022).

One example of this compounding effect is wildfire hazard. Wildfire is a natural phenomenon essential for ecosystem health, yet it poses a significant risk to human safety, health, and property, and causes rapid thermal, hydrological, and vegetation changes. Two-thirds of wildfires occur in Africa **(Figure 4.10)**, followed by Oceania and South America, regions with extensive grassland and savanna areas where fires occur cyclically (FAO 2020). Forest fire trends are evolving (Tyukavina et al. 2022; Agbeshie et al. 2022). It is estimated that over the last 250 years the frequency of fire regime change has increased 10-fold compared to the previous ten millennia (Sayedi et al. 2024).

Wildfires are influenced by human population growth, forest clearing, landscape fragmentation, fire management practices such as forest clearing and prescribed burning, and climate change (Pausas and Keeley 2021) **(Figure 4.11)**. Research shows an increase in severity and length of extreme fire weather incidents, driven by decreasing air humidity, increasing temperature, and longer fire season (Jain et al. 2022; Jolly et al. 2015; Jones et al. 2022) **(Figure 4.12)**. More than half of the documented increases in aridity since the 1970s and the expansion of cumulative forest fire area across western United States of America forests since 1984 are attributed to anthropogenic climate change (Williams and Abatzoglou 2016). In 2023, Canada experienced its worst wildfire season on record (Byrne et al. 2024). Even Arctic wildfires are accelerating, with burned area and CO_2 emissions reaching record highs in 2021 (Zheng et al. 2023).

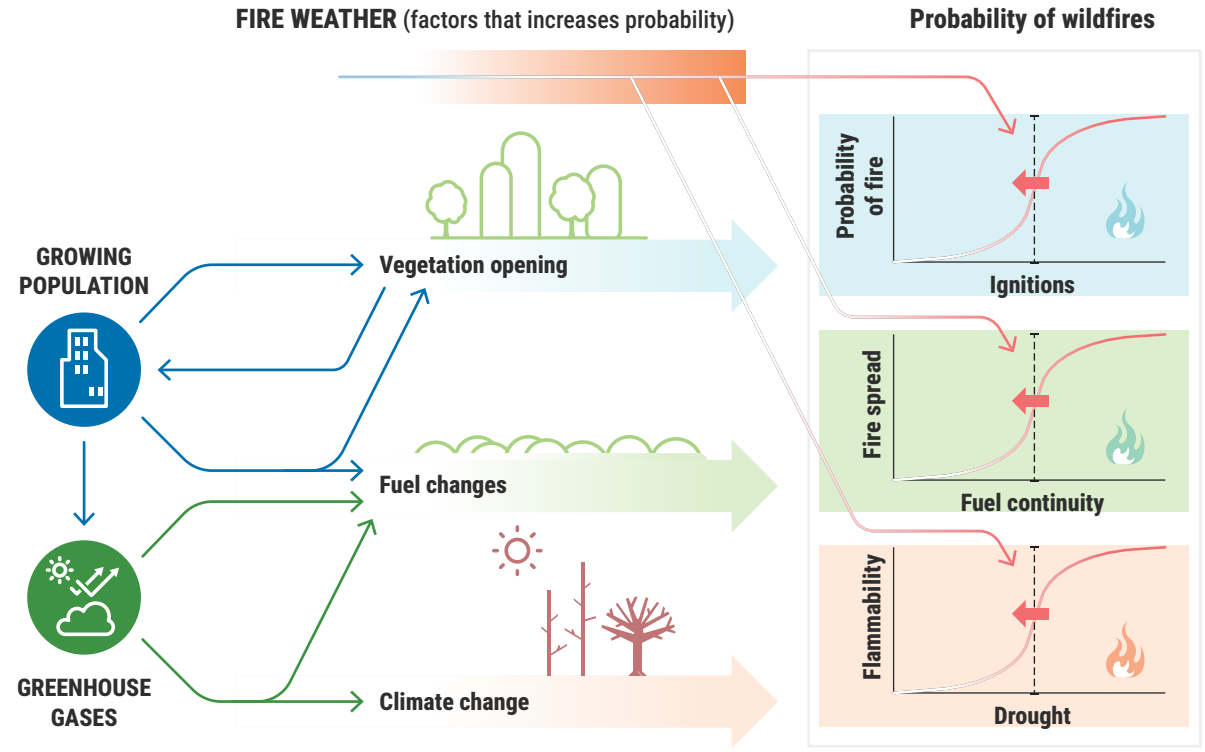
Models indicate a 22 per cent increase in days with extreme fire danger across global burnable land area, including Amazonia, southern Europe, Scandinavia, western United States of America, Canada, and other regions (Abatzoglou et al. 2019). This trend can be dampened by landscape fragmentation, forest clearing, and fire management efforts. However, overall burned area is declining (FAO 2023b), primarily due to agriculture expansion in savannas and grasslands (Andela et al. 2017), while the associated CO_2 emissions are stable (Zheng et al. 2023). The seeming contradiction is explained by a higher burned biomass density in forests than in savannas (Zheng et al. 2023; **Figure 4.13)**.

Figure 4.10: Mean annual burned area and burned biomass by forest and savanna fires



Source: FAO (2024)

Figure 4.11: A conceptual model showing the drivers affecting wildfire occurrence and severity



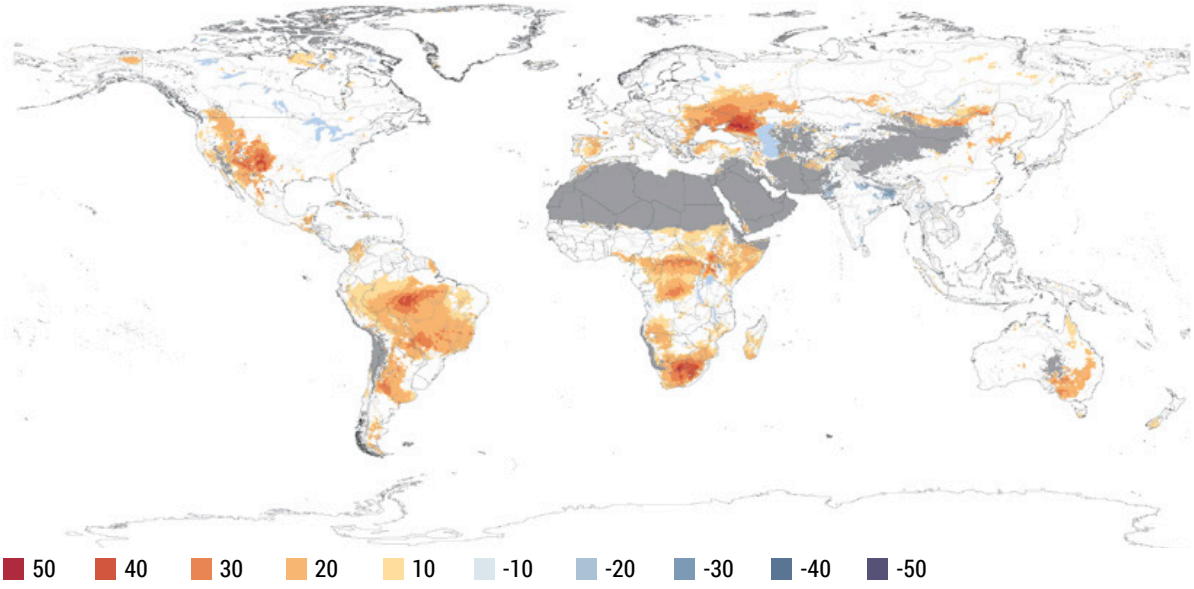
Source: Pausas and Keeley (2021)

4.3.4. Terrestrial biodiversity

The interdependence among biodiversity, climate, and human societies is a key finding of the 6th IPCC assessment report, highlighting trade-offs and synergies between climate and biodiversity actions (Pörtner et al. 2021; IPCC 2023).

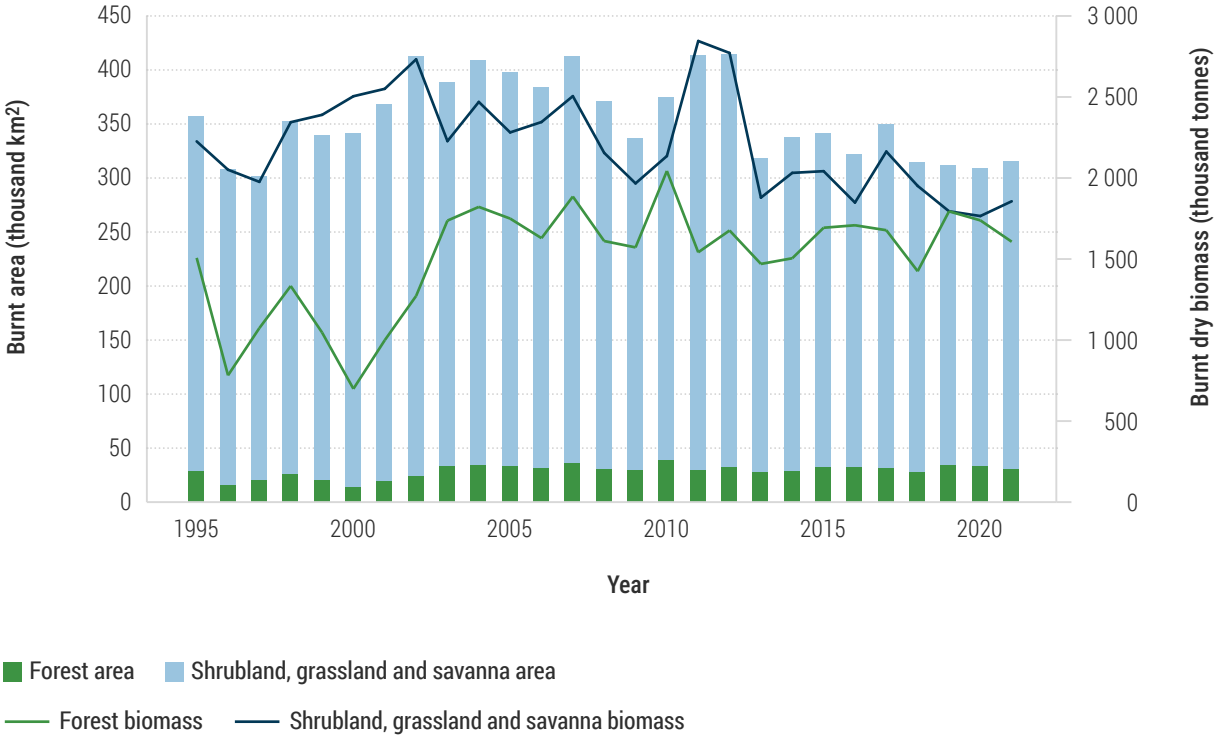
Under IPCC medium (SSP2-4.5) and high (SSP3-7 and SSP5-8.5 8.5) emission scenarios, potential terrestrial

Figure 4.12: Extreme fire weather trends from 1979 to 2020



Source: Jain et al (2022)

Figure 4.13: Burned area and biomass of forests, grasslands, shrublands, and savannas globally



Source: FAOSTAT (2023)

biodiversity loss has an exponential trajectory and can occur much faster than expected and on a vast scale. If temperature rises from 1.5°C to 3°C, the risk of extinction for endemic species in biodiversity hotspots could increase at least tenfold. At 3°C, risks in many regions reach high or very high levels, suggesting widespread systemic impacts, irreversible change, and significant limits to adaptation. Warming increases the risk of species extinction and irreversible biodiversity loss in forest ecosystems and in Arctic regions (IPCC 2023).

The global rate of species extinction is increasing rapidly, with 30 per cent of species at risk of extinction, mainly in the tropics. This decline is driven by the loss of genetic diversity and the collapse of many wildlife populations (IPBES 2019). Biodiversity loss diminishes ecosystem functioning and nature's contributions to people by 10-70 per cent **(Figure 4.14)**.

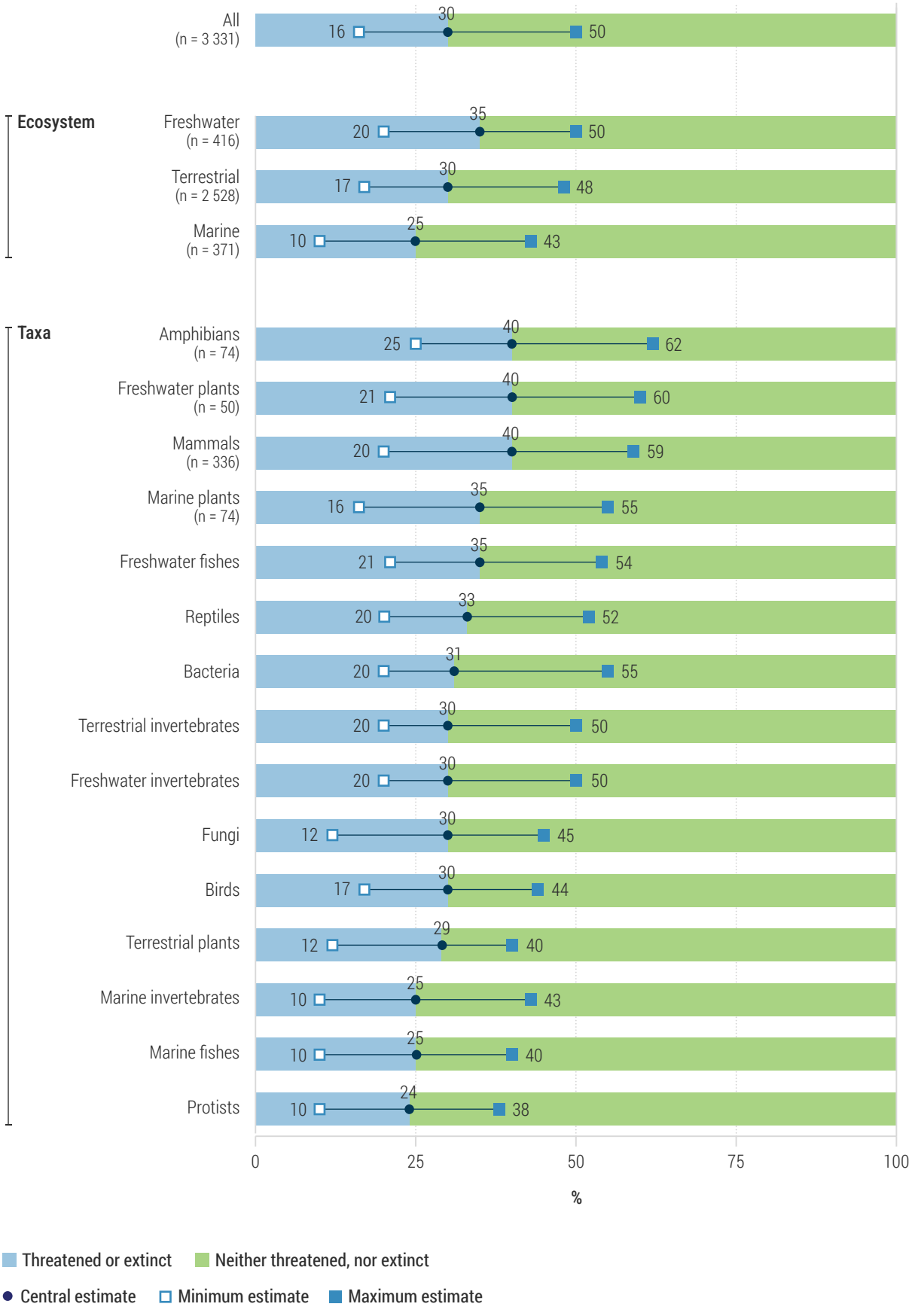
Land use change and intensification of agricultural practices, climate change, pollution, invasive alien species (IPBES 2023), overexploitation and illegal trade are the main direct drivers of biodiversity loss (IPBES 2019; Van Der Putten et al. 2023) and diminishing ecosystem services, including resilience to pests, pathogens, pandemics, and climatic changes (Harvey et al. 2023). Human population dynamics and trends, technological innovations, production and consumption models, and local and global governance are powerful indirect drivers of biodiversity loss (IPBES 2019).

Terrestrial ecosystems provide essential services, but these are diminished due to the widespread biodiversity loss, especially in highly biodiverse areas, such as the Neotropics and Afrotropics. Climate change increasingly generates critical pressure, rivalling the impacts of land use change (Pereira et al. 2024).

An estimated 200,000 or 2.3 ± 1.7 per cent of the planet's 9 million species, including approximately 1.2 per cent of vertebrates, went extinct during the 20th century (Pereira et al. 2024). If current trends persist, another 1 million species are at risk of extinction (IPBES 2019). Despite considerable data gaps, particularly for terrestrial invertebrates, amphibians are considered the most at-risk group, followed by mammals, while birds are currently the least vulnerable (IPBES 2019).

Deforestation and agriculture (Pereira et al. 2024) are primary drivers of extinction for mammals and

Figure 4.14: Expert estimates of global biodiversity loss



Source: IUCN

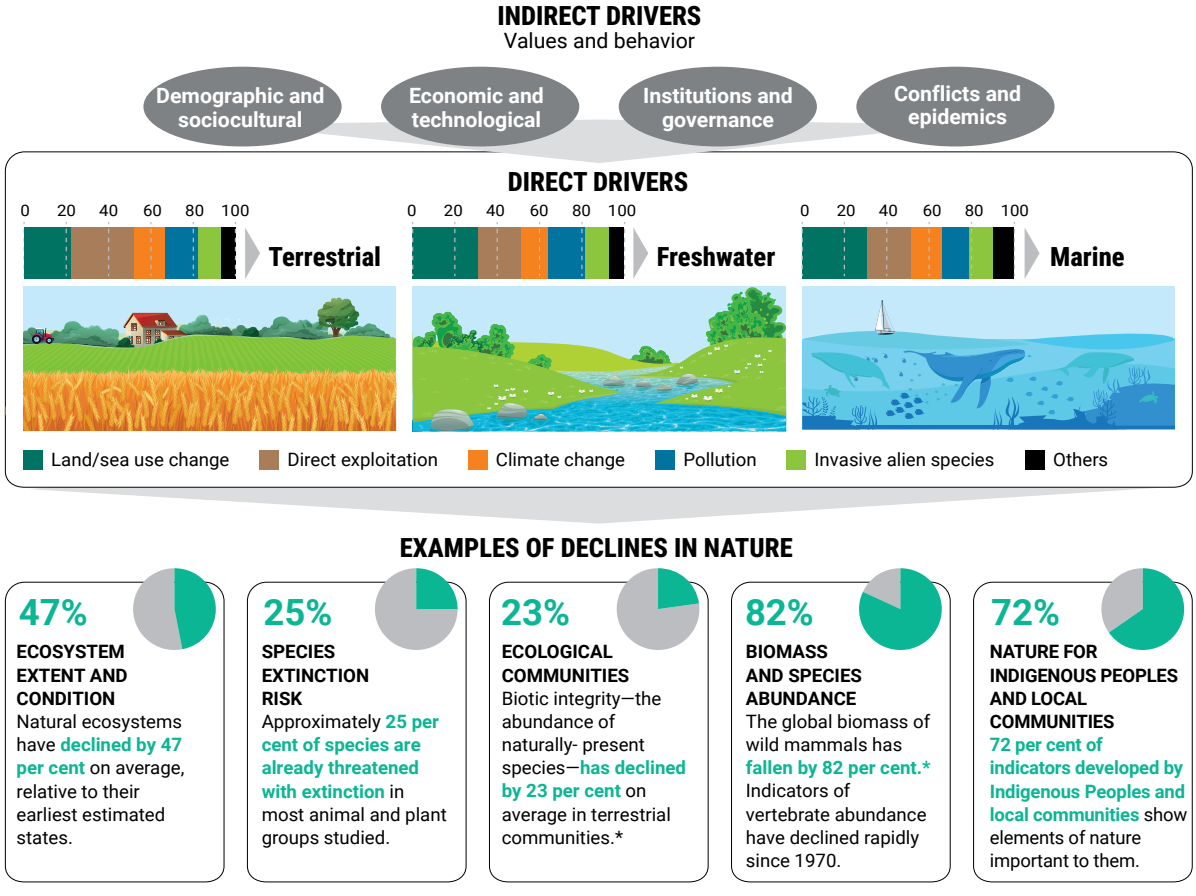
amphibians in the northern boreal region, the Amazon and central Africa, which together support 62 per cent of the Earth's terrestrial biodiversity (FAO 2020; Pillay et al. 2022). Grasslands are affected by climatic extremes, land degradation, fires, and herbivory (Petermann et al. 2021). Mountain drylands and tundra are highly sensitive to climate change, and while less biotically rich, harbour many unique species adapted to extreme environments (Lewin et al. 2024; Maes et al. 2024).

Protected land area is increasing in some regions, but habitat loss continues globally; most protected areas are effective at halting the expansion of built-up areas but are not so successful in preventing deforestation and conversion to agricultural land (Li et al. 2024). The targets of the Kunming-Montreal Global Biodiversity Framework (Secretariat of the CBD 2022) for 2030 include halting the extinction of threatened species by 2050 and conserving 30 per cent of Earth's land and sea area by 2030.

4.3.4.1. Ecosystems

Protection of all 14 global terrestrial biomes and their 846 ecoregions has declined. Restoration through conservation strategies, including Indigenous-led strategies (Goolmeer et al. 2022) and the empowerment of Indigenous Peoples, could protect half the terrestrial realm by 2050, while supporting livelihoods (Dinerstein et al. 2017). **Figure 4.15** illustrates the main direct and indirect drivers of biodiversity loss. Key indicators show significant declines in biomass and species abundance, including an 82 per cent drop in global wild mammal biomass and a 23 per cent decline in naturally occurring species, with cascading effects on ecological and terrestrial communities (Diaz et al. 2019; Declerk et al. 2023). Biodiversity loss, such as declines in insect populations and changes in density and composition linked to climate change and air pollution, diminishes ecosystem functioning and nature's contributions to people, including the

Figure 4.15: Biodiversity loss: drivers and examples of loss in nature



* Since prehistory

Source: Diaz et al (2019)

potential to rehabilitate degraded lands and restore land biodiversity and ecosystem health (Isbell et al. 2023; Harvey et al. 2023).

Biodiversity loss threatens human well-being and ecosystem health through land degradation and food insecurity (Diaz et al. 2006; Malhi et al. 2020; Read et al. 2022; Petrosillo et al. 2023). Land degradation drives biodiversity loss, contributing to climate change and inducing poverty. Land degradation harms habitats, ecosystems' adaptive capacity, and their ability to provide ecosystem services, while it exacerbates biodiversity loss, environmental hazards, poverty and climate change (Ekka et al. 2023). The growing demand for export commodities for foods, livestock feed, and biofuel drives land degradation and biodiversity loss (Santini et al. 2022; Hughes et al. 2023).

Large-scale, intensive, unsustainable practices, such as biofuel production and rapid land use change, contribute to biodiversity decline. Driven by the need to feed livestock and satisfy booming demands for meat, croplands are now expanding 58 times faster than 20 years ago (Meng et al. 2023). On the other hand, sustainable livestock and grazing management can play a positive role in food security and support ecosystems (Leroy et al. 2022; Escobar and Ferrari 2024).

Biodiversity loss has hindered our ability to achieve the Sustainable Development Goals (SDGs) (Adebayo 2019). Addressing this challenge requires solutions that improve resources efficiency and build resilience to climate change, boosting ecosystem services and human well-being (Santini et al. 2022; Petrosillo et al. 2023). Established in 1993 and signed by 196 nations, the United Nations Convention on Biological Diversity plays a central role in tackling biodiversity loss and promoting conservation efforts.

4.3.4.2. Species loss

According to the Red List, released annually by the International Union for the Conservation of Nature (IUCN), the conservation status of only 2 per cent of invertebrates, 17 per cent of plants, and 0.5 per cent of protists and fungi have been assessed (IUCN 2024). Updated reports show 241 mammals, 223 birds, and 798 amphibians as Critically Endangered. Hunting and trapping are prominent drivers of bird and mammal biodiversity loss (World Wildlife Fund 2022). Nearly 39.5 per cent of plant species are at risk of extinction, with many newly identified species are already endangered (Antonelli et al. 2023). Declines in plant and fungal diversity, as well as in detritivores that support plant diversity by feeding on decomposing organic matter, weaken ecosystem resilience (Rubio-Ríos et al. 2021).

Areas from the Himalayas, the dry forests of Madagascar, and the Amazon basin, among others, are high-priority areas for biodiversity conservation (World Wildlife Fund 2022). The Living Planet Index shows that there has been a 73 per cent decline in the average size of monitored populations between 1970 and 2020, with wild mammal populations dropping by 85 per cent, despite representing only 4 per cent of all species (World Wildlife Fund 2024). Tropical forests host 62 per cent of global terrestrial vertebrate species, more than double the biodiversity of any other biome on Earth. Up to 29 per cent of global vertebrate species are endemic to tropical forests, over 20 per cent of these species are at risk of extinction (Pillay et al. 2020).

4.3.4.3. Genetic diversity

Genetic composition can be observed at four levels: species as differentiation in the sense of number and distance of genetic units; populations as diversity richness and heterozygosity; inbreeding and effective population size; and individuals' diversity and heterozygosity) (Hoban et al. 2022). Genetic diversity is increasingly threatened by habitat fragmentation and destruction; resource overexploitation of forests, peatlands, and grasslands; and other anthropogenic activities, including creation of genetically modified seeds, with significant social and cultural implications (Jaques and Jaques 2012). Protecting genetic integrity of populations is crucial for biodiversity conservation (Hoban et al. 2023). Recent DNA-based studies report high genetic variability loss in the past 50 to 100 years, including 28 per cent loss in island species and 14 per cent in harvested fish species (Leigh et al. 2019). The Kunming-Montreal Global Biodiversity Framework (Secretariat of the CBD, 2022) emphasizes the importance of conserving diversity among and within populations of all species, re-establishing genetic connectivity, and developing national genetic conservation strategies and indicators to monitor policy progress (Hoban et al. 2023). Despite ongoing population declines due to habitat destruction or other factors, off-site seed banks remain crucial for preserving plant genetic diversity and enabling the reintroduction of endangered, rare, and extinct species (Wambugu et al. 2023).

4.3.4.4. Soil biodiversity

Soil is likely home to over 50 per cent of life on Earth, from microbes to mammals (Anthony et al. 2023), making it the most biodiverse habitat and the main global reservoir of biodiversity **(Figure 4.16)**. A single gram of soil can contain more than 40,000 different organisms (FAO 2020). Soil biota play a vital role in nutrient dynamics, carbon sequestration and biodiversity (Labouyrie et al. 2023). While only 1 per cent of soil biodiversity is known, it underpins ecosystem health and is pivotal for most ecosystem services, such as food supply, human health, and climate control (Angst et al. 2019; Maaroufi et al. 2020; Coyne et al. 2022). Specific measures that can be undertaken to preserve and enhance native soil biodiversity (FAO 2017) and the risk of soil biodiversity loss are available and must always be considered (Tibbett et al. 2020). Unfortunately, soil biodiversity remains underrepresented in the international,

Figure 4.16: The complex nature of soil biodiversity

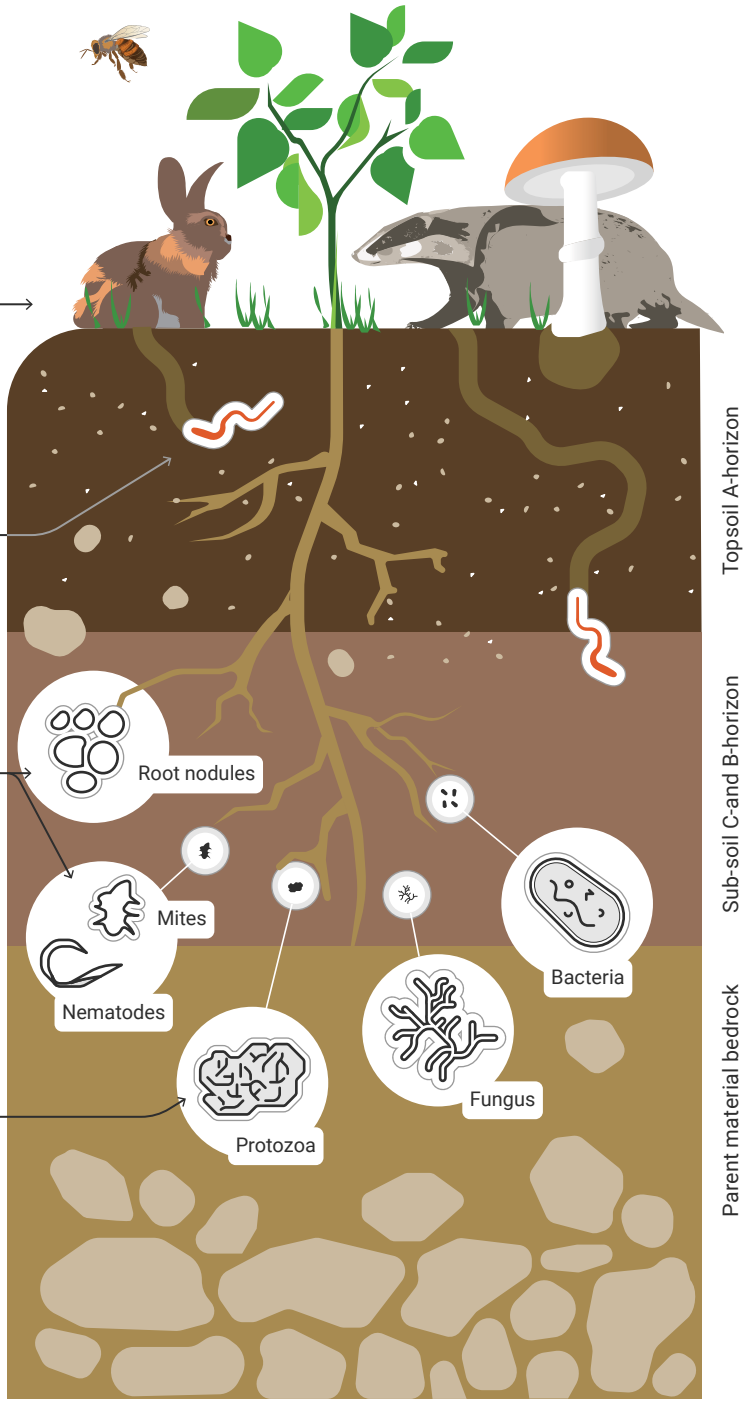
Plants support a hidden ecosystem of soil-dwelling organisms, which in turn nourish and safeguard them. This rich variety of life maintains the soil's vitality and productivity. Known as soil biodiversity, this intricate web of life drives essential biogeochemical cycles that sustain life on our planet.

MEGAFAUNA
Toads, **moles**, **beavers**, **rabbits**, and **badgers** play a key role in mixing and redistributing soil.

MACROFAUNA
Several centimeters
Earthworms, **termites**, **ants**, **millipedes** and **woodlice** improve soil drainage and aeration.

MESOFAUNA
Less than 2mm
Tiny invertebrates such as **nematodes, mites, tardigrades, collembolans, diplura, and proturans** and help break down and recycle dead plant material.

MICROFAUNA AND MICROORGANISMS
1-100 micrometers
Bacteria, fungi, protozoans, and **nematodes are the** smallest and most abundant organisms underground. They drive essential nutrient cycles that sustain ecosystems.



Source: Modified from FAO (2020)

national and regional IUCN Red Lists, despite its importance.

4.4 Impacts of natural ecosystems on human well-being and human systems

4.4.1 Impacts on human health and well-being

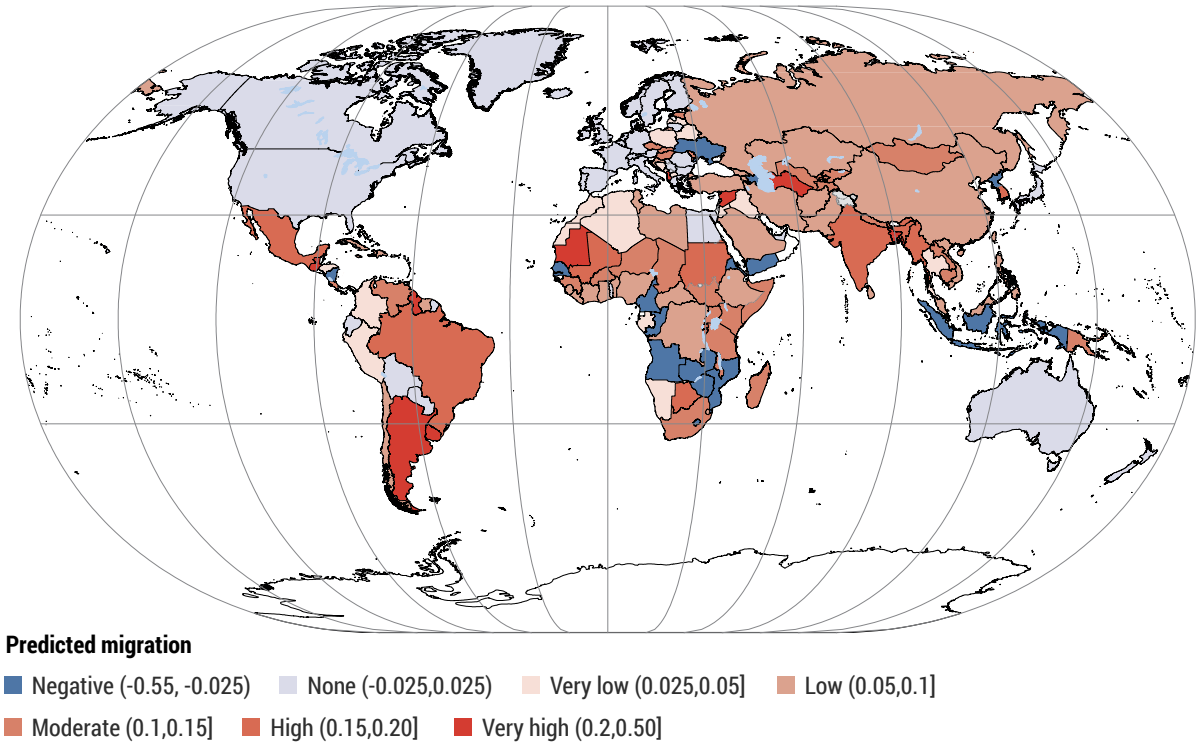
Land use changes significantly affect various aspects of human well-being, including physical and mental health, financial and job security, and social and spiritual needs. Deforestation, agricultural expansion, soil degradation and desertification, permafrost thawing, biodiversity loss, and extreme events all contribute to these impacts. While migration can be seen as a traditional reaction to environmental change, (Hsiao et al .2024) environmental degradation, along with wars and conflicts, has displaced tens of millions of people, leading to a growing number of environmental refugees (Myers 2002; Internal Displacement Monitoring Centre 2023; UNEP 2023b; Kaczan and Orgill-Meyer 2020), particularly affecting developing countries **(Figure 4.17)**.

Shortages of clean water and nutritious food pose serious risks to human health (WHO 2023; De-la-Torre 2020). In 2022, 735 million people experienced hunger, 258 million faced acute food insecurity (WHO 2023a), and another billion were obese. Growing evidence suggests that long-term exposure to microplastics in drinking water, food, and the environment may also pose risks to human health (WHO 2023b; Münzel et al. 2023) **(Figure 4.18)**.

Wildfire exposure is linked to several health issues, including respiratory and infectious diseases, cardiovascular mortality, reduced lung function, mental disorders, and stunted growth of children (Gao et al. 2023). These risks will likely increase as climate change advances (Clarke et al. 2023). Severe droughts increase the likelihood of dust storms linked to various respiratory diseases (Schweitzer et al. 2018). Thawing permafrost elevates the risk of exposure to bacterial, fungal, and viral pathogens currently trapped in permafrost (Miner et al. 2021) and the increased mobility of contaminants.

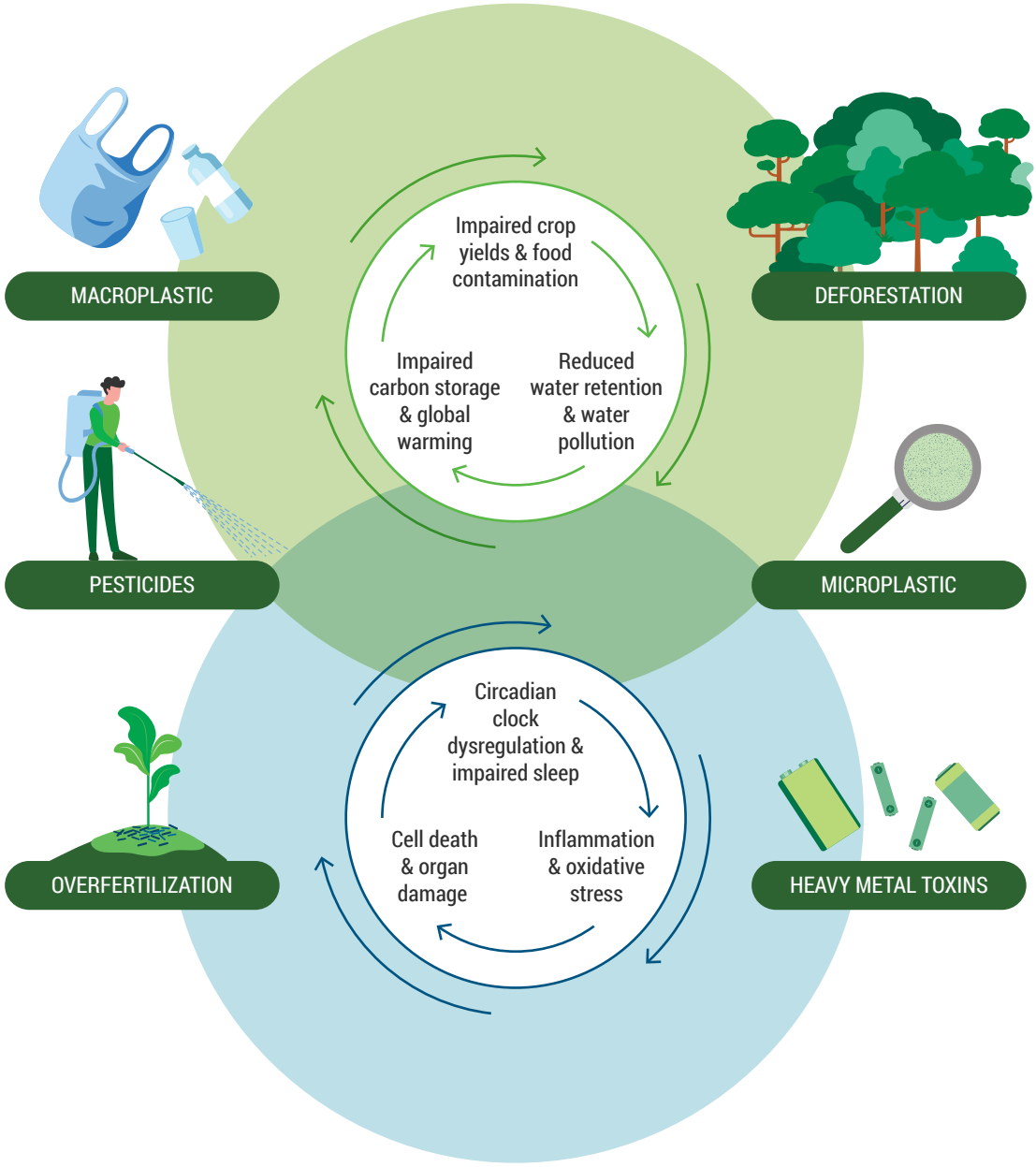
Access to green space significantly benefits physical and mental health. For instance, improving the distribution of green spaces in Barcelona could

Figure 4.17: Predicted environmental migration worldwide measured in standard deviation changes in migration



Source: Hoffmann et al. (2020)

Figure 4.18: Implications of human health affected by agricultural management practices



Source: Münzel et al. 2023

prevent 178 premature deaths each year (Iungman et al. 2025). Sustainable and climate-resilient planning, especially with adequate tree cover, can help mitigate the impacts of climate change, including premature deaths linked to the urban heat island effects (UNEP and the United Nations Human Settlements Programme 2021, Iungman et al. 2023).

Studies have found links between proximity to rich biodiversity and reduced depression (Cox et al. 2017), lower blood pressure (Lindemann-Matthies and Matthies 2018), self- perceived restoration (Hoyle et al. 2019; Hussain et al. 2019), and self-reported health and well-being (Houlden et al. 2021; Mavoa et al. 2019; Mavoa et al. 2019b). These benefits are often more pronounced in groups with low socioeconomic status (Rigolon et al. 2021), yet such communities frequently have limited access to green spaces (Rigolon et al. 2016; Rigolon et al. 2018; Sun et al. 2022), as do ethnic minority communities (Comber et al. 2008; Dai et al. 2011; Liu et al. 2021), and youth and older people (Sikorska et al. 2020). In the context of Indigenous Peoples, access to land is a fundamental factor of well-being (Tsuji et al. 2023). In this context, soil and land degradation must be viewed from a political economy lens, particularly regarding the role of large enterprises and agribusiness (Blaikie 1985).

4.4.2 Land systems, economy and equity.

Land degradation reduces agricultural productivity, income, livelihoods, and resilience and can provoke social tensions. It affects millions of people's lives, with economic losses reaching up to US$ 10.6 trillion annually (Le et al. 2017), approximately 10 per cent of the global gross domestic product (IPBES 2018).

Issues with land availability and ownership, including land grabbing that is often driven by international capital markets, are closely related to gender inequalities. In many contexts, women and men have different roles, responsibilities, and dependencies on land. Women are disproportionately affected by biodiversity loss, facing higher domestic work burdens, income loss, declining health, increased exposure to gender-based violence, eroded cultural and traditional knowledge, and poorer well-being overall (Booker et al. 2022). For example, in India in the Nilgiri Biosphere Reserve, market-driven expansion of chemically intensive agriculture and monoculture tea plantations encroached on Indigenous lands (Sudhakar Reddy et al. 2018), disrupting ecosystem services, soil and forest health, and local livelihoods for both women and men (Krishnakumar and Roy 2021; Tsuji et al. 2023).

Women's extreme poverty is driven by multiple factors, including insecure land rights, limited access to finance and technology, poor market conditions, and structural gender inequality, such as underpaid or unpaid labour (UNEP 2016). Despite these challenges, women have proven to be effective land stewards and managers. In developing countries while facing desertification, land degradation and drought, women produce up to 80 per cent of the food (FAO 2011). UNCCD's Gender Action Plan 2018-2030 (UNCCD 2018) is a powerful and strategic tool aimed at transforming the livelihoods of millions of families.

4.5 Progress towards internationally agreed environmental goals

The SDG 15: Life on Land focuses on managing forests sustainably, halting and reversing land and natural habitat degradation, combating desertification, and stopping biodiversity loss. **(Figure 4.19)**. Targets 15.1 and 15.4, related to global protected and conserved area coverage of terrestrial and mountain ecosystems, showed substantial improvements before 2000, but this growth has stagnated over the last two decades. Particularly worrying are Central, South and West Asia, and North Africa, where less than 30 per cent of Key Biodiversity Areas are protected (United Nations Department for Economic and Social Affairs 2024). In contrast, countries in North America, Europe, Sub-Saharan Africa, Latin America and the Caribbean, as well as Australia and New Zealand have increased their protected Key Biodiversity Area coverage to over 40 per cent (United Nations Department for Economic and Social Affairs 2021).

4.5.1 Land degradation neutrality

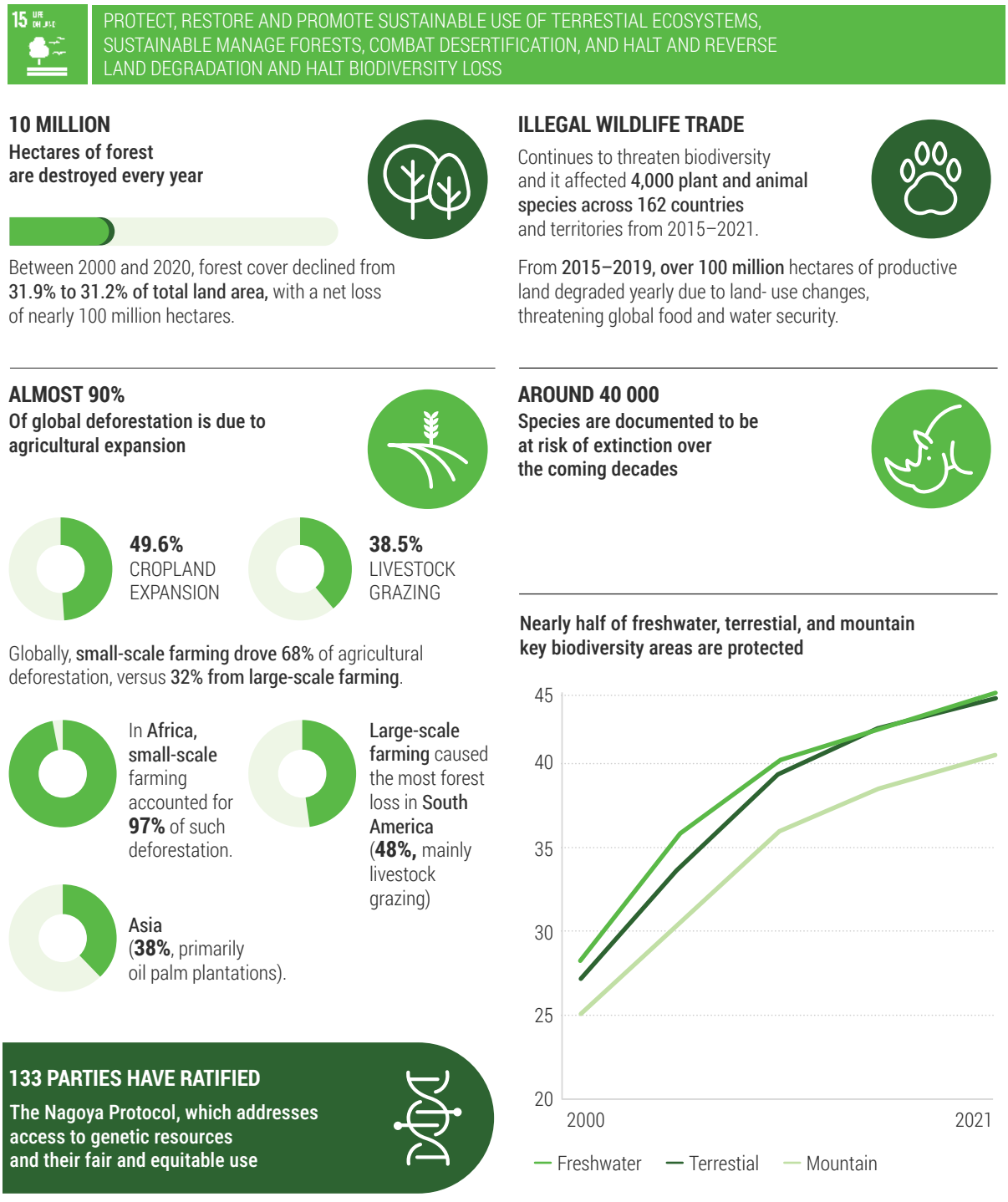
The SDG target 15.3 is: "By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world." It is monitored through indicator SDG 15.3.1., which the UNCCD tracks by using trends in land cover, land productivity, and carbon stocks above and below ground (Sims et al. 2021). Land productivity is estimated by Net Primary Productivity, represented in kg/ha/yr. Land cover is assessed using local knowledge and observed land degradation trends, while soil organic carbon is assessed based on land cover over 20 years.

Global Earth observation systems provide key metrics for tracking changes in land productivity and land cover dynamics. The results for each Target 15.3 sub-indicator are integrated using a "one-out-all-out" method, where if any one metric shows decline, the entire area is classified as degraded (Teich et al. 2019; Teich et al. 2023). The one-out-all-out approach has limitations: it can be overly sensitive to short-term fluctuations and may potentially overlook localized improvements, suggesting the need for complementary methods to depict a more nuanced picture.

These criteria align with the concept of land degradation neutrality (UNCCD 2016, Decision 3/COP12). The neutrality principle allows for trade-offs among competing interests across a landscape (Orr et al. 2017), and it supports coordination between the mandates of the three Rio Conventions to which land is central.

To support achieving this objective by 2030, the UNCCD Global Mechanism established the Land Degradation Neutrality Target Setting Programme, resulting in

Figure 4.19: Status of SDG 15 and the main issues of concern

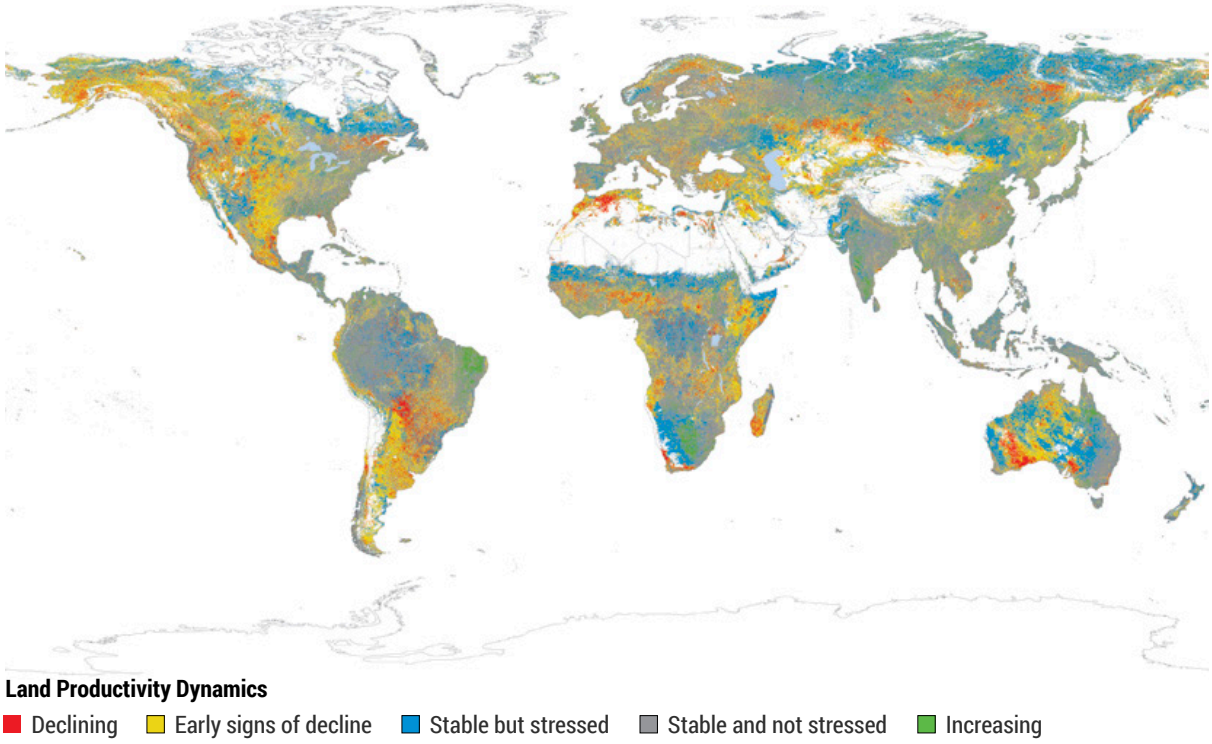


Source: UNSTATS

voluntary commitments to restore over 450 million hectares of degraded land. However, the world is falling short on reaching land degradation neutrality by 2030. Indicators show worrying trends in land degradation with declining land productivity (**Figure 4.20**) (Li et al 2025), worsening land cover, and slowing growth of soil organic carbon stocks (FAO 2024c)

Based on present trends, SDG Target 15.3 is unlikely to be met by 2030, unless further action is taken to avoid, reduce, and reverse land degradation, indicating that land governance is the main obstacle (Debonne et al. 2021). Strengthening governance frameworks and implementing reforms could enhance accountability and performance, while

Figure 4.20: A 30-meter resolution global land productivity dynamics dataset from 2013 to 2022



Source: Li et al, 2025

using such emerging technologies as artificial intelligence could have profound implications for addressing land and soil environmental challenges, including land degradation neutrality. Furthermore, international financial support is needed for developing countries to achieve these goals.

4.5.2 Achieving the Paris Agreement through land-based solutions

Article 5 of the Paris Agreement reinforces the role of land use activities in climate change mitigation, building on the 2013 UNFCCC COP19 Framework for REDD+, which provides key guidance on several essential aspects of REDD+ implementation. At COP27 in 2022, parties also launched joint efforts to implement climate action on agriculture and food security. According to the IPCC 6th Assessment Report, the Agriculture, Forestry and Other Land Use sector holds the most significant mitigation potential between 2020 and 2050, particularly targeting measures in forests and other natural ecosystems (IPCC 2022b).

Nature-based solutions aim to increase carbon sequestration and reduce greenhouse gas emissions, while delivering benefits to human well-being, ecosystem services, resilience and biodiversity. Nature-based solutions often combine various actions to protect, conserve, restore, and sustainably manage natural or modified terrestrial, fresh water, coastal and marine ecosystems (Nolan et al. 2021, Sun et al. 2024). Nature-based solutions could deliver up to 30 per cent of the emission reductions needed to meet the 2°C target (Griscom et al. 2017) and reduce peak warming by 0.3°C this century (Girardin et al. 2021).

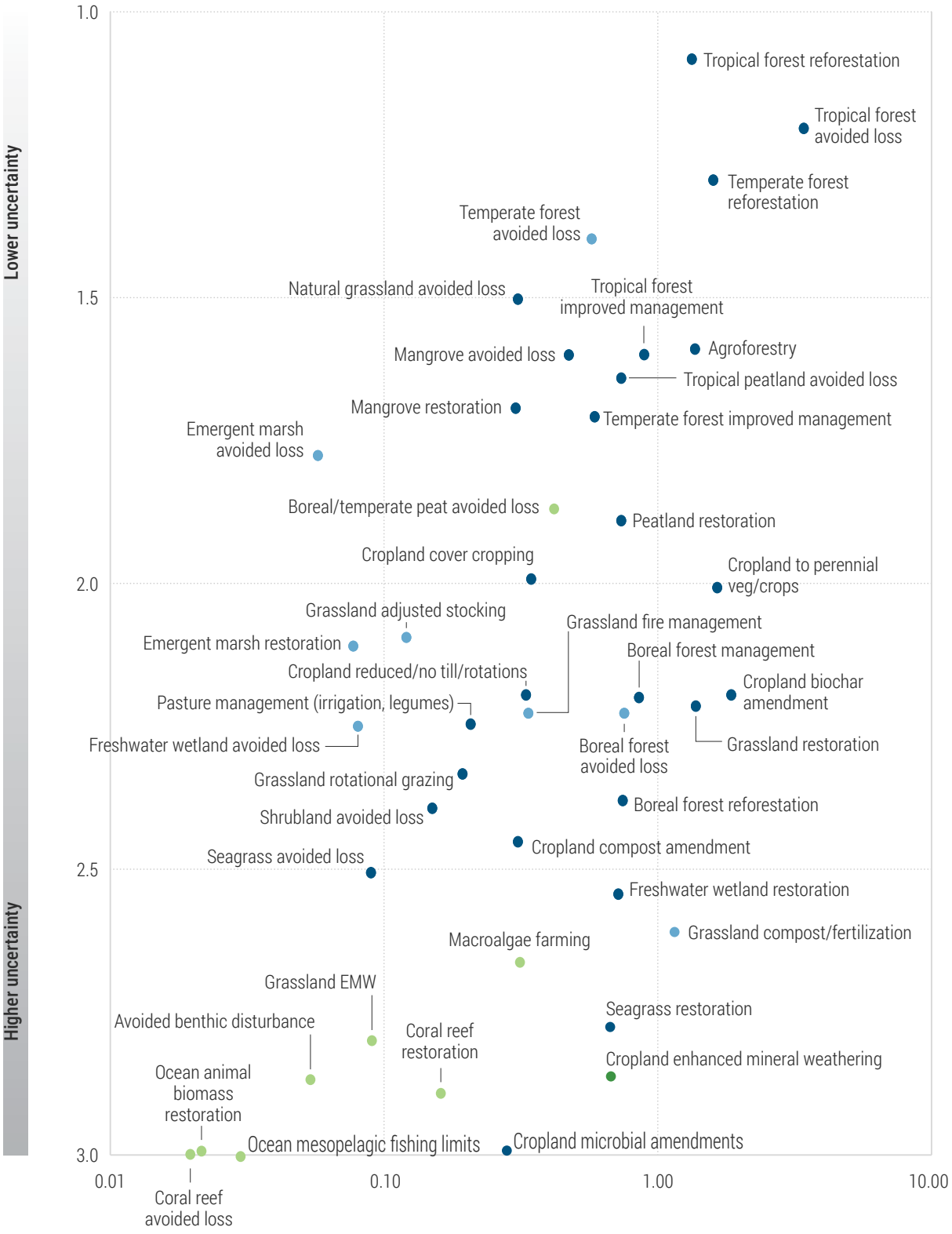
However, land-based mitigation needs to consider ecological limits, taking biodiversity impacts and conservation into account (Deprez et al. 2024). A recent study by Buma et al. 2024 identified the types of nature-based solutions that are supported by scientific evidence and those lacking demonstrated effectiveness **(Figure 4.21)**.

4.5.3 International conventions on chemical and waste pollution

Fuller et al. (2022) summarized progress on addressing chemical pollution: "We cannot continue to ignore pollution. We are going backwards."

While international agreements for managing pollution tend to be generic and broad in scope by addressing

Figure 4.21: Mean categorization of each nature-based solution pathway and its scale of estimated potential impact



Source: Buma et al. (2024)

pollution occurring in air, soil or water, some of them target specific pollutants, such as solid waste.

The Basel Convention covers a range of hazardous wastes and their effects on human and environmental health. Considering that plastic pollution has a footprint in every stage of its life cycle, the Convention adopts actions to assist in managing plastic waste (Secretariat of the Basel Convention 2023). It also emphasizes the management of transboundary waste.

Disposal of electronic waste generated in one country and transferred to another raised concerns, often due to a lack of capacity building, regulatory harmonization, and unclear responsibility (Shittu et al. 2021).

The Global Framework on Chemicals, a voluntary initiative, provides a comprehensive plan to manage chemicals across their entire lifecycle and enable a holistic approach. With five strategic objectives and 28 targets, it promotes stakeholder collaboration in phasing out harmful chemicals, enhancing capacity building, and fostering connections across the health, agriculture, energy, and transport sectors.

The success of these conventions and agreements heavily depend on the number of participating countries and their levels of compliance. For example, even though many developing countries are signatories of the Basel Convention, some continue to import hazardous toxic waste, mainly due to socioeconomic pressures, which has caused them to become the dumping ground for wealthier countries. The United States of America is a signatory without ratification, exempting a major waste-producing country from obligations (Kummer 2000; Shukla 2020).

4.5.4 Biodiversity Targets 2011-2020 and the Kunming-Montreal Global Biodiversity Framework 2022-2030

In 2010, Parties to the Convention on Biological Diversity agreed on a Strategic Plan for Biodiversity 2011-2020, setting the 20 Aichi Biodiversity Targets. These targets aimed to tackle the fundamental drivers of biodiversity loss, address direct pressures on biodiversity, improve the status of biodiversity, enhance biodiversity benefits, and accelerate implementation. Each target included several components.

In summary, by 2020, none of the 20 Aichi Biodiversity Targets were fully achieved, while for three targets, there was insufficient data to assess progress (IPBES 2019). Notable setbacks included a steep decline in monitored populations of birds, mammals, reptiles and fish between 1970 and 2016. While biodiversity financing has doubled, these advances were overshadowed by activities harmful to biodiversity, such as fossil fuel extraction and use and agricultural subsidies (Secretariat of the CBD 2020).

Nonetheless, there were some positive developments. Conservation actions have prevented some extinctions, protected area coverage increased both on land and at sea, and many countries developed national biodiversity strategies and action plans, including those for the recovery of fish stocks in well-managed fisheries. However, the overall trend was negative, with 12 of 16 indicators used for reporting showing significantly worsening trends.

The Kunming-Montreal Global Biodiversity Framework was adopted in 2022, replacing the Aichi Targets. It includes 23 targets, four overarching goals, and a monitoring framework endorsed at COP 15 in 2022. An interim assessment of global progress towards these targets is pending; however, some of the headline indicators adopted are already operational. For example, as of 2024, 17.4 per cent of Earth's terrestrial and inland waters have been protected or conserved, an increase from 16.6 per cent at the beginning of the decade. (UNEP-WCMC and IUCN 2024). These indicators relate to Target 3, which is to protect 30 per cent of land, waters, and seas by 2030.

4.6 Indigenous as well as Local Knowledge in land and soil management

Indigenous Communities as well as local communities, particularly Indigenous women (Kermoal and Altamirano-Jiménez 2016; Snehlata et al. 2020), deeply understand their environments, including environmental changes related to their daily activities. For instance, Indigenous Communities in the Pachmarhi Biosphere Reserve of India have developed their own soil classification system and apply it to land-use decision-making in crop production systems (Kala 2013). Similarly, Indigenous savannah communities in Ghana use such indicators as the presence of specific plants, plant vigour, soil colour, texture, tilth, and compaction to understand soil health and adjust land management (Omari et al. 2018). Farmers in Uganda use biotic environmental signals for climate forecasts and early

warning systems, shaping their crop and livestock management practices (Nkuba et al. 2020a, 2020b).

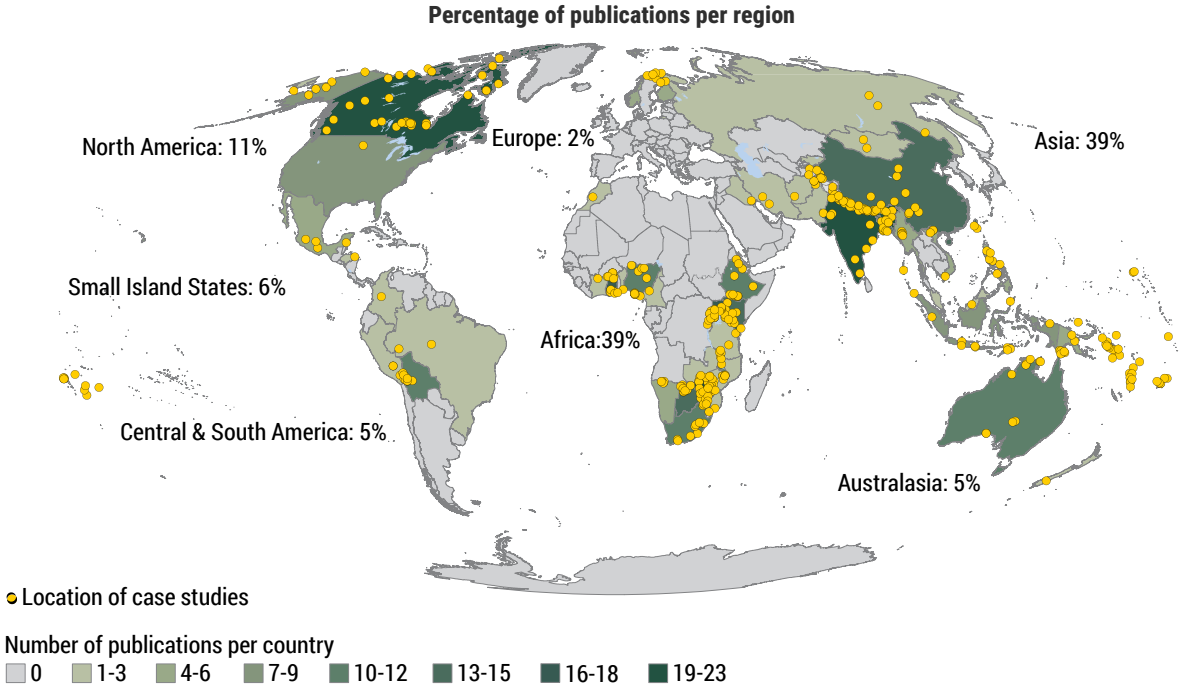
Examples of long-term sustainable land management include Inca platforms in Altiplano, Peru, the terraces of Cinque Terre in Italy, the tea terraces of Sri Lanka, and the agroforestry practices in the Amazon (Gebara 2023). Apple growers in the Himalayas successfully adapt to climate change (Vedwan 2006). Indigenous Knowledge has enabled Indigenous Communities to survive in harsh climates, from the arid oases of Africa with only 50 mm of rain to the icy and rocky landscapes of Greenland. This rich knowledge is based on the sustainable management of the agroecosystems inhabited by communities deeply connected to their land (Santini and Miquelajauregui 2022). These lands are usually rich in agrobiodiversity, supported by traditional knowledge, and constitute invaluable cultures and landscapes that are sustainably managed by farmers, herders, fishers, and forest people in ways that contribute to their livelihoods and food security (FAO 2024a).

Nevertheless, despite its recognized value, Indigenous Knowledge and Local Knowledge are rarely integrated into mainstream land management planning, and when it is, the local communities are unlikely to benefit. The World Overview of Conservation Approaches and Technologies and FAO's Globally Important Agricultural Heritage Systems aim to collect and preserve traditional practices for future generations. Yet, studies of Local Knowledge on climate adaptation mostly concentrate on a few regions **(Figure 4.22)** (Petzold et al. 2020), leaving Local Knowledge in much of the world unrepresented.

In Indigenous Communities, biodiversity is significantly better preserved than in typical agricultural landscapes (Farrell et al. 2021). Data from Australia, Brazil and Canada shows that Indigenous-managed lands have equal or higher biodiversity than officially designated protected areas, mainly due to sustainable land management (Fa et al. 2020). Land management practices used by Indigenous Peoples include traditional burning, fishing traps, and forestry practices that are often uniquely adapted to local ecosystems. This wealth of knowledge can also be incorporated into the ecological restoration of degraded lands. Furthermore, integrating Indigenous Knowledge in conservation efforts can safeguard cultural diversity (Levis et al. 2024).

Unfortunately, the benefits of Indigenous Knowledge rarely flow back to community members. This disconnect can be attributed mainly to a lack of recognition of Indigenous governance that promotes land

Figure 4.22: Global distribution of publications on Indigenous Knowledge and Local Knowledge in climate change adaptation practices. Each yellow dot is a case study



Source: Petzold et al (2020)

stewardship (Fernandez-Llamazares et al. 2024). According to the International Fund for Agricultural Development (2024), between 2011 and 2020, less than 1 per cent of climate finance supported Indigenous land and tenure management. Additionally, failure to uphold the principles of "free, prior and informed consent" and "do no harm" in land-use decisions and resource extraction contribute not only to resource exploitation and land degradation, but also to the appropriation of Indigenous Knowledge, particularly using digitization techniques (Smyth et al. 2020). Inequitable benefit sharing, despite the Nagoya Protocol, contributes to the overall vulnerability of Indigenous Peoples (IK and LK Dialogues 2025).

Gebara (2023) surveyed representatives of the Indigenous Communities in the Brazilian Amazon on their concerns about the bioeconomy, using as a case study the traditional medicine kambo, derived from the secretion of a tropical frog. The study unveiled significant concerns regarding the transfer of Indigenous Knowledge and Local Knowledge, along with general mistrust towards protective initiatives. Another study (den Braber et al. 2024) revealed that incomes in Indigenous territories were as much as 36 per cent lower than in areas with other land uses, underscoring the trade-offs decision makers face when establishing and expanding forest conservation projects.

Globally, Indigenous Peoples manage or hold tenure rights to a quarter of land (Garnett et al. 2018). This intersects with 40 per cent of ecologically intact and protected territories (Garnett et al. 2018). However, at least 16 per cent of Indigenous-managed land is at risk globally from future development and resource extraction.

On Indigenous-managed lands, outsiders deforest areas frequently without consent (Fa et al. 2020), leading to the loss of life, land, livelihoods, and conflicts over land. Between 2009 and 2019, more than 300 people, many of whom were members of Indigenous Communities, were killed in land-use disputes in the Amazon (Gómez-Upegui 2021). Restrictions on hunting and fishing, integral to the Indigenous way of life, further jeopardize their lives and livelihoods (Schuster et al. 2019).

Crucially, Indigenous Knowledge holds transformative potential for creating a shared vision of a prosperous future for all and ways to shift the current trajectories of climate change, environmental degradation and broader planetary crisis (van Velden et al. 2025).

References

Abatzoglou, J.T., Battisti, D.S., Williams, A.P., Hansen, W.D., Harvey, B.J. and Kolden, C.A. (2021). Projected increases in western US forest fire despite growing fuel constraints. Communications Earth & Environment 2(1), 227. 10.1038/s43247-021-00299-0. https://doi.org/10.1038/s43247-021-00299-0

Adebayo, O. (2019). Loss of biodiversity: the burgeoning threat to human health. Annals of Ibadan Postgraduate Medicine 17(1), 1-3. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6871202/pdf/AIPM-17-1.pdf

AFP (2025). Indonesia deforestation rises for third year running: NGO. France24, https://www.france24.com/en/live-news/20250131-indonesia-deforestation-rose-again-in-2024-ngo

Agbeshie, A.A., Abugre, S., Atta-Darkwa, T. and Awuah, R. (2022). A review of the effects of forest fire on soil properties. Journal of Forestry Research 33(5), 1419-1441. 10.1007/s11676-022-01475-4. https://doi.org/10.1007/s11676-022-01475-4

Aguilera, E., Díaz-Gaona, C., García-Laureano, R., Reyes-Palomo, C., Guzmán, G.I., Ortolani, L. et al. (2020). Agroecology for adaptation to climate change and resource depletion in the Mediterranean region. A review. Agricultural Systems 181, 102809. https://doi.org/10.1016/j.agsy.2020.102809. https://www.sciencedirect.com/science/article/pii/S0308521X19310005

Alves, B. (2023). Global waste generation- statistics and facts. [Statista https://www.statista.com/topics/4983/waste-generation-worldwide/#topicOverview (Accessed: October 24 2024).

Andela, N., Morton, D.C., Giglio, L., Chen, Y., van der Werf, G.R., Kasibhatla, P.S. et al. (2017). A human-driven decline in global burned area. Science 356(6345), 1356-1362. doi:10.1126/science.aal4108. https://www.science.org/doi/abs/10.1126/science.aal4108

Anderegg, W.R.L., Anderegg, L.D.L., Kerr, K.L. and Trugman, A.T. (2019). Widespread drought-induced tree mortality at dry range edges indicates that climate stress exceeds species' compensating mechanisms. Glob Chang Biol 25(11), 3793-3802. 10.1111/gcb.14771. https://onlinelibrary.wiley.com/doi/10.1111/gcb.14771

Angst, G., Mueller, C.W., Prater, I., Angst, S., Frouz, J., Jílková, V. et al. (2019). Earthworms act as biochemical reactors to convert labile plant compounds into stabilized soil microbial necromass. Communications Biology 2. 10.1038/s42003-019-0684-z. https://doi.org/10.1038/s42003-019-0684-z

Anthony, M.A., Bender, S.F. and van der Heijden, M.G.A. (2023). Enumerating soil biodiversity. PNAS 120(33). https://doi.org/10.1073/pnas.2304663120.

Antonelli, A., Fry, C., Smith, R.J., Eden, J., Govaerts, R.H.A., Kersey, P. et al. (2023). State of the World's Plants and Fungi 2023. https://www.kew.org/sites/default/files/2023-10/State%20of%20the%20World%27s%20Plants%20and%20Fungi%202023_V2.pdf

Armenteras, D., Espelta, J.M., Rodríguez, N. and Retana, J. (2017). Deforestation dynamics and drivers in different forest types in Latin America: Three decades of studies (1980–2010). Global Environmental Change 46, 139-147. https://doi.org/10.1016/j.gloenvcha.2017.09.002. https://www.sciencedirect.com/science/article/pii/S0959378016304745

Atube, F., Malinga, G.M., Nyeko, M., Okello, D.M., Alarakol, S.P. and Okello-Uma, I. (2021). Determinants of smallholder farmers' adaptation strategies to the effects of climate change: Evidence from northern Uganda. Agriculture & Food Security 10(1), 6. 10.1186/s40066-020-00279-1. https://doi.org/10.1186/s40066-020-00279-1

Baltzer, J.L., Veness, T., Chasmer, L.E., Sniderhan, A.E. and Quinton, W.L. (2014). Forests on thawing permafrost: fragmentation, edge effects, and net forest loss. Global Change Biology 20(3), 824-834. https://doi.org/10.1111/gcb.12349. https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.12349

Barr, S.L., Wyld, B., McQuaid, J.B., Neely, R.R., III and Murray, B.J. (2023). Southern Alaska as a source of atmospheric mineral dust and ice-nucleating particles. Science Advances 9(33). 10.1126/sciadv.adg3708. https://www.science.org/doi/10.1126/sciadv.adg3708

Beamer, K., Elkington, K., Souza, P., Tuma, A., Thorenz, A., Köhler, S. et al. (2023). Island and Indigenous systems of circularity: how Hawai'i can inform the development of universal circular economy policy goals. Ecology and Society 28(1). 10.5751/ES-13656-280109. https://www.ecologyandsociety.org/vol28/iss1/art9/

Belay, A., Recha, J.W., Woldeamanuel, T. and Morton, J.F. (2017). Smallholder farmers' adaptation to climate change and determinants of their adaptation decisions in the Central Rift Valley of Ethiopia. Agriculture & Food Security 6(1), 24. 10.1186/s40066-017-0100-1. https://doi.org/10.1186/s40066-017-0100-1

Bezner Kerr, R., Postigo, J.C., Smith, P., Cowie, A., Singh, P.K., Rivera-Ferre, M. et al. (2023). Agroecology as a transformative approach to tackle climatic, food, and ecosystemic crises. Current Opinion in Environmental Sustainability 62, 101275. https://doi.org/10.1016/j.cosust.2023.101275. https://www.sciencedirect.com/science/article/pii/S1877343523000222

Biswas, B., Qi, F., Biswas, J.K., Wijayawardena, A., Khan, M.A.I. and Naidu, R. (2018). The Fate of Chemical Pollutants with Soil Properties and Processes in the Climate Change Paradigm—A Review. Soil Systems 2(3), 51. https://www.mdpi.com/2571-8789/2/3/51

Blaikie, P. (1985). The Political Economy of Soil Erosion in Developing Countries. 1st edn. Routledge Revivals. New York, NY: Routledge.

Boardman, J., Vandaele, K., Evans, R. and Foster, I.D.L. (2019). Off-site impacts of soil erosion and runoff: Why connectivity is more important than erosion rates. Soil Use and Management 35(2), 245-256. 10.1111/sum.12496. https://doi.org/10.1111/sum.12496

Bombardi, L.M. (2019). A Geography of Agrotoxins use in Brazil and its Relations to the European Union. São Paulo, Brazil: Universidade de São Paulo. Faculdade de Filosofia, Letras e Ciências Humanas. FFLCH - USP. https://www.livrosabertos.abcd.usp.br/portaldelivrosUSP/catalog/book/352

Booker, F., Allison, H., Nash, F. and Green, A. (2022). Women, girls and biodiversity loss: An evidence and policy review (part 1). International Institute for Environment and Development (IIED). https://www.iied.org/21061x

Borrelli, P., Alewell, C., Yang, J.E., Bezak, N., Chen, Y., Fenta, A.A. et al. (2023). Towards a better understanding of pathways of multiple co-occurring erosion processes on global cropland. International Soil and Water Conservation Research 11(4), 713-725. https://doi.org/10.1016/j.iswcr.2023.07.008. https://www.sciencedirect.com/science/article/pii/S209563392300062X

Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C. et al. (2017). An assessment of the global impact of 21st century land use change on soil erosion. Nature Communications 8(1), 2013. 10.1038/s41467-017-02142-7. https://doi.org/10.1038/s41467-017-02142-7

Borrelli, P., Robinson, D.A., Panagos, P., Lugato, E., Yang, J.E., Alewell, C. et al. (2020). Land use and climate change impacts on global soil erosion by water (2015-2070). Proceedings of the National Academy of Sciences 117(36), 21994-22001. doi:10.1073/pnas.2001403117. https://www.pnas.org/doi/abs/10.1073/pnas.2001403117

Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Güneralp, B., Erb, K., Haberl, H., Creutzig, F., & Seto, K.C. (2017) Future urban land expansion and implications for global croplands. Proc. Natl. Acad. Sci. U.S.A. 114 (34) 8939-8944, https://doi.org/10.1073/pnas.1606036114

Brubacher, L.J., Peach, L., Chen, T.T.-W., Longboat, S., Dodd, W., Elliott, S.J. et al. (2024). Climate change, biodiversity loss, and Indigenous Peoples' health and wellbeing: A systematic umbrella review. PLOS Global Public Health 4(3), e0002995. 10.1371/journal.pgph.0002995. https://doi.org/10.1371/journal.pgph.0002995

Bruley, E., Locatelli, B. and Lavorel, S. (2021). Nature's contributions to people: coproducing quality of life from multifunctional landscapes. Ecology and Society 26(1). 10.5751/ES-12031-260112. https://www.ecologyandsociety.org/vol26/iss1/art12/

Build Europe (2022). No net land take by 2050 Solving the Unsolvable. 10 Solutions for an improved management of European Land. https://buildeurope.net/wp-content/uploads/2022/01/No-net-land-take-by-2050-Solving-the-unsolvable.pdf

Buma, B., Gordon, D.R., Kleisner, K.M., Bartuska, A., Bidlack, A., DeFries, R. et al. (2024). Expert review of the science underlying nature-based climate solutions. Nature Climate Change 14(4), 402-406. 10.1038/s41558-024-01960-0. https://doi.org/10.1038/s41558-024-01960-0

Burney, J. and Ramanathan, V. (2014). Recent climate and air pollution impacts on Indian agriculture. PNAS 111(46), 16319-16324. https://doi.org/10.1073/pnas.1317275111

Byrne, B., Liu, J., Bowman, K.W., Pascolini-Campbell, M., Chatterjee, A., Pandey, S. et al. (2024). Carbon emissions from the 2023 Canadian wildfires. Nature 633(8031), 835-839. 10.1038/s41586-024-07878-z. https://doi.org/10.1038/s41586-024-07878-z

Canadell, J.G., Monteiro, P.M.S., Costa, M.H., Cotrim da Cunha, L., Cox, P.M., Eliseev, A.V. et al. (2021). Global Carbon and other Biogeochemical Cycles and Feedbacks. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (eds.). Cambridge, United Kingdom. https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/

Canadians for a Sustainable Society (2023). Farmland Loss. https://sustainablesociety.com/research-material/farmland-loss/2023

Cao, Y., Zhang, Y., Tian, J., Li, X., Tang, Z., Yang, X. et al. (2024). Strong Agricultural Resilience to 2022 Southern China Drought. Earth's Future 12(3), e2023EF004243. https://doi.org/10.1029/2023EF004243. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2023EF004243

Cardell, L., Zereyesus, Y.A., Ajewole, K., Farris, J., Johnson, M.E., Lin, J. et al. (2024). International food security assessment, 2024–34 (GFA-35). U.S. Department of Agriculture, E.R.S., https://ers.usda.gov/sites/default/files/_laserfiche/outlooks/109853/GFA-35.pdf?v=64548

Ceballos, G. and Ehrlich, P.R. (2018). The misunderstood sixth mass extinction. Science 360(6393), 1080-1081. 10.1126/science.aau0191. https://doi.org/10.1126/science.aau0191

Ceballos, G., Ehrlich, P.R., Barnosky, A.D., García, A., Pringle, R.M. and Palmer, T.M. (2015). Accelerated modern human–induced species losses: Entering the sixth mass extinction. Science Advances 1(5), e1400253. doi:10.1126/sciadv.1400253. https://www.science.org/doi/abs/10.1126/sciadv.1400253

Chen, I.-C., Hill, J.K., Ohlemüller, R., Roy, D.B. and Thomas, C.D. (2011). Rapid Range Shifts of Species Associated with High Levels of Climate Warming. Science 333(6045), 1024-1026. doi:10.1126/science.1206432. https://www.science.org/doi/abs/10.1126/science.1206432

Chen, L., Zhou, M., Wang, J., Zhang, Z., Duan, C., Wang, X. et al. (2022). A global meta-analysis of heavy metal(loid)s pollution in soils near copper mines: Evaluation of pollution level and probabilistic health risks. Science of The total Environment 835. https://doi.org/10.1016/j.scitotenv.2022.155441

Cheng, S., Keang, K. and Cross, J.S. (2024). Evidence that microplastics at environmentally relevant concentration and size interfere with energy metabolism of microalgal community. J Hazard Mater 476, 134995. https://doi.org/10.1016/j.jhazmat.2024.134995

Cheok, J., van Velden, J., Fulton, E.A., Gordon, I.J., Lyons, I., Peterson, G.D. et al. (2025). Framings in Indigenous futures thinking: barriers, opportunities, and innovations. Sustainability Science. 10.1007/s11625-024-01615-1. https://doi.org/10.1007/s11625-024-01615-1

Chiang, F., Mazdiyasni, O. and AghaKouchak, A. (2021). Evidence of anthropogenic impacts on global drought frequency, duration, and intensity. Nature Communications 12(1), 2754. 10.1038/s41467-021-22314-w. https://doi.org/10.1038/s41467-021-22314-w

Chinweze, C. (2023). Desertification, Land Degradation and Drought Resilience. Göttingen, Germany: Culliver Verlag.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogee, J., Allard, V. et al. (2005). Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437, 529–533. 10.1038/nature03972. https://www.nature.com/articles/nature03972

Clarke, H., Cirulis, B., Borchers-Arriagada, N., Bradstock, R., Price, O. and Penman, T. (2023). Health costs of wildfire smoke to rise under climate change. Npj Climate and Atmospheric Science 6(1), 102. 10.1038/s41612-023-00432-0. https://doi.org/10.1038/s41612-023-00432-0

Comber, A., Brundson, C. and Ednumd, G. (2008). Using a GIS-based network analysis to determine urban greenspace accessibility for different ethnic and religious groups. Landscape and Urban Planning 86(1), 103-114. 10.1016/j.landurbplan.2008.01.002. http://dx.doi.org/10.1016/j.landurbplan.2008.01.002

Cowie, R.H., Bouchet, P. and Fontaine, B. (2022). The Sixth Mass Extinction: fact, fiction or speculation? Biological Reviews 97(2), 640-663. https://doi.org/10.1111/brv.12816. https://onlinelibrary.wiley.com/doi/abs/10.1111/brv.12816

Cox, D.T.C., Shanahan, D.F., Hudson, H.L., Plummer, K.E., Siriwardena, G.M., Fuller, R.A. et al. (2017). Doses of neighborhood nature: The benefits for mental health of living with nature. BioScience 62(2), 147-155. https://doi.org/10.1093/biosci/biw173

Coyne, M.S., Pena-Yewtukhiw, E.M., Grove, J.H., Sant'Anna, A.C. and Mata-Padrino, D. (2022). Soil health – It's not all biology. Soil Security 6, 100051. https://doi.org/10.1016/j.soisec.2022.100051. https://www.sciencedirect.com/science/article/pii/S2667006222000181

Crawford, C.L., Wiebe, R.A., Yin, H., Radeloff, V.C. and Wilcove, D.S. (2024). Biodiversity consequences of cropland abandonment. Nature Sustainability 7(12), 1596-1607. 10.1038/s41893-024-01452-1. https://doi.org/10.1038/s41893-024-01452-1

Cribb, J. (2023). How to fix a broken planet: Advice for surviving the 21st century. Cambridge, United Kingdon: Cambridge University Press.

Cusack, D.F., Dietterich, L.H. and Sulman, B.N. (2023). Soil respiration responses to throughfall exclusion are decoupled from changes in soil moisture for four tropical forests, suggesting processes for ecosystem models. Global Biogeochemical Cycles 37(4). 10.1029/2022GB007473. https://doi.org/10.1029/2022GB007473

da Silva, R.F.B., de Castro Victoria, D., Nossack, F.Á., Viña, A., Millington, J.D.A., Vieira, S.A. et al. (2023). Slow-down of deforestation following a Brazilian forest policy was less effective on private lands than in all conservation areas. COmmunications Earth and Environment 4. https://doi.org/10.1038/s43247-023-00783-9

Dai, D. (2011). Racial/ethnic and socioeconomic disparities in urban green space accessibility: Where to intervene? Landscape and Urban Planning 102(4), 234-244. https://doi.org/10.1016/j.landurbplan.2011.05.002

Das, P., Arias E, V.A., Kambala, V., Mallavarapu, M. and Naidu, R. (2013). Remediation of Perfluorooctane Sulfonate in Contaminated Soils by Modified Clay Adsorbent—a Risk-Based Approach. Water, Air, & Soil Pollution 224(12), 1714. 10.1007/s11270-013-1714-y. https://doi.org/10.1007/s11270-013-1714-y

Das, S., McEwen, A., Prospero, J., Spalink, D. and Chellam, S. (2023). Respirable Metals, Bacteria, and Fungi during a Saharan-Sahelian Dust Event in Houston, Texas. Environ Sci Technol 57(48), 19942-19955. https://doi.org/10.1021/acs.est.3c04158

Davidson, D. (2016). Gaps in agricultural climate adaptation research. Nature Climate Change 6(5), 433-435. 10.1038/nclimate3007. https://doi.org/10.1038/nclimate3007

Davidson, S.C., Bohrer, G., Gurarie, E., LaPoint, S., Mahoney, P.J., Boelman, N.T. et al. (2020). Ecological insights from three decades of animal movement tracking across a changing Arctic. Science 370(6517), 712-715. doi:10.1126/science.abb7080. https://www.science.org/doi/abs/10.1126/science.abb7080

Debonne, N., van Vliet, J., Metternicht, G. and Verburg, P. (2021). Agency shifts in agricultural land governance and their implications for land degradation neutrality. Global Environmental Change 66, 102221. https://doi.org/10.1016/j.gloenvcha.2020.102221. https://www.sciencedirect.com/science/article/pii/S0959378020308049

Debortoli, N.S., Pearce, T.D. and Ford, J.D. (2023). Estimating future costs for infrastructure in the proposed Canadian Northern Corridor at risk from climate

change. University of Clagary The School of Public Policy Publications 15(39), 1-54. http://dx.doi.org/DOI-10.11575/sppp.v16i1.74925

DeClerck, F.A.J., Koziell, I., Benton, T., Garibaldi, L.A., Kremen, C., Maron, M. et al. (2023). A Whole Earth Approach to Nature-Positive Food: Biodiversity and Agriculture. In Science and Innovations for Food Systems Transformation. von Braun, J., Afsana, K., Fresco, L.O. and Hassan, M.H.A. (eds.). Cham: Springer International Publishing. 469-496. https://doi.org/10.1007/978-3-031-15703-5_25

De-la-Torre, G.E. (2020). Microplastics: an emerging threat to food security and human health. Journal of Food Science and Technology 57(5), 1601-1608. 10.1007/s13197-019-04138-1. https://doi.org/10.1007%2Fs13197-019-04138-1

den Braber, B., Oldekop, J.A., Devenish, K., Godar, J., Nolte, C., Schmoeller, M. et al. (2024). Socio-economic and environmental trade-offs in Amazonian protected areas and Indigenous territories revealed by assessing competing land uses. Nature Ecology & Evolution. 10.1038/s41559-024-02458-w. https://doi.org/10.1038/s41559-024-02458-w

Deprez, A., Leadley, P., Dooley, K., Williamson, P., Cramer, W., Gattuso, J.-P. et al. (2024). Sustainability limits needed for CO_2 removal. Science 383(6682), 484-486. doi:10.1126/science.adj6171. https://www.science.org/doi/abs/10.1126/science.adj6171

Díaz, S., Fargione, J., Chapin, F.S., III and Tilman, D. (2006). Biodiversity Loss Threatens Human Well-Being. PLOS Biology 4(8), e277. 10.1371/journal.pbio.0040277. https://doi.org/10.1371/journal.pbio.0040277

Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Agard, J., Arneth, A. et al. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. Science 366(6471), eaax3100. doi:10.1126/science.aax3100. https://www.science.org/doi/abs/10.1126/science.aax3100

Dinerstein, E., Olson, D., Joshi, A., Vynne, C., Burgess, N.D., Wikramanayake, E. et al. (2017). An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm. BioScience 67(6), 534-545. 10.1093/biosci/bix014. https://doi.org/10.1093/biosci/bix014

Dittus, A.J., Collins, M., Sutton, R. and Hawkins, E. (2024). Reversal of Projected European Summer Precipitation Decline in a Stabilizing Climate. Geophysical Research Letters 51(6), e2023GL107448. https://doi.org/10.1029/2023GL107448. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2023GL107448

Du, E., Terrer, C., Pellegrini, A.F.A., Ahlström, A., van Lissa, C.J., Zhao, X. et al. (2020). Global patterns of terrestrial nitrogen and phosphorus limitation. Nature Geoscience 13, 221-226. https://doi.org/10.1038/s41561-019-0530-4

Du, Z., Yu, L., Yang, J., Coomes, D., Kanniah, K., Fu, H. et al. (2023). Mapping Annual Global Forest Gain From 1983 to 2021 With Landsat Imagery. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 16, 4195-4204. https://doi.org/10.1109/JSTARS.2023.3267796

Ekka, P., Patra, S., Upreti, M., Kumar, G., Kumar, A. and Saikia, P. (2023). Land Degradation and Its Impacts on Biodiversity and Ecosystem Services. In Land and Environmental Management through Forestry. Raj, A., Jhariya, M.K., Banerjee, A., Nema, S. and Bargali, K. (eds.). Beverly, MA, USA: Scrivener Publishing. Wiley. 77-101. https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119910527

Ellis, M. and Bajracharya, B. (2023). Reducing community risk to coastal erosion with managed relocation. Australian Journal of Emergency Management 38(4), 52-58. https://classic.austlii.edu.au/au/journals/AUJlEmMgmt/2023/63.html http://www.doi.org/10.47389.38.4.52

Escobar, W.Z. and Ferrari, M. (2024). Introduction to a new narrative for livestock and biodiversity: Livestock must be part of the solution to sustainably managing Earth's biodiversity. CGIAR. https://cgspace.cgiar.org/server/api/core/bitstreams/11cdfd71-61c6-4226-b470-7512945b8b84/content

Espinoza-Tofalos, A., Fourvel, G., Tock, P. and Biwer, A. (2025). Quantifying the economic impact: a methodological approach to estimate soil pollution costs in Luxembourg. Integrated Environmental Assessment and Management. 10.1093/inteam/vjae021. https://doi.org/10.1093/inteam/vjae021

European Commission (2020). Caring for soil is caring for life - Ensure 75% of soils are healthy by 2030 for food, people, nature and climate. https://op.europa.eu/en/publication-detail/-/publication/4ebd2586-fc85-11ea-b44f-01aa75ed71a1/

European Commission Joint Research Centre and United Nations Convention to Combat Desertification (2024). World Drought Atlas. A. Toreti, D. Tsegai and Rossi, L. (eds.). Luxembourg. https://www.unccd.int/sites/default/files/2024-12/World%20Drought%20Atlas%202024.pdf

European Environment Agency (2006). The changing faces of Europe's coastal areas. Copenhagen, Denmark: Office for Official Publications of the European Communities. https://op.europa.eu/en/publication-detail/-/publication/91f2dece-3b60-4607-b0df-588013f2dd08

European Union Papillons Project Papillons Horizon 2020. https://www.papillons-h2020.eu

Fa, J.E., Watson, J.E., Leiper, I., Potapov, P., Evans, T.D., Burgess, N.D. et al. (2020). Importance of Indigenous Peoples' lands for the conservation of Intact Forest Landscapes. Frontiers in Ecology and the Environment 18(3), 135-140. https://doi.org/10.1002/fee.2148. https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1002/fee.2148

Farrell, J., Burow, P.B., McConnell, K., Bayham, J., Whyte, K. and Koss, G. (2021). Effects of land dispossession and forced migration on Indigenous peoples in North America. Science 374(6567), eabe4943. doi:10.1126/science.abe4943. https://www.science.org/doi/abs/10.1126/science.abe4943

Feeley, K.J., Bernal-Escobar, M., Fortier, R. and Kullberg, A.T. (2023). Tropical Trees Will Need to Acclimate to Rising Temperatures—But Can They? Plants 12(17), 3142. doi:10.3390/plants12173142. https://www.mdpi.com/2223-7747/12/17/3142

Feng, X., Merow, C., Liu, Z., Park, D.S., Roehrdanz, P.R., Maitner, B. et al. (2021). How deregulation, drought and increasing fire impact Amazonian biodiversity. Nature 597(7877), 516-521. 10.1038/s41586-021-03876-7. https://doi.org/10.1038/s41586-021-03876-7

Fernández-Llamazares, Á., Fa, J.E., Brockington, D., Brondízio, E.S., Cariño, J., Corbera, E. et al. (2024). No basis for claim that 80% of biodiversity is found in Indigenous territories. Nature 633(8028), 32-35. 10.1038/d41586-024-02811-w. https://www.nature.com/articles/d41586-024-02811-w

Fierros-González, I. and López-Feldman, A. (2021). Farmers' Perception of Climate Change: A Review of the Literature for Latin America. Frontiers in Environmental Science 9. 10.3389/fenvs.2021.672399. https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2021.672399

Fischer, H.W., Chhatre, A., Duddu, A., Pradhan, N. and Agrawal, A. (2023). Community forest governance and synergies among carbon, biodiversity and livelihoods. Nature Climate Change 13(12), 1340-1347. 10.1038/s41558-023-01863-6. https://doi.org/10.1038/s41558-023-01863-6

Folberth, C., Khabarov, N., Balkovič, J., Skalský, R., Visconti, P., Ciais, P. et al. (2020). The global cropland-sparing potential of high-yield farming. Nature Sustainability 3, 281–289. https://www.nature.com/articles/s41893-020-0505-x.pdf

Folkard-Tapp, H., Banks-Leite, C. and Cavan, E.L. (2021). Nature-based Solutions to tackle climate change and restore biodiversity. Journal of Applied Ecology 58(11), 2344-2348. https://doi.org/10.1111/1365-2664.14059. https://besjournals.onlinelibrary.wiley.com/doi/abs/10.1111/1365-2664.14059

Food and Agriculture Organization of the United Nations and United Nations Environment Programme (2021). Global assessment of soil pollution - Summary for policy makers. Rome, Italy: Food and Agriculture Organization of the United Nations, United Nations Environment Programme. https://doi.org/10.4060/cb4827en

Food and Agriculture Organization of the United Nations and United Nations Environment Programme (2021). Global assessment of soil pollution: Report. Rome, Italy: FAO https://doi.org/10.4060/cb4894en

Food and Agriculture Organization of the United Nations (2017). Voluntary Guidelines for Sustainable Soil Management. Rome, Italy: Food and Agriculture Organization of the United Nations. https://openknowledge.fao.org/handle/20.500.14283/i6874en

Food and Agriculture Organization of the United Nations (2019). The State of the World's Biodiversity for Food and Agriculture. Rome, Italy: FAO Commission on Genetic Resources for Food and Agriculture. https://doi.org/10.4060/CA3129EN

Food and Agriculture Organization of the United Nations (2020). Global Forest Resources Assessment 2020: Main Report. Rome, Italy: FAO. https://doi.org/10.4060/ca9825en

Food and Agriculture Organization of the United Nations (2021). FAOSTAT: Commodities by county. FAO https://www.fao.org/faostat/en/#rankings/commodities_by_country_exports

Food and Agriculture Organization of the United Nations (2022a). The State of the World's Forests 2022. Forest pathways for green recovery and building inclusive, resilient and sustainable economies. The State of the World's Forests. Rome, Italy. https://doi.org/10.4060/cb9360en

Food and Agriculture Organization of the United Nations (2022b). The State of the World's Land and Water Resources for Food and Agriculture – Systems at breaking point. Main report. Rome, Italy. https://openknowledge.fao.org/handle/20.500.14283/i1688e

Food and Agriculture Organization of the United Nations (2022c). Land use statistics and indicators. Global, regional and country trends -- 2000-2020. FAOSTAT Analytical Brie. Rome, Italy: FAO. https://openknowledge.fao.org/server/api/core/bitstreams/cf954c53-e7fa-49ec-aebf-3e14a61acf8c/content

Food and Agriculture Organization of the United Nations (2023a). Crop Prospects and Food Situation – Quarterly Global Report No. 1, March 2023. Rome, Italy: Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/cc4665en

Food and Agriculture Organization of the United Nations (2023b). FAOSTAT: Emissions from fires. https://www.fao.org/faostat/en/#data/GI

Food and Agriculture Organization of the United Nations (2023c). Sand and dust storms - A guide to mitigation, adaptation, policy and risk management measures in agriculture. Rome, Italy: Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/cc8071en

Food and Agriculture Organization of the United Nations (2024a). GIAHS: Globally Important Agricultural Heritage Systems. Food and Agriculture Organization of the United Nations. https://www.fao.org/giahs/en/

Food and Agriculture Organization of the United Nations (2024b). Land, Inputs and Sustainability: Land Use. http://www.fao.org/faostat/en/#data/RL

Food and Agriculture Organization of the United Nations (2024c). SDG Indicators Data Portal: Indicator 15.3.1 Proportion of land that is degraded over total land area. Food and Agriculture Organization of the United Nations. https://www.fao.org/sustainable-development-goals-data-portal/data/indicators/1531-proportion-of-land-that-is-degraded-over-total-land-area/en

Food and Agriculture Organization of the United Nations (2024). Land, Inputs and Sustainability: Land Use. http://www.fao.org/faostat/en/#data/RL

Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, United Nations Children's Fund (UNICEF), World Food Programme and World Health Organization (2023). The State of Food Security and Nutrition in the World 2023. Urbanization, agrifood systems transformation and healthy diets across the rural–urban continuum. The State of Food Security and Nutrition in the World (SOFI). Rome, Italy: FAO. https://openknowledge.fao.org/handle/20.500.14283/cc3017en

Foster, S. and Chilton, J. (2021). Policy experience with groundwater protection from diffuse pollution – a review. Current Opinion in Environmental Science & Health 23. https://doi.org/10.1016/j.coesh.2021.100288

Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Gregor, L., Hauck, J. et al. (2022). Global Carbon Budget 2022. Earth System Science Data 14(11), 4811-4900. 10.5194/essd-14-4811-2022. https://essd.copernicus.org/articles/14/4811/2022/

Fuller, R., Landrigan, P.J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M. et al. (2022). Pollution and health: a progress update. The Lancet Planetary Health 6, e535–e547. https://doi.org/10.1016/s2542-5196(22)00090-0

Gao, Y., Huang, W., Yu, P., Xu, R., Yang, Z., Gasevic, D. et al. (2023). Long-term impacts of non-occupational wildfire exposure on human health: A systematic review. Environmental Pollution 320. 10.1016/j.envpol.2023.121041. https://doi.org/10.1016/j.envpol.2023.121041

Garnett, S.T., Burgess, N.D., Fa, J.E., Fernández-Llamazares, Á., Molnár, Z., Robinson, C.J. et al. (2018). A spatial overview of the global importance of Indigenous lands for conservation. Nature Sustainability 1(7), 369-374. 10.1038/s41893-018-0100-6. https://doi.org/10.1038/s41893-018-0100-6

Gebara, M.F., Ramcilovic-Suominen, S. and Schmidlehner, M.F. (2023). Indigenous Knowledge in the Amazon's Bioeconomy: Unveiling Bioepistemicide through the case of Kambo Medicine. Forest Policy and Economics 154, 103012. https://doi.org/10.1016/j.forpol.2023.103012. https://www.sciencedirect.com/science/article/pii/S1389934123001077

Gilbert, J. (2017). Land grabbing, investments and indigenous peoples' rights to land and natural resources: Case studies and legal analysis. IWGIA Report. Wiben Jensen, M. and Rose, G. (eds.). Copenhagen, Denmark: International Work Group for Indigenous Affairs. https://iwgia.org/images/publications/new-publications/land-grabbing-indigenous-peoples-rights.compressed.pdf

Giobellina, B. and Vitale, J. (2024). Periurbanos hacia el consenso 2-2022: Segundo Encuentro Nacional y Congreso Científico : libro de resúmenes. Córdoba, Spain: Facultad de Arquitectura, Urbanismo y Diseño de la Universidad Nacional de Córdoba. http://hdl.handle.net/11086/553665

Girardin, C.A.J., Jenkins, S., Seddon, N., Allen, M., Lewis, S.L., Wheeler, C.E. et al. (2021). Nature-based solutions can help cool the planet- if we act now. Nature 593, 191-194. 10.1038/d41586-021-01241-2. https://www.nature.com/articles/d41586-021-01241-2

Global Environment Outlook – GEO-6: Healthy Planet, Healthy People. (2019). Cambridge: Cambridge University Press. https://doi.org/10.1017/9781108627146

Global Forest Watch (2023). Country dashboard: Bolivia. https://www.globalforestwatch.org/dashboards/country/BOL/?category=summary

Goldscheider, N., Chen, Z., Auler, A.S., Bakalowicz, M., Broda, S., Drew, D. et al. (2020). Global distribution of carbonate rocks and karst water resources. Hydrogeology Journal 28(5), 1661-1677. 10.1007/s10040-020-02139-5. https://doi.org/10.1007/s10040-020-02139-5

Golroudbary, S.R., Makarava, I., Kraslawski, A. and Repo, E. (2022). 2. Science of The total Environment 832, 155022. https://doi.org/10.1016/j.scitotenv.2022.155022. https://www.sciencedirect.com/science/article/pii/S0048969722021155

Gómez-Upegui, S. (2021). The Amazon rainforest's most dogged defenders are in peril. [Vox https://www.vox.com/down-to-earth/22641038/indigenous-forest-guardians-brazil-guajajara (Accessed: February 2 2024)

Goolmeer, T., Skroblin, A., Grant, C., van Leeuwen, S., Archer, R., Gore-Birch, C. et al. (2022). Recognizing culturally significant species and Indigenous-led management is key to meeting international biodiversity obligations. Conservation Letters 15(6), e12899. https://doi.org/10.1111/conl.12899. https://conbio.onlinelibrary.wiley.com/doi/abs/10.1111/conl.12899

Grecequet, M. (2022). Spring thaw nitrous oxide. Nature Climate Change 12, 884. https://doi.org/10.1038/s41558-022-01498-z

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A. et al. (2017). Natural climate solutions. Proceedings of the National Academy of Sciences 114(44), 11645-11650. doi:10.1073/pnas.1710465114. https://www.pnas.org/doi/abs/10.1073/pnas.1710465114

Gudmundsson, L., Kirchner, J., Gädeke, A., Noetzli, J. and Biskaborn, B.K. (2022). Attributing observed permafrost warming in the northern hemisphere to anthropogenic climate change. Environmental Research Letters 17(9). https://doi.org/10.1088/1748-9326/ac8ec2

Hallam, A. and Wignall, P.B. (1997). Mass Extinctions and their Aftermath. Oxford, United Kingdon: Oxford University Press.

Hang, X., Li, Y., Luo, X., Xu, M. and Han, X. (2020). Assessing the Ecological Quality of Nanjing during Its Urbanization Process by Using Satellite, Meteorological, and Socioeconomic Data. Journal of Meteorological Research 34(2), 280-293. 10.1007/s13351-020-9150-6. https://doi.org/10.1007/s13351-020-9150-6

Hansen, J.E., Pushker, K., Makiko, S., George, T., Joseph, K., E., B.S. et al. (2025). Global Warming Has Accelerated: Are the United Nations and the Public Well-Informed? Environment: Science and Policy for Sustainable Development 67(1), 6-44. 10.1080/00139157.2025.2434494. https://doi.org/10.1080/00139157.2025.2434494

Hartmann, M. and Six, J. (2023). Soil structure and microbiome functions in agroecosystems. Nature Reviews Earth & Environment 4, 4-18. https://doi.org/10.1038/s43017-022-00366-w

Harvey, F. (2023). 'Improving soil could keep world within 1.5C heating target, research suggests'. The Guardian https://www.theguardian.com/environment/2023/jul/04/improving-farming-soil-carbon-store-global-heating-target?CMP=share_btn_link

Harvey, J.A., Tougeron, K., Gols, R., Heinen, R., Abarca, M., Abram, P.K. et al. (2023). Scientists' warning on climate change and insects. Ecological Monographs 93(1), e1553. https://doi.org/10.1002/ecm.1553. https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1002/ecm.1553

Hazardous Waste Haulers Environmental (2025). Hazardous Waste Statistics to Know in 2025. https://www.hwhenvironmental.com/facts-and-statistics-about-waste/#:~:text=Over%20350%20million%20tons%20of,%2C%20up%20184%25%20from%2020002025

Heger, M.P. and Vashold, L. (2021). Disappearing coasts in the Maghreb: Coastal erosion and its costs. Maghreb Technical Notes SeriesWorld Bank Group. https://thedocs.worldbank.org/en/doc/8320c30ab5eee11e7ec39f7f9496b936-0280012021/original/Note-Cost-of-Coastal-Erosion-En.pdf

Heinrich, V.H.A., Vancutsem, C., Dalagnol, R., Rosan, T.M., Fawcett, D., Silva-Junior, C.H.L. et al. (2023). The carbon sink of secondary and degraded humid tropical forests. Nature 615(7952), 436-442. 10.1038/s41586-022-05679-w. https://doi.org/10.1038/s41586-022-05679-w

Hill, J., Von Maltitz, G., Sommer, S., Reynolds, J. et al (eds) (2018). World atlas of desertification – Rethinking land degradation and sustainable land management. Third edn. Luxembourg: Publications Office of the European Union. https://op.europa.eu/en/publication-detail/-/publication/2c39108f-9ab7-11e8-a408-01aa75ed71a1

Hjort, J., Streletskiy, D., Doré, G., Wu, Q., Bjella, K. and Luoto, M. (2022). Impacts of permafrost degradation on infrastructure. Nature Reviews Earth & Environment 3(1), 24-38. 10.1038/s43017-021-00247-8. https://doi.org/10.1038/s43017-021-00247-8

Hoban, S., Archer, F.I., Bertola, L.D., Bragg, J.G., Breed, M.F., Bruford, M.W. et al. (2022). Global genetic diversity status and trends: towards a suite of Essential Biodiversity Variables (EBVs) for genetic composition. Biological Reviews 97(4), 1511-1538. https://doi.org/10.1111/brv.12852. https://onlinelibrary.wiley.com/doi/abs/10.1111/brv.12852

Hoban, S., Bruford, M.W., da Silva, J.M., Funk, W.C., Frankham, R., Gill, M.J. et al. (2023). Genetic diversity goals and targets have improved, but remain insufficient for clear implementation of the post-2020 global biodiversity framework. Conservation Genetics 24(2), 181-191. 10.1007/s10592-022-01492-0. https://doi.org/10.1007/s10592-022-01492-0

Hoffmann, R., Dimitrova, A., Muttarak, R., Crespo Cuaresma, J. and Peisker, J. (2020). A meta-analysis of country-level studies on environmental change and migration. Nature Climate Change 10(10), 904-912. 10.1038/s41558-020-0898-6. https://doi.org/10.1038/s41558-020-0898-6

Hong, F., Hedges, S.B., Yang, Z., Suh, J.W., Qiu, S., Timyan, J. et al. (2025). Decoding primary forest changes in Haiti and the Dominican Republic using Landsat time series. Remote Sensing of Environment 318, 114590. https://doi.org/10.1016/j.rse.2024.114590. https://www.sciencedirect.com/science/article/pii/S0034425724006163

Houlden, V., Jani, A. and Hong, A. (2021). Is biodiversity of greenspace important for human health and wellbeing? A bibliometric analysis and systematic literature review. Urban Forestry & Urban Greening 66, 127385. https://doi.org/10.1016/j.ufug.2021.127385. https://www.sciencedirect.com/science/article/pii/S161886672100412X

Hoyle, H., Jorgensen, A. and Hitchmough, J.D. (2019). What determines how we see nature? Perceptions of naturalness in designed urban green spaces. People and Nature 1(2), 167-180. https://doi.org/10.1002/pan3.19. https://besjournals.onlinelibrary.wiley.com/doi/abs/10.1002/pan3.19

Hsiao, E., Matthew, R., Le Billon, P., & Saintz, G. (Eds.) (2024). Planet on the move – Reimagining conservation at the intersection of migration, environmental change, and conflict. Gland, Switzerland: IUCN. https://portals.iucn.org/library/node/51492

Huang, A., Shen, R., Jia, G. and Xu, X. (2022). Reforestation enhanced landscape connectivity for thermal buffering in China. Environmental Research Letters 17(1), 014056. 10.1088/1748-9326/ac3fda. https://dx.doi.org/10.1088/1748-9326/ac3fda

Hubau, W., Lewis, S.L., Phillips, O.L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A. et al. (2020). Asynchronous carbon sink saturation in African and Amazonian tropical forests. Nature 579(7797), 80-87. https://doi.org/10.1038/s41586-020-2035-0

Hughes, A.C., Tougeron, K., Martin, D.A., Menga, F., Rosado, B.H.P., Villasante, S. et al. (2023). Smaller human populations are neither a necessary nor sufficient condition for biodiversity conservation. Biological Conservation 277, 109841. https://doi.org/10.1016/j.biocon.2022.109841. https://www.sciencedirect.com/science/article/pii/S0006320722003949

Hultgren, A., Carleton, T., Delgado, M., Gergel, D. R., Greenstone, M., Houser, T., & Yuan, J. (2025). Impacts of climate change on global agriculture accounting for adaptation. Nature, 642(8068), 644-652. https://doi.org/10.1038/s41586-025-09085-w

Hussain, R.I., Walcher, R., Eder, R., Allex, B., Wallner, P., Hutter, H.-P. et al. (2019). Management of mountainous meadows associated with biodiversity attributes, perceived health benefits and cultural ecosystem services. Scientific Reports 9(1), 14977. 10.1038/s41598-019-51571-5. https://doi.org/10.1038/s41598-019-51571-5

IAASTD (2009). International Assessment of Agricultural Knowledge, Science and Technology for Development: Global report. McIntyre, B.D., Herren, H.R., Wakhungu, J. and Watson, R.T. (eds.). Washington, DC. https://www.fao.org/fileadmin/templates/est/Investment/Agriculture_at_a_Crossroads_Global_Report_IAASTD.pdf

IK & LK Dialogues. (2025) Indigenous Knowledge and Local Knowledge Dialogues. Global Environment Outlook 7. Mexico City: CopIt-arXives,. https://copitarxives.fisica.unam.mx/SC0011EN/SC0011EN.php Indigenous Knowledge and Local Knowledge Dialogues - Copit Arxives (2025)

Inouye, D.W. (2022). Climate change and phenology. WIREs Climate Change 13(3), e764. https://doi.org/10.1002/wcc.764. https://wires.onlinelibrary.wiley.com/doi/abs/10.1002/wcc.764

Intergovernmental Panel on Climate Change (2014). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom. https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-PartA_FINAL.pdf

Intergovernmental Panel on Climate Change (2019a). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts et al. (eds.). https://www.ipcc.ch/site/assets/uploads/2019/11/SRCCL-Full-Report-Compiled-191128.pdf

Intergovernmental Panel on Climate Change (2019b). Summary for policymakers. In Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C. et al. (eds.). Cambridge, United Kingdom: Cambridge University Press. Summary for policymakers. 1-36. https://doi.org/10.1017/9781009157988.001

IPCC (2022a). Climate Change 2022: Impacts, Adaptation and Vulnerability. Pörtner, H. O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., ... & Rama, B. (2022). Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK New York, NY, USA: Cambridge University Press. https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/

Intergovernmental Panel on Climate Change (2022b). Climate Change 2022: Mitigation of Climate Change. Working Group III Contribution to the IPCC Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom. New York, NY, USA: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf

Intergovernmental Panel on Climate Change (2023a). Global Carbon and Other Biogeochemical Cycles and Feedbacks. In Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate, C. (ed.). Cambridge: Cambridge University Press. 673-816. https://www.cambridge.org/core/product/93DFD13E855AC1F1B502965CABE28B7F

Intergovernmental Panel on Climate Change (2023b). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team , Lee, H. and Romero, J. (eds.). Geneva, Switzerland: Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2018). The IPBES assessment report on land degradation and restoration. Bonn, Germany: Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://doi.org/10.5281/zenodo.3237393

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES Secretariat. https://doi.org/10.5281/zenodo.3831673

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2023). Summary for Policymakers of the Thematic Assessment Report on Invasive Alien Species and their Control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In Roy, H.E., Pauchard, A., Stoett, P., Renard Truong, T., Bacher, S., Galil, B.S. et al. (eds.). Bonn, Germany: IPBES Secretariat. https://doi.org/10.5281/zenodo.7430692

Internal Displacement Monitoring Centre (2023). Global Internal Displacement Database. https://www.internal-displacement.org/publications/2023-global-report-on-internal-displacement-grid/

International Fund for Agricultural Development (2024). Climate Action Report2024.IFAD.https://www.ifad.org/documents/48415603/50347946/climate-action-report-2024_eng.pdf/22c855db-c999-c990-be6e-5a527876740a?t=1731324736848

International Livestock Research Institute, International Union for Conservation of Nature , World Wide Fund for Nature , Food and Agriculture Organization of the United Nations , United Nations Environment Programme and Coalition, I.L. (2021). Rangelands Atlas. Nairobi, Kenya: ILRI. https://hdl.handle.net/10568/114064

International Observatory on Food and Sustainability (2024). Cross Country Report Waste Watcher International Observatory Food & Waste around the World. https://www.sprecozero.it/waste-watcher (Accessed: 19 March 2025)

Isbell, F., Balvanera, P., Mori, A.S., He, J.-S., Bullock, J.M., Regmi, G.R. et al. (2023). Expert perspectives on global biodiversity loss and its drivers and impacts on people. Frontiers in Ecology and the Environment 21(2), 94-103. https://doi.org/10.1002/fee.2536. https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1002/fee.2536

Isbell, F., Gonzalez, A., Loreau, M., Cowles, J., Díaz, S., Hector, A. et al. (2017). Linking the influence and dependence of people on biodiversity across scales. Nature 546(7656), 65-72. https://doi.org/10.1038/nature22899

IUCN (2024) The IUCN Red List of Threatened Species. Version 2024-1. https://www.iucnredlist.org. (Accessed on 15 September 2024)

Iungman, T., Caballé, S.V., Segura-Barrero, R., Cirach, M., Mueller, N., Daher, C. et al. (2025). Co-benefits of nature-based solutions: A health impact assessment of the Barcelona Green Corridor (Eixos Verds) plan. Environment International 196, 109313. https://doi.org/10.1016/j.envint.2025.109313. https://www.sciencedirect.com/science/article/pii/S0160412025000649

Iungman, T., Cirach, M., Marando, F., Pereira Barboza, E., Khomenko, S., Masselot, P. et al. (2023). Cooling cities through urban green infrastructure: a health impact assessment of European cities. The Lancet 401(10376), 577-589. https://doi.org/10.1016/S0140-6736(22)02585-5. https://www.sciencedirect.com/science/article/pii/S0140673622025855

Jacques, P.J. and Jacques, J.R. (2012). Monocropping Cultures into Ruin: The Loss of Food Varieties and Cultural Diversity. Sustainability 4(11), 2970-2997. https://www.mdpi.com/2071-1050/4/11/2970

Jactel, H., Koricheva, J. and Castagneyrol, B. (2019). Responses of forest insect pests to climate change: not so simple. Current Opinion in Insect Science 35, 103-108. https://doi.org/10.1016/j.cois.2019.07.010. https://www.sciencedirect.com/science/article/pii/S2214574519300227

Jägermeyr, J., Müller, C., Ruane, A.C., Elliott, J., Balkovic, J., Castillo, O. et al. (2021). Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. Nature Food 2(11), 873-885. 10.1038/s43016-021-00400-y. https://doi.org/10.1038/s43016-021-00400-y

Jaglo, K., Kenny, S. and Stephenson, J. (2021). The Environmental Impacts of U.S. Food Waste. From Farm to Kitchen. Chaudhary, A., Neff, R. and Xue Romeiko, X. (eds.)U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2021-11/from-farm-to-kitchen-the-environmental-impacts-of-u.s.-food-waste_508-tagged.pdf

Jain, P., Castellanos-Acuna, D., Coogan, S.C.P., Abatzoglou, J.T. and Flannigan, M.D. (2022). Observed increases in extreme fire weather driven by atmospheric humidity and temperature. Nature Climate Change 12(1), 63-70. 10.1038/s41558-021-01224-1. https://doi.org/10.1038/s41558-021-01224-1

Jin, H.-J., Wu, Q.-B. and Romanovsky, V.E. (2021). Degrading permafrost and its impacts. Advances in Climate Change Research 12(1), 1-5. https://doi.org/10.1016/j.accre.2021.01.007. https://www.sciencedirect.com/science/article/pii/S1674927821000241

Johnson, A.C., Jin, X., Nakada, N. and Sumpter, J.P. (2020). Learning from the past and considering the future of chemicals in the environment. Science 367(6476), 384-387. doi:10.1126/science.aay6637. https://www.science.org/doi/abs/10.1126/science.aay6637

Jolly, W.M., Cochrane, M.A., Freeborn, P.H., Holden, Z.A., Brown, T.J., Williamson, G.J. et al. (2015). Climate-induced variations in global wildfire danger from 1979 to 2013. Nature Communications 6(1), 7537. 10.1038/ncomms8537. https://doi.org/10.1038/ncomms8537

Jones, M.W., Abatzoglou, J.T., Veraverbeke, S., Andela, N., Lasslop, G., Forkel, M. et al. (2022). Global and Regional Trends and Drivers of Fire Under Climate Change. Reviews of Geophysics 60(3), e2020RG000726. https://doi.org/10.1029/2020RG000726. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020RG000726

Jones, N. (2023). When will global warming actually hit the landmark 1.5 ºC limit? Nature 618. https://www.nature.com/articles/d41586-023-01702-w .

Kaczan, D.J. and Orgill-Meyer, J. (2020). The impact of climate change on migration: a synthesis of recent empirical insights. Climatic Change 158(3), 281-300. 10.1007/s10584-019-02560-0. https://doi.org/10.1007/s10584-019-02560-0

Kala, C.P. (2013). Traditional ecological knowledge on characteristics, conservation and management of soil in tribal communities of Pachmarhi Biosphere Reserve, India. Journal of Soil Science and Plant Nutrition 13, 201-214. 10.4067/S0718-95162013005000018. http://dx.doi.org/10.4067/S0718-95162013005000018

Kanakidou, M., Sfakianaki, M. and Probst, A. (2022). Impact of Air Pollution on Terrestrial Ecosystems. In Atmospheric Chemistry in the Mediterranean Region: Volume 2 - From Air Pollutant Sources to Impacts. Dulac, F., Sauvage, S. and Hamonou, E. (eds.). Cham: Springer International Publishing. 511-542. https://doi.org/10.1007/978-3-030-82385-6_24

Katikas, L., Krzywoszynska, A., Naciph Mora, K. and Roca Vallejo, R. (2024). Preliminary assessment of the knowledge gaps related to soil literacy. Soils for Europe 1, e118883. https://doi.org/10.3897/soils4europe.e118883

Keenan, R.J. (2015). Climate change impacts and adaptation in forest management: a review. Annals of Forest Science 72(2), 145-167. 10.1007/s13595-014-0446-5. https://doi.org/10.1007/s13595-014-0446-5

Kelly, B.C., Ikonomou, M.G., Blair, J.D., Morin, A.E. and Gobas, F.A.P.C. (2007). Food web-specific biomagnification of persistent organic pollutants. Science 317(5835), 236-239. doi:10.1126/science.1138275. https://www.science.org/doi/abs/10.1126/science.1138275

Kermoal, N. and Altamirano-Jiménez, I. (2016). Living on the land: Indigenous women's understanding of place. Edmonton, Canada: Athabascai University Press, Keystone Foundation. https://www.aupress.ca/app/uploads/120256_99Z_Kermoal_Altamirano-Jim%C3%A9nez_2016-Living_on_the_Land.pdf

Khan, I., Lei, H., Shah, I.A., Ali, I., Khan, I., Muhammad, I. et al. (2020). Farm households' risk perception, attitude and adaptation strategies in dealing with climate change: Promise and perils from rural Pakistan. Land Use Policy 91, 104395. https://doi.org/10.1016/j.landusepol.2019.104395. https://www.sciencedirect.com/science/article/pii/S0264837719315078

Kirilenko, A. and Dronin, N. (2022). Recent grain production boom in Russia in historical context. Climatic Change 171(3), 22. 10.1007/s10584-022-03332-z. https://doi.org/10.1007/s10584-022-03332-z

Klein Goldewijk, C.G.M., Beusen, A., Doelman, J. and Stehfest, E. (2023). History Database of the Global Environment 3.3 (HYDE 3.3). Utrecht University/PBL Netherlands Environmental Assessment Agency, https://doi.org/10.24416/UU01-AEZZIT

Klein Goldewijk, K., Beusen, A., Doelman, J. and Stehfest, E. (2017). Anthropogenic land use estimates for the Holocene–HYDE 3.2. Earth System Science Data, 9(2), 927-953.http://dx.doi.org/10.5194/essd-2016-58

Knapp, C.W., Turner, R., Salifu, E., Khan, S., Stillings, M. and Tonner, R. (2021). Climate Change: Any Dangers from Antimicrobial Resistant Bacteria? In Microbiomes and the Global Climate Change. Lone, S.A. and Malik, A. (eds.). Singapore: Springer Singapore. 145-171. https://doi.org/10.1007/978-981-33-4508-9_10

Kopittke, P.M., Menzies, N.W., Wang, P., McKenna, B.A. and Lombi, E. (2019). Soil and the intensification of agriculture for global food security. Environment International 132, 105078. https://doi.org/10.1016/j.envint.2019.105078. https://www.sciencedirect.com/science/article/pii/S0160412019315855

Krishnakumar, J. and Roy, P. (2021). Community well-being and the 'invisible' subjectivities of Indigenous People: A focus on the Irulas of the Nilgiri Biosphere Reserve, Tamil Nadu, India. Current Science 121(1). http://dx.doi.org/10.18520/cs/v121/i1/37-43. https://www.currentscience.ac.in/Volumes/121/01/0037.pdf

Kummer, K. (2000). The Basel Convention: an Analysis and Assessment. In International Management of Hazardous Wastes: The Basel Convention and Related Legal Rules. Oxford, United Kingdom: Oxford University Press. Chapter 2. 38-86. https://doi.org/10.1093/acprof:oso/9780198259947.003.0003 (Downloaded: 8/24/2023)

Labouyrie, M., Ballabio, C., Romero, F., Panagos, P., Jones, A., Schmid, M.W. et al. (2023). Patterns in soil microbial diversity across Europe. Nature Communications 14(1). 10.1038/s41467-023-37937-4. https://doi.org/10.1038/s41467-023-37937-4

Lal, R. (2015). Cover cropping and the "4 per Thousand" proposal. Journal of Soil and Water Conservation 70(6), 141A-141A. 10.2489/jswc.70.6.141A. https://www.jswconline.org/content/jswc/70/6/141A.full.pdf

Lal, R., Bouma, J., Brevik, E., Dawson, L., Field, D.J., Glaser, B. et al. (2021). Soils and sustainable development goals of the United Nations: An International Union of Soil Sciences perspective. Geoderma Regional 25, e00398. https://doi.org/10.1016/j.geodrs.2021.e00398. https://www.sciencedirect.com/science/article/pii/S2352009421000432

Lang, T., Jelić, F. and Wechselberger, C. (2024). From Cradle to Grave: Microplastics—A Dangerous Legacy for Future Generations. Environments 11(12), 263. doi:10.3390/environments11120263. https://www.mdpi.com/2076-3298/11/12/263

Lapola, D.M., Pinho, P., Barlow, J., Aragão, L.E.O.C., Berenguer, E., Carmenta, R. et al. (2023). The drivers and impacts of Amazon forest degradation. Science 379(6630), eabp8622. doi:10.1126/science.abp8622. https://www.science.org/doi/abs/10.1126/science.abp8622

Le Quéré, C., Moriarty, R., Andrew, R.M., Peters, G.P., Ciais, P., Friedlingstein, P. et al. (2015). Global carbon budget 2014. Earth Syst. Sci. Data 7(1), 47-85. 10.5194/essd-7-47-2015. https://essd.copernicus.org/articles/7/47/2015/.

Le, Q.B., Mirzabaev, A., Nkonya, E. and van Lynden, G.W.J. (2017). The extent and cost of land degradation. In Land degradation and the Sustainable Development Goals: Threats and potential remedies. Vlek, P.L.G., Khamzina, A. and Tamene, L. (eds.). Nairobi, Kenya: CGIAR Research Program on Dryland Systems and Center for Tropical Agriculture. http://ciat-library.ciat.cgiar.org/Articulos_Ciat/biblioteca/LAND_DEGRADATION_AND_THE_SDGs-THREATS_AND_POTENTIAL_REMEDIES.pdf

Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R. et al. (2018). Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. Scientific Reports 8(1), 4666. 10.1038/s41598-018-22939-w. https://doi.org/10.1038/s41598-018-22939-w

Lee, J.-W., Hong, E.-M., Jang, W.-J. and Kim, S.-J. (2022). Assessment of socio-economic drought information using drought-related Internet news data (Part A: Socio-economic drought data construct and evaluation socio-economic drought information). International Journal of Disaster Risk Reduction 75, 102961. https://doi.org/10.1016/j.ijdrr.2022.102961. https://www.sciencedirect.com/science/article/pii/S2212420922001807.

Lehmann, J. and Kleber, M. (2015). The contentious nature of soil organic matter. Nature 528(7580), 60-68. 10.1038/nature16069. https://doi.org/10.1038/nature16069

Leigh, D.M., Hendry, A.P., Vázquez-Domínguez, E. and Friesen, V.L. (2019). Estimated six per cent loss of genetic variation in wild populations since the industrial revolution. Evolutionary Applications 12(8), 1505-1512. https://doi.org/10.1111/eva.12810. https://onlinelibrary.wiley.com/doi/abs/10.1111/eva.12810

Leroy, F., Abraini, F., Beal, T., Dominguez-Salas, P., Gregorini, P., Manzano, P. et al. (2022). Animal board invited review: Animal source foods in healthy, sustainable, and ethical diets – An argument against drastic limitation of livestock in the food system. animal 16(3), 100457. https://doi.org/10.1016/j.animal.2022.100457. https://www.sciencedirect.com/science/article/pii/S1751731122000040

Levis, C., Flores, B.M., Campos-Silva, J.V., Peroni, N., Staal, A., Padgurschi, M.C.G. et al. (2024). Contributions of human cultures to biodiversity and ecosystem conservation. Nature Ecology & Evolution 8(5), 866-879. 10.1038/s41559-024-02356-1. https://doi.org/10.1038/s41559-024-02356-1

Levy, S.A., Cammelli, F., Munger, J., Gibbs, H.K. and Garrett, R.D. (2023). Deforestation in the Brazilian Amazon could be halved by scaling up the implementation of zero-deforestation cattle commitments. Global Environmental Change 80, 102671. https://doi.org/10.1016/j.gloenvcha.2023.102671. https://www.sciencedirect.com/science/article/pii/S0959378023000377

Lewin, A., Murali, G., Rachmilevitch, S. and Roll, U. (2024). Global evaluation of current and future threats to drylands and their vertebrate biodiversity. Nature Ecology & Evolution 8(8), 1448-1458. 10.1038/s41559-024-02450-4. https://doi.org/10.1038/s41559-024-02450-4

Li, G., Fang, C., Watson, J.E.M. Sun, S., Qi, W.,Wang, Z., Liu, J. (2024) Mixed effectiveness of global protected areas in resisting habitat loss. Nat Commun 15, 8389 (2024). https://doi.org/10.1038/s41467-024-52693-9

Li, C., Li, M., Zeng, J., Yuan, S., Luo, X., Wu, C. et al. (2024). Migration and distribution characteristics of soil heavy metal(loid)s at a lead smelting site. Journal of Environmental Sciences 135, 600-609. https://doi.org/10.1016/j.jes.2023.02.007. https://www.sciencedirect.com/science/article/pii/S1001074223000517

Li, W.C., Tse, H.F. and Fok, L. (2016). Plastic waste in the marine environment: A review of sources, occurrence and effects. Science of The total Environment 566-567, 333-349. https://doi.org/10.1016/j.scitotenv.2016.05.084. https://www.sciencedirect.com/science/article/pii/S0048969716310154

Lindemann-Matthies, P. and Matthies, D. (2018). The influence of plant species richness on stress recovery of humans. Web Ecology 18(2), 121-128. 10.5194/we-18-121-2018. https://we.copernicus.org/articles/18/121/2018/

Liu, D., Kwan, M.-P. and Kan, Z. (2021). Analysis of urban green space accessibility and distribution inequity in the City of Chicago. Urban Forestry & Urban Greening 59. https://doi.org/10.1016/j.ufug.2021.127029. https://www.sciencedirect.com/science/article/pii/S1618866721000546

Liu, X. and Desai, A.R. (2021). Significant reductions in crop yields from air pollution and heat stress in the United States. Earth's Future 9(8). https://doi.org/10.1029/2021EF002000. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2021EF002000

Lobell, D.B., Schlenker, W. and Costa-Roberts, J. (2011). Climate Trends and Global Crop Production Since 1980. Science 333(6042), 616-620. doi:10.1126/science.1204531. https://www.science.org/doi/abs/10.1126/science.1204531

Maaroufi, N.I. and De Long, J.R. (2020). Global change impacts on forest soils: Linkage between soil biota and carbon-nitrogen-phosphorus stoichiometry. Frontiers in Forests and Global Change 3. 10.3389/ffgc.2020.00016. https://www.frontiersin.org/articles/10.3389/ffgc.2020.00016

MacLeod, M., Arp, H.P.H., Tekman, M.B. and Jahnke, A. (2021). The global threat from plastic pollution. Science 373(6550), 61-65. doi:10.1126/science.abg5433. https://www.science.org/doi/abs/10.1126/science.abg5433

Maes, S.L., Dietrich, J., Midolo, G., Schwieger, S., Kummu, M., Vandvik, V. et al. (2024). Environmental drivers of increased ecosystem respiration in a warming tundra. Nature 629(8010), 105-113. 10.1038/s41586-024-07274-7. https://doi.org/10.1038/s41586-024-07274-7

Malhi, Y., Franklin, J., Seddon, N., Solan, M., Turner, M.G., Field, C.B. et al. (2020). Climate change and ecosystems: threats, opportunities and solutions. Philosophical Transactions of the Royal Society B: Biological Sciences 375(1794), 20190104. doi:10.1098/rstb.2019.0104. https://royalsocietypublishing.org/doi/abs/10.1098/rstb.2019.0104

Marengo, J.A., Ambrizzi, T., Barreto, N., Cunha, A.P., Ramos, A.M., Skansi, M. et al. (2022). The heat wave of October 2020 in central South America. International Journal of Climatology 42(4), 2281-2298. https://doi.org/10.1002/joc.7365. https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.7365

Masolele, R.N., Marcos, D., De Sy, V., Abu, I.-O., Verbesselt, J., Reiche, J. et al. (2024). Mapping the diversity of land uses following deforestation across Africa. Scientific Reports 14(1), 1681. 10.1038/s41598-024-52138-9. https://doi.org/10.1038/s41598-024-52138-9

Masson, D., Pédrot, M., Davranche, M., Cabello-Hurtado, F., Ryzhenko, N., El Amrani, A. et al. (2023). Are nanoplastics potentially toxic for plants and rhizobiota? Current knowledge and recommendations. NanoImpact 31, 100473. https://doi.org/10.1016/j.impact.2023.100473. https://www.sciencedirect.com/science/article/pii/S2452074823000241

Mavoa, S., Davern, M., Breed, M. and Hahs, A. (2019a). Higher levels of greenness and biodiversity associate with greater subjective wellbeing in adults living in Melbourne, Australia. Health & Place 57, 321-329. https://doi.org/10.1016/j.healthplace.2019.05.006. https://www.sciencedirect.com/science/article/pii/S1353829218307780

Mavoa, S., Lucassen, M., Denny, S., Utter, J., Clark, T. and Smith, M. (2019b). Natural neighbourhood environments and the emotional health of urban New Zealand adolescents. Landscape and Urban Planning 191. https://doi.org/10.1016/j.landurbplan.2019.103638. https://www.sciencedirect.com/science/article/pii/S0169204619304360

McDowell, N.G., Sapes, G., Pivovaroff, A., Adams, H.D., Allen, C.D., Anderegg, W.R.L. et al. (2022). Mechanisms of woody-plant mortality under rising drought, CO2 and vapour pressure deficit. Nature Reviews Earth & Environment 3(5), 294-308. 10.1038/s43017-022-00272-1. https://doi.org/10.1038/s43017-022-00272-1

McFarlane, K.J., Cusack, D.F., Dietterich, L.H., Hedgpeth, A.L., Finstad, K.M. and Nottingham, A.T. (2024). Experimental warming and drying increase older carbon contributions to soil respiration in lowland tropical forests. Nature Communications 15(1), 7084. 10.1038/s41467-024-51422-6. https://doi.org/10.1038/s41467-024-51422-6

McNabb, D.E. (2019). Global Pathways to Water Sustainability. Cham, Switzerland: Palgrave Macmillan Cham. https://link.springer.com/book/10.1007/978-3-030-04085-7?utm_medium=referral&utm_source=google_books&utm_campaign=3_pier05_buy_print&utm_content=en_08082017

Meng, Z., Dong, J., Ellis, E.C., Metternicht, G., Qin, Y., Song, X.-P. et al. (2023). Post-2020 biodiversity framework challenged by cropland expansion in protected areas. Nature Sustainability 6(7), 758-768. 10.1038/s41893-023-01093-w. https://doi.org/10.1038/s41893-023-01093-w

Miner, K.R., D'Andrilli, J., Mackelprang, R., Edwards, A., Malaska, M.J., Waldrop, M.P. et al. (2021). Emergent biogeochemical risks from Arctic permafrost degradation. Nature Climate Change 11(10), 809-819. 10.1038/s41558-021-01162-y. https://doi.org/10.1038/s41558-021-01162-y

Moghimi Dehkordi, M., Pournuroz Nodeh, Z., Soleimani Dehkordi, K., salmanvandi, H., Rasouli Khorjestan, R. and Ghaffarzadeh, M. (2024). Soil, air, and water pollution from mining and industrial activities: Sources of pollution, environmental impacts, and prevention and control methods. Results in Engineering 23, 102729. https://doi.org/10.1016/j.rineng.2024.102729. https://www.sciencedirect.com/science/article/pii/S2590123024009848

Mooney, H., Larigauderie, A., Cesario, M., Elmquist, T., Hoegh-Guldberg, O., Lavorel, S. et al. (2009). Biodiversity, climate change, and ecosystem services. Current Opinion in Environmental Sustainability 1(1), 46-54. https://doi.org/10.1016/j.cosust.2009.07.006. https://www.sciencedirect.com/science/article/pii/S1877343509000086

Moran Cortes, J.J., Castro Vallejo, N.V., Herrera Pinza, A. and Ordoñez Tulcán, N. (2022). Importancia de páramos y frailejones. Boletín Informativo CEI 9(1), 125-127. https://revistas.umariana.edu.co/index.php/BoletinInformativoCEI/article/view/3025

Móstiga, M., Armenteras, D., Vayreda, J. and Retana, J. (2024). Decoding the drivers and effects of deforestation in Peru: a national and regional analysis. Environment, Development and Sustainability. 10.1007/s10668-024-04638-x. https://doi.org/10.1007/s10668-024-04638-x

Müller, J., Hothorn, T., Yuan, Y., Seibold, S., Mitesser, O., Rothacher, J. et al. (2023). Weather explains the decline and rise of insect biomass over 34 years. Nature. 10.1038/s41586-023-06402-z. https://pubmed.ncbi.nlm.nih.gov/37758943/

Münzel, T., Hahad, O., Daiber, A. and Landrigan, P.J. (2023). Soil and water pollution and human health: what should cardiologists worry about? Cardiovascular Research 119(2), 440-449. 10.1093/cvr/cvac082. https://doi.org/10.1093/cvr/cvac082

Muscat, A., de Olde, E.M., de Boer, I.J.M. and Ripoll-Bosch, R. (2020). The battle for biomass: A systematic review of food-feed-fuel competition. Global Food Security 25, 100330. https://doi.org/10.1016/j.gfs.2019.100330. https://www.sciencedirect.com/science/article/pii/S2211912418301366

Myers, N. (2002). Environmental refugees: a growing phenomenon of the 21st century. Philos Trans R Soc Lond B Biol Sci 357(1420), 609-613. 10.1098/rstb.2001.0953. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1692964/

Nadal, M., Marquès, M., Mari, M. and Domingo, J.L. (2015). Climate change and environmental concentrations of POPs: A review. Environmental Research 143, 177-185. https://doi.org/10.1016/j.envres.2015.10.012. https://www.sciencedirect.com/science/article/pii/S0013935115301109

Naidu, R., Biswas, B., Willett, I.R., Cribb, J., Kumar Singh, B., Paul Nathanail, C. et al. (2021). Chemical pollution: A growing peril and potential catastrophic risk to humanity. Environment International 156, 106616. https://doi.org/10.1016/j.envint.2021.106616. https://www.sciencedirect.com/science/article/pii/S0160412021002415

Namsaraev, Z., Bobrik, A., Kozlova, A., Krylova, A., Rudenko, A., Mitina, A. et al. (2023). Carbon emission and biodiversity of Arctic soil microbial communities of the Novaya Zemlya and Franz Josef Land Archipelagos. Microorganisms 11(2), 482. https://www.mdpi.com/2076-2607/11/2/482

Nath, S., Krishnakumar, J., Varghese, A. and Murthy, A. (2020). NTFP and Gender-roles, practices and knowledge amongst some indigenous communities in India. NTFP-EP India. https://www.academia.edu/100498525/NTFP_and_Gender_roles_practices_and_knowledge_amongst_some_indigenous_communities_in_India

National Aeronautics and Space Administration (2023). Tracking Canada's extreme 2023 fire season. https://earthobservatory.nasa.gov/images/151985/tracking-canadas-extreme-2023-fire-season

National Geographic (2023). Drought. https://education.nationalgeographic.org/resource/drought/

Nature Medicine (2024) Microplastics are everywhere — we need to understand how they affect human health. (2024). Nature Medicine 30(4), 913-913. 10.1038/s41591-024-02968-x. https://doi.org/10.1038/s41591-024-02968-x

Nielsen, D.M., Pieper, P., Barkhordarian, A., Overduin, P., Ilyina, T., Brovkin, V. et al. (2022). Increase in Arctic coastal erosion and its sensitivity to warming in the twenty-first century. Nature Climate Change 12(3), 263-270. 10.1038/s41558-022-01281-0. https://doi.org/10.1038/s41558-022-01281-0

Nkuba, M.R., Chanda, R., Mmopelwa, G., Kato, E., Mangheni, M.N. and Lesolle, D. (2020a). Influence of Indigenous Knowledge and Scientific Climate Forecasts on Arable Farmers' Climate Adaptation Methods in the Rwenzori region, Western Uganda. Environmental Management 65(4), 500-516. 10.1007/s00267-020-01264-x. https://doi.org/10.1007/s00267-020-01264-x

Nkuba, M.R., Chanda, R., Mmopelwa, G., Mangheni, M.N., Lesolle, D. and Kato, E. (2020b). Indigenous Knowledge Systems and Indicators of Rain: Evidence from Rwenzori Region, Western Uganda. Weather, Climate, and Society 12(2), 213-234. https://doi.org/10.1175/WCAS-D-19-0027.1. https://journals.ametsoc.org/view/journals/wcas/12/2/wcas-d-19-0027.1.xml

Nkuba, M.R., Raban, C., Gagoitseope, M., Edward, K., Margaret, N.M., David, L. et al. (2023). Effect of indigenous and scientific forecasts on pastoralists' climate change perceptions in the Rwenzori region, Western Uganda. Climate

and Development 15(6), 522-534. 10.1080/17565529.2022.2119831. https://doi.org/10.1080/17565529.2022.2119831

Nolan, C.J., Field, C.B. and Mach, K.J. (2021). Constraints and enablers for increasing carbon storage in the terrestrial biosphere. Nature Reviews Earth & Environment 2(6), 436-446. 10.1038/s43017-021-00166-8. https://doi.org/10.1038/s43017-021-00166-8

Nuissl, H. and Siedentop, S. (2021). Urbanisation and Land Use Change. In Sustainable Land Management in a European Context: A Co-Design Approach. Weith, T., Barkmann, T., Gaasch, N., Rogga, S., Strauß, C. and Zscheischler, J. (eds.). Cham: Springer International Publishing. 75-99. https://doi.org/10.1007/978-3-030-50841-8_5

Ohnemus, D.C., Kollman, C., Marsay, C.M., Ricci, M. and Buck, C.S. (2025). The Hawaii Dust Regime: Patterns and Variability in Aerosol Mineral Dust From MERRA-2 at Station ALOHA and the Hawaii Aerosol Time-Series. Journal of Geophysical Research: Atmospheres 130(1), e2024JD041860. https://doi.org/10.1029/2024JD041860. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2024JD041860

Okur, B. and Örçen, N. (2020). Chapter 12 - Soil salinization and climate change. In Climate Change and Soil Interactions. Prasad, M.N.V. and Pietrzykowski, M. (eds.). Elsevier. 331-350. http://dx.doi.org/10.1016/B978-0-12-818032-7.00012-6

Oladele, O.I. and Amara, A. (2024). Farmers' use of Indigenous knowledge on climate change adaptation across farming systems and agroecological zones of Sierra Leone. AlterNative: An International Journal of Indigenous Peoples 20(3), 473-483. 10.1177/11771801241251862. https://journals.sagepub.com/doi/abs/10.1177/11771801241251862

Omari, R.A., Bellingrath-Kimura, S.D., Sarkodee Addo, E., Oikawa, Y. and Fujii, Y. (2018). Exploring Farmers' Indigenous Knowledge of Soil Quality and Fertility Management Practices in Selected Farming Communities of the Guinea Savannah Agro-Ecological Zone of Ghana. Sustainability 10(4), 1034. https://www.mdpi.com/2071-1050/10/4/1034

Orr, B.J., Cowie, A.L., Sanchez, V.M.C., Chasek, P., Crossman, N.D., Erlewein, A. et al. (2017). Scientific conceptual framework for Land Degradation Neutrality. A report of the science-policy interface. Bonn, Germany: United Nations Convention to Combat Desertification. https://www.unccd.int/sites/default/files/2018-09/LDN_CF_report_web-english.pdf

Ortiz-Bobea, A., Ault, T.R., Carrillo, C.M., Chambers, R.G. and Lobell, D.B. (2021). Anthropogenic climate change has slowed global agricultural productivity growth. Nature Climate Change 11(4), 306-312. 10.1038/s41558-021-01000-1. https://doi.org/10.1038/s41558-021-01000-1

Outhwaite, C.L., McCann, P. and Newbold, T. (2022). Agriculture and climate change are reshaping insect biodiversity worldwide. Nature 605(7908), 97-102. 10.1038/s41586-022-04644-x. https://doi.org/10.1038/s41586-022-04644-x

Pagaling, E., Hough, R., Avery, L., Robinson, L., Freitag, T., Coull, M. et al. (2023). Antibiotic resistance patterns in soils across the Scottish landscape. Communications Earth & Environment 4(1), 403. 10.1038/s43247-023-01057-0. https://doi.org/10.1038/s43247-023-01057-0

Panagos, P., Matthews, F., Patault, E., De Michele, C., Quaranta, E., Bezak, N. et al. (2024). Understanding the cost of soil erosion: An assessment of the sediment removal costs from the reservoirs of the European Union. Journal of Cleaner Production 434, 140183. https://doi.org/10.1016/j.jclepro.2023.140183. https://www.sciencedirect.com/science/article/pii/S095965262304341X

Parmesan, C., Morecroft, M.D., Trisurat, Y., Adrian, R., Anshari, G.Z., Arneth, A. et al. (2022). Terrestrial and freshwater ecosystems and their services. In Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 197–377, https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_Chapter02.pdf

Patzner, M.S., Mueller, C.W., Malusova, M., Baur, M., Nikeleit, V., Scholten, T. et al. (2020). Iron mineral dissolution releases iron and associated organic carbon during permafrost thaw. Nature Communications 11(1), 6329. 10.1038/s41467-020-20102-6. https://doi.org/10.1038/s41467-020-20102-6

Paul, K.L. and Caplins, L.B. (2020). Narratives of Injustice: An Investigation of Toxic Dumping within the Blackfeet Nation. Human Biology 92(1), 27-35. https://muse.jhu.edu/pub/27/article/772230

Pausas, J.G. and Keeley, J.E. (2021). Wildfires and global change. Frontiers in Ecology and the Environment 19(7), 387-395. https://doi.org/10.1002/fee.2359. https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1002/fee.2359

Pavlova, V., Shkolnik, I., Pikaleva, A., Efimov, S., Karachenkova, A. and Kattsov, V. (2019). Future changes in spring wheat yield in the European Russia as inferred from a large ensemble of high-resolution climate projections. Environmental Research Letters 14(3), 034010. 10.1088/1748-9326/aaf8be. https://dx.doi.org/10.1088/1748-9326/aaf8be

Pecl, G.T., Araújo, M.B., Bell, J.D., Blanchard, J., Bonebrake, T.C., Chen, I.-C. et al. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. Science 355(6332), eaai9214. doi:10.1126/science.aai9214. https://www.science.org/doi/abs/10.1126/science.aai9214

Pereira, H.M., Martins, I.S., Rosa, I.M.D., Kim, H., Leadley, P., Popp, A. et al. (2024). Global trends and scenarios for terrestrial biodiversity and ecosystem services from 1900 to 2050. Science 384(6694), 458-465. doi:10.1126/science.adn3441. https://www.science.org/doi/abs/10.1126/science.adn3441

Persson, L., Carney Almroth, B.M., Collins, C.D., Cornell, S., de Wit, C.A., Diamond, M.L. et al. (2022). Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. Environmental Science & Technology 56(3), 1510-1521. 10.1021/acs.est.1c04158. https://doi.org/10.1021/acs.est.1c04158

Petermann, J.S. and Buzhdygan, O.Y. (2021). Grassland biodiversity. Current Biology 31(19), R1195-R1201. https://doi.org/10.1016/j.cub.2021.06.060. https://www.sciencedirect.com/science/article/pii/S0960982221008897

Petrosillo, I., Valente, D., Scavuzzo, C.M. and Selvan, T. (2023). Editorial: Land degradation pattern and ecosystem services. Frontiers in Environmental Science 11. 10.3389/fenvs.2023.1137768. https://www.frontiersin.org/articles/10.3389/fenvs.2023.1137768

Petzold, J., Andrews, N., Ford, J.D., Hedemann, C. and Postigo, J.C. (2020). Indigenous knowledge on climate change adaptation: a global evidence map of academic literature. Environmental Research Letters 15(11), 113007. 10.1088/1748-9326/abb330. https://dx.doi.org/10.1088/1748-9326/abb330

Piao, S., Liu, Q., Chen, A., Janssens, I.A., Fu, Y., Dai, J. et al. (2019). Plant phenology and global climate change: Current progresses and challenges. Global Change Biology 25(6), 1922-1940. https://doi.org/10.1111/gcb.14619. https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.14619

Pillay, R., Venter, M., Aragon-Osejo, J., González-Del-Pliego, P., Hansen, A.J., Watson, J.E. et al. (2022). Tropical forests are home to over half of the world's vertebrate species. Front Ecol Environ 20(1), 10-15. 10.1002/fee.2420. https://pubmed.ncbi.nlm.nih.gov/35873358/.

Pörtner, H.O., Scholes, R.J., Agard, J., Archer, E., Arneth, A., Bai, X. et al. (2021). IPBES-IPCC co-sponsored workshop report on biodiversity and climate change. https://files.ipbes.net/ipbes-web-prod-public-files/2021-06/20210609_workshop_report_embargo_3pm_CEST_10_june_0.pdf

Potapov, P., Turubanova, S., Hansen, M.C., Tyukavina, A., Zalles, V., Khan, A. et al. (2022). Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. Nature Food 3(1), 19-28. 10.1038/s43016-021-00429-z. https://doi.org/10.1038/s43016-021-00429-z

Prăvălie, R. (2016). Drylands extent and environmental issues. A global approach. Earth-Science Reviews 161, 259-278. https://doi.org/10.1016/j.earscirev.2016.08.003. https://www.sciencedirect.com/science/article/pii/S0012825216302239

Prăvălie, R., Patriche, C., Borrelli, P., Panagos, P., Roșca, B., Dumitrașcu, M. et al. (2021). Arable lands under the pressure of multiple land degradation processes. A global perspective. Environmental Research 194, 110697. https://doi.org/10.1016/j.envres.2020.110697. https://www.sciencedirect.com/science/article/pii/S0013935120315966

Ray, L. (2024). Impact of mercury released from permafrost on food safety in Switzerland. Food Risk Assess Europe 2(4), 0045E. https://doi.

org/10.2903/fr.efsa.2024.FR-0045. https://efsa.onlinelibrary.wiley.com/doi/abs/10.2903/fr.efsa.2024.FR-0045

Read, Q.D., Hondula, K.L. and Muth, M.K. (2022). Biodiversity effects of food system sustainability actions from farm to fork. Proceedings of the National Academy of Sciences 119(15), e2113884119. doi:10.1073/pnas.2113884119. https://www.pnas.org/doi/abs/10.1073/pnas.2113884119

Reich, P.B. and Hobbie, S.E. (2013). Decade-long soil nitrogen constraint on the CO2 fertilization of plant biomass. Nature Climate Change 3(3), 278-282. 10.1038/nclimate1694. https://doi.org/10.1038/nclimate1694

Rigolon, A. (2016). A complex landscape of inequity in access to urban parks: A literature review. Landscape and Urban Planning 153, 160-169. https://doi.org/10.1016/j.landurbplan.2016.05.017. https://www.sciencedirect.com/science/article/pii/S0169204616300846

Rigolon, A., Browning, M.H.E.M., Lee, K. and Shin, S. (2018). Access to Urban Green Space in Cities of the Global South: A Systematic Literature Review. Urban Science 2(3), 67. https://www.mdpi.com/2413-8851/2/3/67

Rigolon, A., Browning, M.H.E.M., McAnirlin, O. and Yoon, H. (2021). Green space and health equity: A systematic review on the potential of green space to reduce health disparities. International Journal of Environmental Research and Public Health 18(5), 2563. https://www.mdpi.com/1660-4601/18/5/2563

Rillig, M.C., van der Heijden, M.G.A., Berdugo, M., Liu, Y.-R., Riedo, J., Sanz-Lazaro, C. et al. (2023). Increasing the number of stressors reduces soil ecosystem services worldwide. Nature Climate Change 13(5), 478-483. 10.1038/s41558-023-01627-2. https://doi.org/10.1038/s41558-023-01627-2

Ritchie, H. and Roser, M. (2024). Half of the world's habitable land is used for agriculture. https://ourworldindata.org/global-land-for-agriculture#article-citation

Ritchie, H., Spooner, F. and Roser, M. (2022). Biodiversity. OurWorldInData.org https://ourworldindata.org/biodiversity

Rodríguez-Eugenio, N., McLaughlin, M. and Pennock, D. (2018). Soil Pollution: A hidden reality. Rome, Italy: Food and Agriculture Organization of the United Nations. https://www.fao.org/3/I9183EN/i9183en.pdf

Rojas, O. (2020). Agricultural extreme drought assessment at global level using the FAO-Agricultural Stress Index System (ASIS). Weather and Climate Extremes 27, 100184. https://doi.org/10.1016/j.wace.2018.09.001. https://www.sciencedirect.com/science/article/pii/S2212094718300999

Román-Palacios, C. and Wiens, J.J. (2020). Recent responses to climate change reveal the drivers of species extinction and survival. Proceedings of the National Academy of Sciences 117(8), 4211-4217. doi:10.1073/pnas.1913007117. https://www.pnas.org/doi/abs/10.1073/pnas.1913007117

Rubio-Ríos, J., Pérez, J., Salinas, M.J., Fenoy, E., López-Rojo, N., Boyero, L. et al. (2021). Key plant species and detritivores drive diversity effects on instream leaf litter decomposition more than functional diversity: A microcosm study. Science of The total Environment 798, 149266. https://doi.org/10.1016/j.scitotenv.2021.149266

Ruggeri Laderchi, C., Lotze-Campen, H., DeClerck, F., Bodirsky, B.L., Collignon, Q., Crawford, M.S. et al. (2024). The Economics of the Food System Transformation. Food System Economics Commission (FSEC). https://foodsystemeconomics.org/wp-content/uploads/FSEC-Global_Policy_Report.pdf

Salih, A.A.M., Baraibar, M., Mwangi, K.K. and Artan, G. (2020). Climate change and locust outbreak in East Africa. Nature Climate Change 10(7), 584-585. 10.1038/s41558-020-0835-8. https://doi.org/10.1038/s41558-020-0835-8

Sanderman, J., Hengl, T. and Fiske, G.J. (2017). Soil carbon debt of 12,000 years of human land use. Proceedings of the National Academy of Sciences 114(36), 9575-9580. doi:10.1073/pnas.1706103114. https://www.pnas.org/doi/abs/10.1073/pnas.1706103114

Santini, N.S. and Miquelajauregui, Y. (2022). The Restoration of Degraded Lands by Local Communities and Indigenous Peoples. Frontiers in Conservation Science 3. 10.3389/fcosc.2022.873659. https://www.frontiersin.org/journals/conservation-science/articles/10.3389/fcosc.2022.873659

Santini, N.S., Chamizo, S., Lucas-Borja, M.E. and Muñoz-Rojas, M. (2022). Editorial: Restoration of degraded terrestrial ecosystems. Frontiers in Ecology and Evolution 10. 10.3389/fevo.2022.863845. https://www.frontiersin.org/articles/10.3389/fevo.2022.863845

Save Soil (2024). 95% of the Earth's Soil on Course to Be Degraded by 2050. https://earth.org/95-of-the-earths-soil-on-course-to-be-degraded-by-2050/

Sayedi, S.S., Abbott, B.W., Vannière, B., Leys, B., Colombaroli, D., Romera, G.G. et al. (2024). Assessing changes in global fire regimes. Fire Ecology 20(1), 18. 10.1186/s42408-023-00237-9. https://doi.org/10.1186/s42408-023-00237-9

Schug, F., Bar-Massada, A., Carlson, A.R., Cox, H., Hawbaker, T.J., Helmers, D. et al. (2023). The global wildland–urban interface. Nature. 10.1038/s41586-023-06320-0. https://doi.org/10.1038/s41586-023-06320-0

Schuster, R., Germain, R.R., Bennett, J.R., Reo, N.J. and Arcese, P. (2019). Vertebrate biodiversity on indigenous-managed lands in Australia, Brazil, and Canada equals that in protected areas. Environmental Science & Policy 101, 1-6. https://doi.org/10.1016/j.envsci.2019.07.002

Schuur, E.A., McGuire, A.D., Schädel, C., Grosse, G., Harden, J.W., Hayes, D.J. et al. (2015). Climate change and the permafrost carbon feedback. Nature 520(7546), 171-179. https://doi.org/10.1038/nature14338

Schweitzer, M.D., Calzadilla, A.S., Salamo, O., Sharifi, A., Kumar, N., Holt, G. et al. (2018). Lung health in era of climate change and dust storms. Environmental Research 163, 36-42. https://doi.org/10.1016/j.envres.2018.02.001

Secretariat of the Basel Convention (2023). Actions for addressing plastic waste under the Basel Convention. https://www.basel.int/Implementation/Plasticwaste/Overview/tabid/8347/Default.aspx (Accessed: Aug 21 2023).

Secretariat of the Convention on Biological Diversity (2020). Global Biodiversity Outlook 5. Montreal, Quebec, Canada. https://www.cbd.int/gbo/gbo5/publication/gbo-5-en.pdf

Secretariat of the Convention on Biological Diversity (2022). Decision adopted by the Conference of the Parties to the Convention on Biological Diversity 15/4. Kunming-Montreal Global Biodiversity Framework. United Nations Environment Programme, Montreal, Canada https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf

Sedlmeier, K., Feldmann, H. and Schädler, G. (2018). Compound summer temperature and precipitation extremes over central Europe. Theoretical and Applied Climatology 131(3), 1493-1501. 10.1007/s00704-017-2061-5. https://doi.org/10.1007/s00704-017-2061-5

Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Luca, A.D. et al. (2021). Weather and Climate Extreme Events in a Changing Climate. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, USA. pp 1513-1766 https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter11.pdf

Shi, H., Tian, H., Pan, N., Reyer, C.P.O., Ciais, P., Chang, J. et al. (2021). Saturation of global terrestrial carbon sink under a high warming scenario. Global Biogeochemical Cycles 35(10), e2020GB006800. https://doi.org/10.1029/2020GB006800. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020GB006800

Shittu, O.S., Williams, I.D. and Shaw, P.J. (2021). Global E-waste management: Can WEEE make a difference? A review of e-waste trends, legislation, contemporary issues and future challenges. Waste Management 120, 549-563. https://doi.org/10.1016/j.wasman.2020.10.016

Shivanna, K.R. (2022). Climate change and its impact on biodiversity and human welfare. Proceedings of the Indian National Science Academy 88(2), 160-171. 10.1007/s43538-022-00073-6. https://doi.org/10.1007/s43538-022-00073-6

Shukla, N. (2020). How the Basel Convention has harmed developing countries. [Earth.org https://earth.org/how-the-basel-convention-has-harmed-developing-countries/ (Accessed: 3 August 2023)

Sikorska, D., Łaszkiewicz, E., Krauze, K. and Sikorski, P. (2020). The role of informal green spaces in reducing inequalities in urban green space

availability to children and seniors. Environmental Science & Policy 108, 144-154. https://doi.org/10.1016/j.envsci.2020.03.007

Simmonds, J.S., Suarez-Castro, A.F., Reside, A.E., Watson, J.E.M., Allan, J.R., Atkinson, S.C. et al. (2023). Retaining natural vegetation to safeguard biodiversity and humanity. Conservation Biology 37(3), e14040. https://doi.org/10.1111/cobi.14040

Sims, N.C., Newnham, G.J., England, J.R., Guerschman, J., Cox, S.J.D., Roxburgh, S.H. et al. (2021). Good Practice Guidance. SDG Indicator 15.3.1. Proportion of land that Is degraded over total land area. Version 2.0 edn. Bonn, Germany: United Nations Convention to Combat Desertification (UNCCD). https://www.unccd.int/sites/default/files/relevant-links/2021-03/Indicator_15.3.1_GPG_v2_29Mar_Advanced-version.pdf

Singh, S. (2020). Farmers' perception of climate change and adaptation decisions: A micro-level evidence from Bundelkhand Region, India. Ecological Indicators 116, 106475. https://doi.org/10.1016/j.ecolind.2020.106475

Siragusa, L. and Arzyutov, D. (2020). Nothing goes to waste: sustainable practices of re-use among Indigenous groups in the Russian North. Current Opinion in Environmental Sustainability 43, 41-48. https://doi.org/10.1016/j.cosust.2020.02.001

Smith, S.L., O'Neill, H.B., Isaksen, K., Noetzli, J. and Romanovsky, V.E. (2022). The changing thermal state of permafrost. Nature Reviews Earth & Environment 3(1), 10-23. https://doi.org/10.1038/s43017-021-00240-1

Smyth, S.J., Macall, D.M., Phillips, P.W.B. and de Beer, J. (2020). Implications of biological information digitization: Access and benefit sharing of plant genetic resources. The Journal of World Intellectual Property 23(3-4), 267-287. https://doi.org/10.1111/jwip.12151

Snehlata, Rajlaxmi, A. and Kumar, M. (2021). Urban tree carbon density and CO(2) equivalent of National Zoological Park, Delhi. Environ Monit Assess 193(12), 841. https://doi.org/10.1007/s10661-021-09619-5

Soares, J.C., Santos, C.S., Carvalho, S.M.P., Pintado, M.M. and Vasconcelos, M.W. (2019). Preserving the nutritional quality of crop plants under a changing climate: importance and strategies. Plant and Soil 443(1), 1-26.. https://doi.org/10.1007/s11104-019-04229-0

Sobhani, Z., Luo, Y., Gibson, C.T., Tang, Y., Naidu, R. and Fang, C. (2022). Collecting microplastics in gardens: Case study (ii) from ropes. Environmental Technology & Innovation 26, 102322. https://doi.org/10.1016/j.eti.2022.102322

Soubry, B., Sherren, K. and Thornton, T.F. (2020). Are we taking farmers seriously? A review of the literature on farmer perceptions and climate change, 2007–2018. Journal of Rural Studies 74, 210-222. https://doi.org/10.1016/j.jrurstud.2019.09.005

Spinoni, J., Naumann, G., Carrao, H., Barbosa, P. and Vogt, J. (2014). World drought frequency, duration, and severity for 1951–2010. International Journal of Climatology 34(8), 2792-2804. https://doi.org/10.1002/joc.3875 .

Stafford, J. (2024). Land protection initiatives reduced Amazon deforestation by up to 83%, research finds. [The University of Manchester https://www.manchester.ac.uk/about/news/land-protection-initiatives-reduced-amazon-deforestation-by-up-to-83-research-finds/ (Accessed: April 4 2025).

Statista (2023). Distribution of rare earths production worldwide as of 2022, by country. https://www.statista.com/statistics/270277/mining-of-rare-earths-by-country/2023

Sudhakar Reddy, C., Satish, K.V. and Prasada Rao, P.V.V. (2018). Significant decline of forest fires in Nilgiri Biosphere Reserve, India. Remote Sensing Applications: Society and Environment 11, 172-185. https://doi.org/10.1016/j.rsase.2018.07.002

Sun, J., Wang, Y., Lee, T.M., Nie, X., Wang, T., Liang, E. et al. (2024). Nature-based Solutions can help restore degraded grasslands and increase carbon sequestration in the Tibetan Plateau. Communications Earth & Environment 5(1), 154. https://doi.org/10.1038/s43247-024-01330-w

Sun, Y., Saha, S., Tost, H., Kong, X. and Xu, C. (2022). Literature Review Reveals a Global Access Inequity to Urban Green Spaces. Sustainability 14(3), 1062. https://www.mdpi.com/2071-1050/14/3/1062

Sylvester, F., Weichert, F.G., Lozano, V.L., Groh, K.J., Bálint, M., Baumann, L. et al. (2023). Better integration of chemical pollution research will further our understanding of biodiversity loss. Nature Ecology & Evolution 7(10), 1552-1555.. https://doi.org/10.1038/s41559-023-02117-6

Tagesson, T., Schurgers, G., Horion, S., Ciais, P., Tian, F., Brandt, M. et al. (2020). Recent divergence in the contributions of tropical and boreal forests to the terrestrial carbon sink. Nature Ecology & Evolution 4(2), 202-209. https://doi.org/10.1038/s41559-019-1090-0

Tang, Z., Wang, P., Li, Y., Sheng, Y., Wang, B., Popovych, N. et al. (2024). Contributions of climate change and urbanization to urban flood hazard changes in China's 293 major cities since 1980. Journal of Environmental Management 353, 120113. https://doi.org/10.1016/j.jenvman.2024.120113

Taylor, C.A. and Rising, J. (2021). Tipping point dynamics in global land use. Environmental Research Letters 16(12), 125012. https://dx.doi.org/10.1088/1748-9326/ac3c6d

Teich, I., Gonzalez Roglich, M., Corso, M.L. and García, C.L. (2019). Combining Earth Observations, Cloud Computing, and Expert Knowledge to Inform National Level Degradation Assessments in Support of the 2030 Development Agenda. Remote Sensing 11(24), 2918. https://doi.org/10.3390/rs11242918

Teich, I., Harari, N., Caza, P., Henao-Henao, J.P., Lopez, J.C., Raviolo, E. et al. (2023). An interactive system to map land degradation and inform decision-making to achieve land degradation neutrality via convergence of evidence across scales: A case-study in Ecuador. Land Degradation & Development 34(15), 4475-4487. https://doi.org/10.1002/ldr.4645

Teixido, A.L., Fuzessy, L.F., Souza, C.S., Gomes, I.N., Kaminski, L.A., Oliveira, P.C. et al. (2022). Anthropogenic impacts on plant-animal mutualisms: A global synthesis for pollination and seed dispersal. Biological Conservation 266, 109461. https://doi.org/10.1016/j.biocon.2022.109461

Teng, W., Yu, Q., Yellen, B., Turek, B. and Woodruff, J.D. (2025). Blue Carbon Mapping Using Temporally Optimized Satellite Remote Sensing Imagery: A Regional Study of Northeast US Salt Marshes. Journal of Geophysical Research: Biogeosciences 130(2), e2024JG008254. https://doi.org/10.1029/2024JG008254

TheWorldCounts (2023). The State of the Planet. https://www.theworldcounts.com/challenges/planet-earth/state-of-the-planet (Accessed: February 6 2024)

TheWorldCounts (2024). Tons of waste dumped globally this year. https://www.theworldcounts.com/challenges/planet-earth/waste/global-waste-problem

Tian, H., Xu, R., Canadell, J.G., Thompson, R.L., Winiwarter, W., Suntharalingam, P. et al. (2020). A comprehensive quantification of global nitrous oxide sources and sinks. Nature 586(7828), 248-256. https://doi.org/10.1038/s41586-020-2780-0

Tibbett, M., Fraser, T.D. and Duddigan, S. (2020). Identifying potential threats to soil biodiversity. PeerJ 8, e9271. 10.7717/peerj.9271. https://pubmed.ncbi.nlm.nih.gov/32566399/

Tong, D.Q., Gill, T.E., Sprigg, W.A., Van Pelt, R.S., Baklanov, A.A., Barker, B.M. et al. (2023). Health and Safety Effects of Airborne Soil Dust in the Americas and Beyond. Reviews of Geophysics 61(2), e2021RG000763. https://doi.org/10.1029/2021RG000763

Toreti, A., Deryng, D., Tubiello, F.N., Müller, C., Kimball, B.A., Moser, G. et al. (2020). Narrowing uncertainties in the effects of elevated CO_2 on crops. Nature Food 1(12), 775-782.. https://doi.org/10.1038/s43016-020-00195-4.

Trends.Earth (2023). UNCCD Reporting-SDG 15.3.1. [Trends.Earth https://docs.trends.earth/en/latest/for_users/features/unccdreporting.html

Tripathy, K.P., Mukherjee, S., Mishra, A.K., Mann, M.E. and Williams, A.P. (2023). Climate change will accelerate the high-end risk of compound drought and heatwave events. Proceedings of the National Academy of Sciences 120(28),. https://www.pnas.org/doi/abs/10.1073/pn as.2219825120

Tsuji, S.R.J., Zuk, A.M., Solomon, A., Edwards-Wheesk, R., Ahmed, F. and Tsuji, L.J.S. (2023). What Is Wellbeing, and What Is Important for Wellbeing? Indigenous Voices from across Canada. International Journal of Environmental Research and Public Health 20(17), 6656.. https://www.mdpi.com/1660-4601/20/17/6656

Tyukavina, A., Potapov, P., Hansen, M.C., Pickens, A.H., Stehman, S.V., Turubanova, S. et al. (2022). Global Trends of Forest Loss Due to Fire From

2001 to 2019. Frontiers in Remote Sensing 3. https://www.frontiersin.org/journals/remote-sensing/articles/10.3389/frsen.2022.825190

Udovicki, B., Andjelkovic, M., Cirkovic-Velickovic, T. and Rajkovic, A. (2022). Microplastics in food: scoping review on health effects, occurrence, and human exposure. International Journal of Food Contamination 9(1), 7. https://doi.org/10.1186/s40550-022-00093-6

United Nations Convention to Combat Desertification (2016). Report of the Conference of the Parties on its twelfth session, held in Ankara from 12 to 23 October 2015. https://www.unccd.int/sites/default/files/sessions/documents/2017-09/ICCD_COP%2812%29_20-1520824E.pdf

United Nations Convention to Combat Desertification (2018). Gender Action Plan. https://www.unccd.int/resources/publications/gender-action-plan.

United Nations Convention to Combat Desertification (2019). Preliminary analysis – strategic objective 1: To improve the condition of affected ecosystems, combat desertification/land degradation, promote sustainable land management and contribute to land degradation neutrality. Bonn, Germany https://www.unccd.int/sites/default/files/sessions/documents/2019-03/ICCD_CRIC%2817%29_2-1822319E.pdf

United Nations Convention to Combat Desertification (2022). Global Land Outlook. Second edn. Bonn, Germany: UNCCD. https://www.unccd.int/resources/global-land-outlook/global-land-outlook-2nd-edition

United Nations Convention to Combat Desertification (2024a). Sand and dust storms source base-map: Visualization tool. [United Nations Convention to Combat Desertification https://maps.unccd.int/sds/

United Nations Convention to Combat Desertification (2024b). UNCCD 16th session of the Conference of the Parties: Riyadh, Saudi Arabia | 2-13 December 2024. https://www.unccd.int/cop16 Accessed: 20 March 2025.

United Nations Economic and Social Council (2019). Special edition: Progress towards the Sustainable Development Goals. Report of the Secretary-General. New York, NY, USA: United Nations. https://sustainabledevelopment.un.org/content/documents/24978Report_of_the_SG_on_SDG_Progress_2019.pdf

United Nations Environment Programme and United Nations Human Settlements Program (UN-Habitat) (2021). GEO for Cities: Towards green and just cities. Nairobi, Kenya: UNEP. https://wedocs.unep.org/bitstream/handle/20.500.11822/37413/GEOcities.pdf

United Nations Environment Programme (2016). Global Gender and Environment Outlook. Nairobi, Kenya: UN Environment. https://www.unep.org/resources/report/global-gender-and-environment-outlook-ggeo

United Nations Environment Programme (2022). Global Peatlands Assessment – The State of the World's Peatlands: Evidence for action toward the conservation, restoration, and sustainable management of peatlands. Main Report. Nairobi, Kenya: Global Peatlands Initiative. https://www.unep.org/resources/global-peatlands-assessment-2022

United Nations Environment Programme (2023a). Global Partnership on Nutrient Management. https://www.unep.org/explore-topics/oceans-seas/global-partnership-nutrient-management

United Nations Environment Programme (2023b). Human migration and natural resources: Global assessment of an adaptive complex system. Nairobi, Kenya: United Nations Environment Programme and International Resource Panel. https://www.resourcepanel.org/reports/human-migration-and-natural-resources#:~:text=This%20report%20makes%20it%20clear,Nairobi%2C%20Kenya

United Nations Environment Programme (2024). Global Waste Management Outlook 2024: Beyond an age of waste - Turning rubbish into a resource. Nairobi, Kenya: United Nations Environment Programme and International Solid Waste Association. https://wedocs.unep.org/20.500.11822/44939

United Nations Environment Programme (2024c). Food Waste Index Report 2024. Nairobi. https://www.unep.org/resources/publication/food-waste-index-report-2024

United Nations Environment Programme-World Conservation Monitoring Centre and International Union for Conservation of Nature (2024). Protected Planet Report 2024. Cambridge, United Kingdom https://digitalreport.protectedplanet.net

United Nations Framework Convention on Climate Change (2016). The Paris Agreement. United Nations Framework Convention of Climate Change, https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf

United Nations Office of Disaster Risk Reduction (2022). World "at a crossroads" in drought management, up 29% in a generation and worsening, says UN. https://www.preventionweb.net/news/world-crossroads-drought-management-29-generation-and-worsening-says-un

van der Putten, W.H., Bardgett, R.D., Farfan, M., Montanarella, L., Six, J. and Wall, D.H. (2023). Soil biodiversity needs policy without borders. Science 379(6627), 32-34. https://www.science.org/doi/abs/10.1126/science.abn7248

van Dijk, M., Morley, T., Rau, M.L. and Saghai, Y. (2021). A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. Nature Food 2(7), 494-501. https://doi.org/10.1038/s43016-021-00322-9

van Velden, J., Peterson, G., Gordon, I., Cheok, J. and Hill, R. (2025). Indigenous futures thinking: Four approaches to imagining a better world. https://phys.org/news/2025-02-indigenous-futures-approaches-world.html?utm_source=nwletter&utm_medium=email&utm_campaign=daily-nwletter

Vedwan, N. (2006). Culture, climate and the environment: Local knowledge and perception of climate change among apple growers in Northwestern India. Journal of Ecological Anthropology 10(1), 4-18. DOI:10.5038/2162-4593.10.1.1. http://dx.doi.org/10.5038/2162-4593.10.1.1

Vicente-Serrano, S.M., N. G. Pricope, A. Toreti, E. Morán-Tejeda, J. Spinoni, A. Ocampo-Melgar et al. (2024). The global threat of drying lands: Regional and global aridity trends and future projections. A report of the science-policy interface. UNCCD-SPI Technical Series. Bonn, Germany: United Nations Convention to Combat Desertification https://www.unccd.int/sites/default/files/2024-12/aridity_report.pdf

Vitasse, Y., Baumgarten, F., Zohner, C.M., Rutishauser, T., Pietragalla, B., Gehrig, R. et al. (2022). The great acceleration of plant phenological shifts. Nature Climate Change 12(4), 300-302. 10.1038/s41558-022-01283-y. https://doi.org/10.1038/s41558-022-01283-y

Volkova, I.I., Callaghan, T.V., Volkov, I.V., Chernova, N.A. and Volkova, A.I. (2021). South-Siberian mountain mires: Perspectives on a potentially vulnerable remote source of biodiversity. Ambio 50(11), 1975-1990. 10.1007/s13280-021-01596-w. https://doi.org/10.1007/s13280-021-01596-w

Walker, D.W. and Van Loon, A.F. (2023). Droughts are coming on faster. Science 380(6641), 130-132. doi:10.1126/science.adh3097. https://www.science.org/doi/abs/10.1126/science.adh3097

Wambugu, P.W., Nyamongo, D.O. and Kirwa, E.C. (2023). Role of Seed Banks in Supporting Ecosystem and Biodiversity Conservation and Restoration. Diversity 15(8), 896. https://www.mdpi.com/1424-2818/15/8/896

Wang, B., An, S., Liang, C., Liu, Y. and Kuzyakov, Y. (2021). Microbial necromass as the source of soil organic carbon in global ecosystems. Soil Biology and Biochemistry 162, 108422. https://doi.org/10.1016/j.soilbio.2021.108422. https://www.sciencedirect.com/science/article/pii/S0038071721002960

Wang, C., Hu, Y., Wu, H., Wang, Z., Cai, J., Liu, H. et al. (2025). No-tillage practice enhances soil total carbon content in a sandy Cyperus esculentus L. field. Ecological Processes 14(1), 9. 10.1186/s13717-024-00573-x. https://doi.org/10.1186/s13717-024-00573-x

Wang, F., Harindintwali, J.D., Yuan, Z., Wang, M., Wang, F., Li, S. et al. (2021). Technologies and perspectives for achieving carbon neutrality. Innovation (Camb) 2(4), 100180. 10.1016/j.xinn.2021.100180. https://pubmed.ncbi.nlm.nih.gov/34877561/

Wang, F., Xiang, L., Sze-Yin Leung, K., Elsner, M., Zhang, Y., Guo, Y. et al. (2024). Emerging contaminants: A One Health perspective. The Innovation 5(4). 10.1016/j.xinn.2024.100612. https://doi.org/10.1016/j.xinn.2024.100612

Wang, J., Zhen, J., Hu, W., Chen, S., Lizaga, I., Zeraatpisheh, M. et al. (2023). Remote sensing of soil degradation: Progress and perspective. International Soil and Water Conservation Research 11(3), 429-454. https://doi.org/10.1016/j.iswcr.2023.03.002. https://www.sciencedirect.com/science/article/pii/S209563392300014X

Wang, L., Sun, L., Li, W., Chen, X., Li, Y., Zou, X. et al. (2023). State of China's climate in 2022. Atmospheric and Oceanic Science Letters, 100356. https://

doi.org/10.1016/j.aosl.2023.100356. https://www.sciencedirect.com/science/article/pii/S167428342300034X

Wang, S., Zhang, Y., Ju, W., Chen, J.M., Ciais, P., Cescatti, A. et al. (2020). Recent global decline of CO_2 fertilization effects on vegetation photosynthesis. Science 370(6522), 1295-1300. doi:10.1126/science.abb7772. https://www.science.org/doi/abs/10.1126/science.abb7772

Wang, Y., Zhang, Y., Sun, W. and Zhu, L. (2022). The impact of new urbanization and industrial structural changes on regional water stress based on water footprints. Sustainable Cities and Society 79, 103686. https://doi.org/10.1016/j.scs.2022.103686. https://www.sciencedirect.com/science/article/pii/S2210670722000208

Wang, Z., Walker, G.W., Muir, D.C.G. and Nagatani-Yoshida, K. (2020). Toward a Global Understanding of Chemical Pollution: A First Comprehensive Analysis of National and Regional Chemical Inventories. Environmental Science & Technology 54(5), 2575-2584. 10.1021/acs.est.9b06379. https://doi.org/10.1021/acs.est.9b06379

Wenheng, W. and Shuwen, N. (2008). Impact Study on Human Activity to the Resource-environment Based on the Consumption Level Difference of China's Provinces or Autonomous Regions. China Population, Resources and Environment 18(4), 121-127. https://doi.org/10.1016/S1872-583X(09)60015-2. https://www.sciencedirect.com/science/article/pii/S1872583X09600152

Wiedenhofer, D., Fishman, T., Plank, B., Miatto, A., Lauk, C., Haas, W. et al. (2021). Prospects for a saturation of humanity's resource use? An analysis of material stocks and flows in nine world regions from 1900 to 2035. Global Environmental Change 71, 102410. https://doi.org/10.1016/j.gloenvcha.2021.102410. https://www.sciencedirect.com/science/article/pii/S0959378021001898

Wigneron, J.-P., Fan, L., Ciais, P., Bastos, A., Brandt, M., Chave, J. et al. (2020). Tropical forests did not recover from the strong 2015–2016 El Niño event. Science Advances 6(6), eaay4603. doi:10.1126/sciadv.aay4603. https://www.science.org/doi/abs/10.1126/sciadv.aay4603

Wilhite, D.A. and Glantz, M.H. (1985). Understanding the drought phenomenon: The role of definitions. Water International 10(3), 111-120. 10.1080/02508068508686328. https://doi.org/10.1080/02508068508686328

Wilkinson, J. (2017). Land grabbing e estrangeirização de terras no Brasil. In Questões agrárias, agrícolas e rurais: Conjunturas e políticas públicas. Maluf, R.S. and Flexor, G. (eds.). Rio de Janeiro, Brazil: e-papers. https://oppa.net.br/livros/Questoes_agrarias_agricolas_e_rurais-Renato_Maluf-Georges_Flexor.pdf

Williams, A.P. and Abatzoglou, J.T. (2016). Recent Advances and Remaining Uncertainties in Resolving Past and Future Climate Effects on Global Fire Activity. Current Climate Change Reports 2(1), 1-14. 10.1007/s40641-016-0031-0. https://doi.org/10.1007/s40641-016-0031-0

World Health Organization (2016). Preventing disease through healthy environments: a global assessment of the burden of disease from environmental risks. Geneva, Switzerland: WHO. http://apps.who.int/iris/bitstream/handle/10665/204585/9789241565196_eng.pdf;jsessionid=4365EB4CFC7B3FA4E6CCE4167582A7E6?sequence=1

World Health Organization (2022). Dietary and inhalation exposure to nano-and microplastic particles and potential implications for human health. Geneva, Switzerland: World Health Organization. https://www.who.int/publications/i/item/9789240054608

World Health Organization (2023). Food safety. https://www.who.int/news-room/fact-sheets/detail/food-safety (Accessed: 3 August 2023)

World Overview of Conservation Approaches and Technologies (WOCAT) (2023). World Overview of Conservation Approaches and Technologies. https://www.wocat.net/en/2023

World Wildlife Fund (2022). Living Planet Report 2022 – Building a nature positive society. Almond, R.E.A., Grooten, M., Juffe Bignoli, D. and Petersen, T. (eds.). Gland, Switzerland: World Wildlife Fund. https://wwflpr.awsassets.panda.org/downloads/lpr_2022_full_report.pdf

Xie, Y., Hunter, M., Sorensen, A., Nogeire-McRae, T., Murphy, R., Suraci, J.P. et al. (2023). U.S. farmland under threat of urbanization: Future development scenarios to 2040. Land 12(3), 574. https://www.mdpi.com/2073-445X/12/3/574

Xie, Z., Game, E.T., Hobbs, R.J., Pannell, D.J., Phinn, S.R. and McDonald-Madden, E. (2020). Conservation opportunities on uncontested lands. Nature Sustainability 3(1), 9-15. 10.1038/s41893-019-0433-9. https://doi.org/10.1038/s41893-019-0433-9

Xu, X., Huang, A., Belle, E., De Frenne, P. and Jia, G. (2022). Protected areas provide thermal buffer against climate change. Science Advances 8(44), eabo0119. doi:10.1126/sciadv.abo0119. https://www.science.org/doi/abs/10.1126/sciadv.abo0119

Yan, Y., Liu, T., Wang, N. and Yao, S. (2022). Urban sprawl and fiscal stress: Evidence from urbanizing China. Cities 126, 103699. https://doi.org/10.1016/j.cities.2022.103699. https://www.sciencedirect.com/science/article/pii/S026427512200138X

Yang, L., Zhang, Y., Kang, S., Wang, Z. and Wu, C. (2021). Microplastics in soil: A review on methods, occurrence, sources, and potential risk. Science of The total Environment 780, 146546. https://doi.org/10.1016/j.scitotenv.2021.146546. https://www.sciencedirect.com/science/article/pii/S0048969721016144

Yuan, X., Wang, Y., Ji, P., Wu, P., Sheffield, J. and Otkin, J.A. (2023). A global transition to flash droughts under climate change. Science 380(6641), 187-191. doi:10.1126/science.abn6301. https://www.science.org/doi/abs/10.1126/science.abn6301

Zabel, F., Delzeit, R., Schneider, J.M., Seppelt, R., Mauser, W. and Václavík, T. (2019). Global impacts of future cropland expansion and intensification on agricultural markets and biodiversity. Nature Communications 10(1), 2844. 10.1038/s41467-019-10775-z. https://doi.org/10.1038/s41467-019-10775-z

Zandalinas, S.I., Fritschi, F.B. and Mittler, R. (2021). Global Warming, Climate Change, and Environmental Pollution: Recipe for a Multifactorial Stress Combination Disaster. Trends in Plant Science 26(6), 588-599. https://doi.org/10.1016/j.tplants.2021.02.011. https://www.sciencedirect.com/science/article/pii/S1360138521000583

Zhang, Y., Tariq, A., Hughes, A.C., Hong, D., Wei, F., Sun, H. et al. (2023). Challenges and solutions to biodiversity conservation in arid lands. Science of The total Environment 857, 159695. https://doi.org/10.1016/j.scitotenv.2022.159695. https://www.sciencedirect.com/science/article/pii/S004896972206795X

Zhang, Y., Wang, F., Hudson-Edwards, K.A., Blake, R., Zhao, F., Yuan, Z. et al. (2020). Characterization of mining-related aromatic contaminants in active and abandoned metal(loid) tailings ponds. Environmental Science & Technology 54(23), 15097-15107. 10.1021/acs.est.0c03368. https://doi.org/10.1021/acs.est.0c03368

Zhang, Y., Wang, Z., Lu, Y. and Zuo, L. (2022). Editorial: Biodiversity, ecosystem functions and services: Interrelationship with environmental and human health. Frontiers in Ecology and Evolution 10. 10.3389/fevo.2022.1086408. https://www.frontiersin.org/articles/10.3389/fevo.2022.1086408

Zheng, B., Ciais, P., Chevallier, F., Yang, H., Canadell, J.G., Chen, Y. et al. (2023). Record-high CO_2 emissions from boreal fires in 2021. Science 379(6635), 912-917. doi:10.1126/science.ade0805. https://www.science.org/doi/abs/10.1126/science.ade0805

Zhu, Q., Liu, X., Hao, T., Zeng, M., Shen, J., Zhang, F. et al. (2020). Cropland acidification increases risk of yield losses and food insecurity in China. Environmental Pollution 256, 113145. https://doi.org/10.1016/j.envpol.2019.113145. https://www.sciencedirect.com/science/article/pii/S0269749119322560

Zucca, C., Fleiner, R., Bonaiuti, E., Utchang K. 2022. Land degradation drivers of anthropogenic sand and dust storms. CATENA 219, 106575 https://doi.org/10.1016/j.catena.2022.106575

05

Oceans and Coasts

Coordinating Lead Authors: Pedro Fidelman (Centre for Policy Futures, The University of Queensland) and Karen Helen Wiltshire (Alfred Wegener Institute, Centre for Polar and Marine Research and Trinity College Dublin)

Lead Authors: Fagr Abdel-Gawad (National Research Centre), Salud Deudero Company (Instituto Español de Oceanografia), Isa Olalekan Elegbede (Lagos State University)

Contributing Authors: Catia Motta Domingues (National Oceanography Centre), Sandya Gunasekara (Centre for Policy Futures), Britta Denise Hardesty (Commonwealth Scientific and Industrial Research Organisation), Paul Overduin (Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research), -

Contributing Authors/Fellows: Rose Foster (Centre for Policy Futures, The University of Queensland), Helen Spence-Jones (Alfred-Wegener-Institute Centre for Polar and Marine Research

Credit: biletskiy/Envato

Chapter summary

Credit: tan4ikk/Envato

The global oceans and coastal ecosystems are undergoing accelerated degradation *(well established)*. The global ocean, with its coastal seas, covers more than 70 per cent of the Earth's surface. It absorbs around 25 per cent of anthropogenic carbon dioxide emissions, regulating the Earth's climate system and supporting 90 per cent of the planet's biosphere. Temperature increase, pollution, deoxygenation, acidification, over-exploitation and habitat destruction are altering the distribution, abundance and behaviour of marine organisms, often synergistically. Ocean warming – including the effects of marine heatwaves, altered seasonality and increased storm activity – destroys habitats and disrupts the life cycles of many species {5.2.3}.

Notably, polar and tropical species are severely affected. For example, 99 per cent of coral reefs are predicted to be lost if global temperatures rise by 2°C. Species' range shifts from tropical and subtropical to temperate regions are increasingly common and can introduce non-native species and pathogens. These range shifts, combined with human activities via aquaculture and shipping, are changing marine food webs, marine ecosystems, and thus human livelihoods and food sources. Ocean acidification affects the shells and skeletons of marine organisms, leading to a loss of species fitness, and death. Ocean deoxygenation, often from increased wastewater and organic material inputs, can result in hypoxic zones that impede marine life {5.2.2.2; 5.2.3}. Pollution from sewage, agriculture, aquaculture and industry continuously and severely contaminates the marine environment. Sea level rise and associated saltwater intrusions into soil and groundwater are causing coastal habitat and land loss. Coastal ecosystems such as mangrove forests, saltmarshes, macroalgal forests and seagrass meadows are threatened by sea level rise, habitat destruction, land degradation and polluted coastal run-off {5.2.3}.

Climate change, biodiversity loss, land degradation and pollution continue to drive significant physical, chemical and biological changes *(well established)*.

Climate change is causing accelerated ocean warming, acidification and sea level rise {5.2.1}. Marine heatwaves have doubled in frequency and intensity

since 1982, with some areas predicted to experience near-permanent heatwave conditions by the late 21st century, under high-emission scenarios. Marine heatwaves have significant implications for the ocean-weather system {5.2.1.1}. The ocean has become 26 per cent more acidic as the pH has decreased from 8.11 in 1985 to 8.05 in 2021, due to the absorption of atmospheric carbon dioxide. Ocean acidification is projected to increase by 0.3 to 0.4 pH units towards more acidic conditions by 2100 under high emissions scenarios {5.2.1.6}. Global mean sea level increased by an average of 0.20 m over the period 1901 to 2018, with the rate of rise accelerating to an average of 3.7 mm for the period 2006–2018 (high confidence). Low-lying nations, especially Small Island Developing States, are severely affected. Under a high emissions scenario, sea levels are projected to rise by 0.63 to 1.01 metres per year by 2100, with up to 630 million people living below the projected annual flood levels {5.3.1}. These changes are causing significant adverse effects on marine and coastal ecosystems, biodiversity and human coastal infrastructure {5.3}.

Ever-increasing forms of marine pollution are of growing concern *(well established)*. Marine pollution loads, sources and new contaminants are increasing rapidly in the global ocean. Most are from coastal and land-based activities, entering via rivers; direct atmospheric pollution includes soot and aerosols, and is less understood and known. Plastic pollution is a major contributor from extraction to disposal and along its routes into the sea and in the sea; it impacts aquatic wildlife and ecosystems and affects coastal socioeconomic activities {5.2.2.1}. The accumulation of plastic, particularly microplastics, varies across marine environments, and its occurrence is influenced by hydrography such as gyres and currents. Aquaculture pollution including organic matter, nutrients, chemicals and pathogens in coastal and shelf seas is of great concern, especially with the rapid increase in aquaculture operations in recent years. As the demand for seafood increases, pollution from aquaculture is expected to increase, so legislation and efforts to improve farm management practices are needed {5.2.2.3}. Industrial pollution, which includes heavy metals, persistent organic pollutants, per- and polyfluoroalkyl substances, industrial solvents {5.2.2.5}, and oil pollution {5.2.2.4}, both from land sources and point sources at sea, continue to pose significant environmental challenges. Interaction with local stakeholders and local knowledge is imperative in understanding the real effects on human livelihoods. Continued monitoring and assessment are crucial to mitigation strategies and ensuring the health of marine ecosystems.

Increasing coastal use and development significantly contribute to habitat degradation at the land–ocean interface *(well established)*. Coastal and shelf sea development varies in intensity and type across regions and countries. Approximately 40 per cent of the global population resides within 100 km of the coast, an area that houses significant infrastructure supporting various human activities. However, coastal development including coastal activities such as sand extraction, dredging and land reclamation often results in increased habitat degradation and loss, pollution, erosion, sediment deposits and conflicts of use in the coastal zones and shelf seas. The levels of pollutants entering the ocean via riverine and coastal waters are on the increase. Urbanization and industrialization intensify pressures on coastal and shelf seas for offshore energy production. The trend is accelerating and is often damaging due to inadequate environmental and political governance over marine areas. Environmental refuges for marine organisms are declining. This trend is projected to escalate globally but particularly in developing countries and emerging economies, underscoring the need for corrective, adaptive and integrated management strategies. These strategies include Integrated Coastal Management that can better accommodate the diverse demands and interests of various stakeholders. Traditional knowledge and the ecosystem awareness of local communities should be better integrated into holistic management strategies and practices {5.2.4.1; 5.2.4.2}.

Pollution of the ocean with various types of waste of terrestrial and land-use origin enters the sea via run-off and rivers *(well established)*. Compounds of synthetic origin used for domestic, agricultural and industrial purposes mainly enter the sea from land-based sources. These are increasingly a threat to marine life and disrupt food webs. These substances often bio-accumulate in marine organisms and move up the food web {5.2.3.3}. Agricultural and wastewater run-off, rich in nutrients, causes eutrophication and hypoxia in many coastal areas, often disrupting marine species and food security. Since the mid-20th century, oxygen-minimum zones in the ocean have expanded globally by about 4.5 million km². Sea level

rise results in habitat erosion and saltwater intrusion of coastal systems. Soil erosion causes sediment run-off, which can bury coral reefs and seagrass beds, blocking sunlight and hindering photosynthesis. Furthermore, water quality is degraded, posing risks to human health and livelihoods {5.3.3}. Pollution from catchment run-off needs be prevented by reducing the use and disposal of chemicals and nutrients on land and in aquaculture. Mining waste continues to enter rivers and coastal waters. The best possible use management practices, which may be underpinned by regulations and enforcement, and the upgrading of wastewater systems, are urgently needed. Restoration and protection of natural habitats to enhance their capacity to buffer erosion and pollution are crucial. Involving local expertise and long-term knowledge of the affected ecosystems is often key to better coastal habitat management.

Biodiversity change threatens the provision of important ecosystem services *(well established)*. Ocean and coastal ecosystems provide a range of contributions to human well-being, such as food, livelihoods, space to live, recreation, carbon sequestration and coastal protection. However, these services are threatened by the alteration, degradation and loss of invaluable marine ecosystems and their biodiversity. For example, the annual value of global fisheries is estimated to decline by 10–12 per cent by 2050 due to climate change and overfishing. Overfishing has escalated in recent decades, with over 37 per cent of the fish stocks monitored by the Food and Agriculture Organization now overfished. This situation urgently calls for the regulation and enforcement of sustainable fishing management practices, including ecosystem-based fisheries management. The loss of ecosystem services reduces the economic value of marine resources, disrupts the productivity of marine food sources, and disproportionately affects vulnerable human communities. These changes threaten livelihoods, exacerbate inequalities, and increase the costs of climate change adaptation {5.3}. Consideration of local requirements and involving local and long-term knowledge of the affected ecosystems and species is imperative and needs to be implemented as a matter of course.

Progress towards internationally agreed goals is insufficient and uneven *(well established)*. Numerous international and national policies and initiatives are in place to conserve and restore biodiversity in coastal and marine environments. While there have been some successes, the global targets set for oceans and coasts under the Aichi Biodiversity Targets, Kunming-Montreal Global Biodiversity Framework, and Sustainable Development Goal 14 require sustained global action to address the drivers and pressures of biodiversity loss. The urgent need for more ambitious and coordinated action to protect and restore the ocean and its resources has not yet been met. As of March 2025, over 8 per cent of marine areas within national waters were under protection, constituting 16,503 Marine Protected Areas {5.4}. The aim to reduce sound emissions at sea needs to be rapidly furthered internationally. Consultative processes around marine mining, particularly deep-sea mining, and resource use in polar regions must be sped up and processes to resolve conflicts implemented. The recognition of Indigenous Peoples' interests and local co-ownership of coastal resources needs to be established worldwide. Global guidelines based on stakeholder needs and long-term knowledge are urgently required for spatial use management in coastal and shelf seas.

5.1 Introduction

Coasts, shallow seas and oceans play a critical role in securing human survival and promoting well-being and prosperity. These regions host highly productive marine ecosystems and support biodiversity, as well as a wide and growing range of human uses such as tourism, offshore energy production, transport, land reclamation, and resource extraction, including desalination. They also protect socioeconomic activities and infrastructure from storm surge and filter out pollutants from catchment run-off. However, pressures such as climate change, biodiversity loss, land degradation, pollution, and over-exploitation hinder the marine systems' capacity to continue providing benefits (United Nations Environment Programme [UNEP] 2021a; Intergovernmental Panel on Climate Change [IPCC] 2023). Immediate and proactive measures have the potential to safeguard these valuable environments for the well-being of both present and future generations.

Knowledge of the marine system continues to improve (United Nations [UN] 2021a), but at the same time, pressures on the ocean due to human activities increasingly affect ocean health (UNEP 2019), causing severe degradation of critical habitats (UN 2021a), mass mortality events of species from coral to cetaceans (Garrabou et al. 2022; IPCC 2023), and increasingly irreversible losses in coastal and open-ocean ecosystems. Loss of maritime livelihoods is increasing rapidly and climate injustices imposed on poor coastal communities, Small Island Developing States, and Indigenous Peoples' communities is rife. Pollution, unsustainable practices, rapid urbanization and the adverse effects of climate change pose significant threats to the socioeconomic systems of communities sustained by the marine system (Pecl et al. 2022).

The 6th Synthesis Report of the International Panel for Climate Change (IPCC 2023) highlighted several projections related to ocean ecosystems. Climate risks increase with every increment of warming but differ depending on the ocean and coastal socio-ecosystems. Ocean carbon sinks will take up a decreasing proportion of emissions, causing other changes, including increased ocean acidification and deoxygenation. Ocean ecosystems are predicted to suffer biodiversity loss due to climate change alongside other pressures, such as overfishing and maritime use. Some future changes are irreversible and will persist for thousands of years, such as sea level rise due to continued ocean warming and land-ice melt. However, the rate of change can be reduced, allowing for mitigation efforts and more time for ecosystems and communities to adapt.

The sixth Global Environment Outlook (GEO-6) report assessed three major pressures on oceans and coasts: coral reef bleaching, marine litter, and unsustainable fishing practices. Coral bleaching events, driven largely by rising sea surface temperatures, are increasing in frequency, now recurring approximately every six years. These events undermine fisheries, tourism, livelihoods and biodiversity, with recovery for many reefs projected to take centuries (UNEP 2019). Marine litter, primarily from land-based sources, continues to accumulate across marine environments, from coastal zones to deep-sea sediments and polar regions, posing environmental, social, and potential human health risks (UNEP 2019). Unsustainable fishing remains a critical concern, with one-third of global fish stocks overexploited and catch levels declining in many regions. This threatens food security, economic development and the resilience of marine ecosystems, particularly in developing coastal and island nations (UNEP 2019).

In response to these escalating challenges, a variety of international and national initiatives are under way to address these threats to the oceans, including funding for global adaptation strategies (Global Center on Adaptation 2024). These include the expansion of protected areas, strengthened regulation and oversight of fisheries, and waste reduction and recycling programmes. The IPCC stated that conservation of 30–50 per cent of ocean areas is required to maintain resilience and ecosystem services (IPCC 2023). Management approaches such as Marine Protected Areas (MPAs) have improved, with coverage increasing from the 7.3 per cent of the world's oceans protected in 2019 (UNEP 2019; UN 2021a). However, additional efforts are required to meet targets, and further work is needed to assess and ensure MPA management is effective and equitable (UNEP 2019).

International cooperation, including active participation in global treaties and agreements, plays a crucial role in coordinating efforts aimed at restoring and protecting vital marine ecosystems and ensuring the economic and social sustainability of communities

dependent on the sea (UN 2021a). Equally important is the adoption and enforcement of national legislation that implements international obligations. Local community efforts, such as those by Indigenous Peoples, also play a vital part in gathering, preserving and applying knowledge of the marine environment. Indigenous Peoples and local communities often have sophisticated governance structures for managing aquatic resources, such as the establishment of locally managed marine areas according to the Fa'a Samoa, traditional marine management practices, of Samoa (Food and Agriculture Organization [FAO] 2023b). These structures are typically based on principles of sustainability, community stewardship and equitable resource distribution. Diverse types of policy instruments and governance approaches are needed to respond to the key drivers and pressures facing the oceans (UNEP 2019). By integrating these governance models with modern management practices, the effectiveness of marine conservation efforts can be enhanced.

The following sections will expand on these topics. Section 5.2 primarily covers the state and trends of marine and coastal environments in terms of climate change, pollution, biodiversity loss and habitat degradation. Section 5.3 then briefly addresses the impact of environmental changes on human systems. Lastly, Section 5.4 assesses the progress towards selected internationally agreed goals.

5.2 State and trends

5.2.1 Climate change

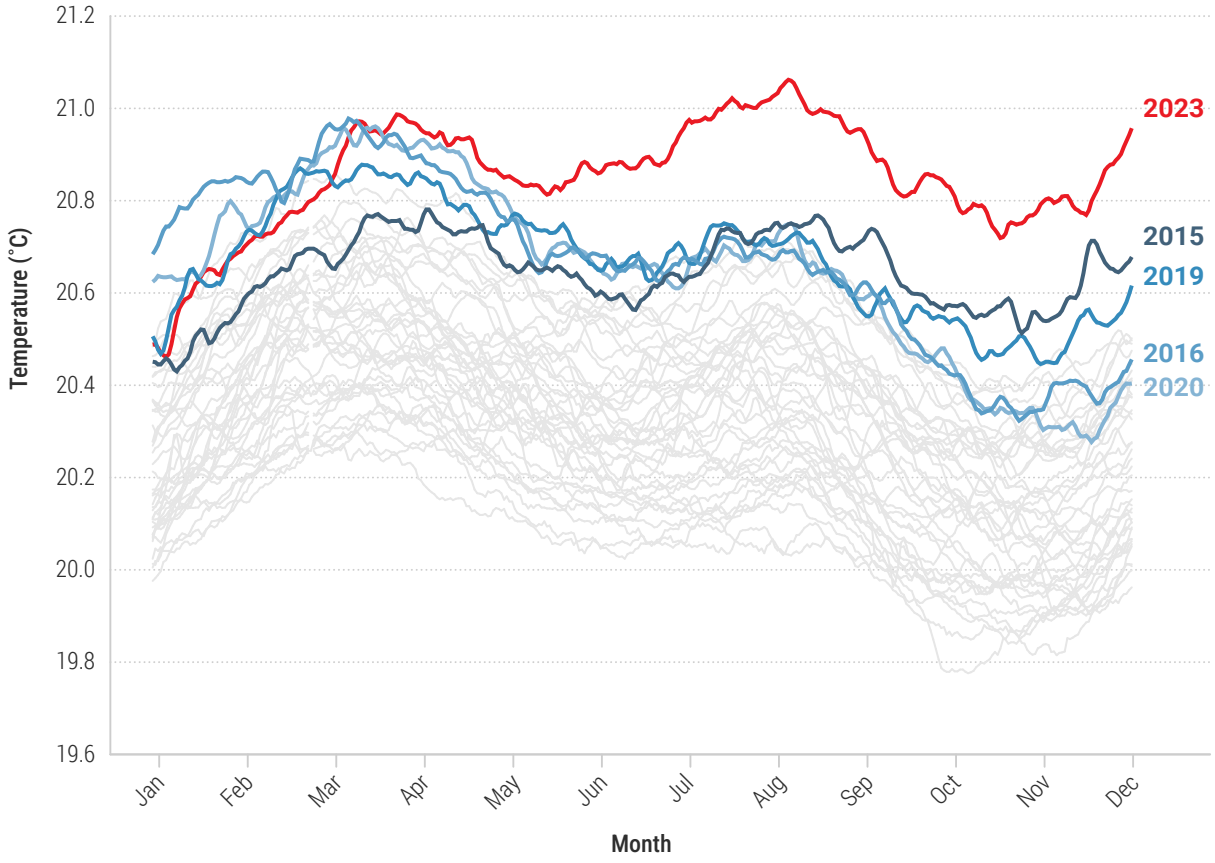
5.2.1.1 Ocean warming

Ocean warming is one of the key indicators of human-induced climate change, with the ocean having absorbed approximately 90 per cent of the Earth's excess heat since the 1970s (IPCC 2021; von Schuckmann et al. 2023), when widespread subsurface ocean observations began. This trend has been traced back to at least the 1900s, consistent with long-term increases in sea surface temperature (Zanna et al. 2019). The rate of increase in sea surface temperature has accelerated from 0.06°C per decade during 1985–89 to 0.27°C per decade during 2019–23 (Merchant, Allan and Embury 2025), a more than fourfold increase in rate over less than 40 years. This acceleration culminated in 2023, when sea surface temperatures reached record-breaking levels, with daily averages remaining at record highs from April onward and achieving an all-time high in August (**Figure 5.1**, next page).

Since the 1990s, ocean warming has intensified (Gulev et al. 2021; Storto and Yang 2024), with unprecedented global ocean temperatures recorded in 2023 and 2024 (National Oceanic and Atmospheric

Credit: PedaltotheStock/Envato

Figure 5.1 (top panel): Daily sea surface temperatures averaged over 60˚N to 60˚S from 1980 to 2023



Source: European Space Agency SST CCI Analysis v3.0 Credit: ESACCI/EOCIS/UKMCAS and C3S/ECMWF

Agency 2025). Some regions have experienced anomalies of 4–5°C above average, with extreme cases such as waters near Florida exceeding 38°C in July of 2023 (Hobday et al. 2023).

This rapid warming is evident in rising sea surface temperatures and heat penetration to deeper layers in the ocean, driving more frequent, intense and prolonged marine heatwaves (Giménez, Boersma and Wiltshire 2024). The upper ocean (0–700 m) accounts for 62 per cent of the total ocean heat content increase, while intermediate layers of 700–2,000 m and depths below 2,000 m contribute 28 per cent and 10 per cent, respectively (Gulev et al. 2021).

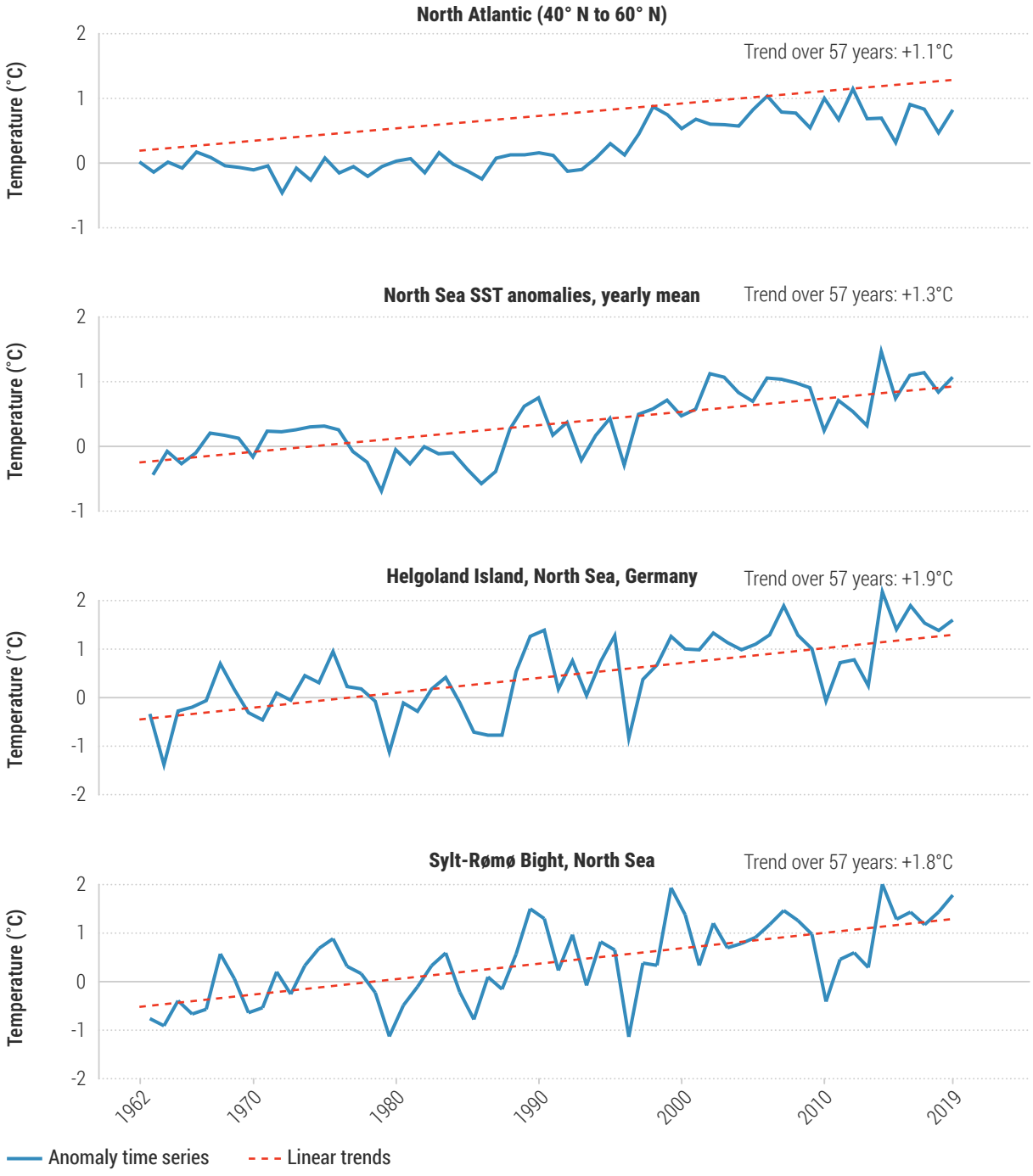
Warming trends are observed across all major ocean basins, with spatial variations influenced by ocean circulation patterns and climate variability (Fox-Kemper et al. 2021). Enhanced heat uptake occurs along major water-mass pathways; localized cooling is observed in some regions due to heat redistribution by currents. The Arctic Ocean is warming rapidly due to polar amplification (Zhou, Leung and Lu 2024). Semi-enclosed, coastal and shelf seas, such as the North Sea, South China Sea, and Mediterranean Sea, are warming nearly twice as fast as the open ocean and with distinctly higher rates in shallow coastal seas. (**Figure 5.1**, bottom panel) (de Amorim et al. 2023).

Ocean warming is projected to continue throughout the 21st century under all emissions scenarios (Fox-Kemper et al. 2021; Varela et al. 2023). High emissions scenarios could result in permanent marine heatwaves in parts of the tropical and Arctic Oceans, while low emissions scenarios could significantly mitigate this risk. However, even with ambitious mitigation, warming from past and ongoing emissions will persist for centuries due to the ocean's thermal inertia and long-term heat storage (IPCC 2023).

5.2.1.2 Ocean circulation

Proxy records suggest the Atlantic Meridional Overturning Circulation (AMOC), the conveyor-

Figure 5.1 (bottom panel): Daily sea surface temperatures averaged over 60˚N to 60˚S from 1980 to 2023 (continue)



Source: de Amorim et al. 2023

belt-like system of currents moving horizontally and vertically in the Atlantic, remained stable for 8,000 years before weakening since the late 19th century (Caesar et al. 2021; Gulev et al. 2021). Observations since 2004 remain too short to confirm anthropogenic weakening and show higher variability than climate-model simulations (Frajka-Williams et al. 2023). Models consistently project 21st century weakening of the Atlantic's overturning circulation but there are significant uncertainties about the size, timing, and potential abruptness of changes (Fox-Kemper et al. 2021; IPCC 2023). Given the potential for severe consequences (van Westen, Kliphuis and Dijkstra 2024), risk mitigation strategies are crucial (Rahmstorf 2024) and sustained monitoring is essential for improving trend detection and projections (Srokosz, Holliday and Bryden 2023). However, efforts are hampered by the complexity of

model biases, system interactions, methodological differences, and observational limitations contributing to ongoing uncertainties (Menary et al. 2020; Jackson et al. 2023; Romanou et al. 2023; Ben-Yami et al. 2024; Lee et al. 2024; Baker et al. 2025).

5.2.1.3 Polar ice melt

Sea ice is melting at both poles. Arctic sea ice has been diminishing under heightened warming four times more rapidly than the global average (Rantanen et al. 2022). Over the 46-year satellite record, the last 18 years were the lowest 18 Arctic sea-ice extent ever recorded, with the largest departure from average conditions occurring in October 2020 (National Snow and Ice Data Centre 2024). Antarctica is also facing rapid warming, resulting in substantial loss of floating sea ice, from the ice shelves around the coastline and from the continental ice sheet. In 2023, Antarctic sea-ice extent reached a record low in the observational record (Fetterer et al. 2017; Purich and Doddridge 2023), with 2024 being the second-lowest year on record. Globally, sea-ice extent reached an all-time low on 5 February 2025 with an extent of 16.20 million km2, more than 12 per cent below the median minimum (1979–2020) (Copernicus 2025a).

Numerous studies using observations or satellite images show shortening ice-covered seasons on lakes and rivers across the northern hemisphere (Newton and Mullan 2021; Wang et al. 2024). Seasonal ice cover is decreasing both in duration and extent (Sharma et al. 2021; Wang et al. 2021a), with many implications for ecosystems and human activity (Hampton et al. 2024).

Glaciers are retreating at an accelerating pace worldwide (Hugonnet et al. 2021), driven mostly by human activity (Marzeion et al. 2014). Melting mountain glaciers threaten annual cycles of water supply and food security throughout their drainage basins and all the way to the coasts. Eventually new cycles will result in altered terrestrial, freshwater and marine ecosystems (Bosson et al. 2023).

The world's largest ice sheets, on Antarctica and Greenland, are losing ice mass at alarming rates, mainly through thawing and calving from marine-terminating glaciers (Hanna et al. 2024). Combined, these two ice sheets contribute 1.1 mm per year of sea level rise, outstripping losses from all the world's mountain glaciers (Otosaka et al. 2023; Dussaillant et al. 2024). The Antarctic Ice Sheet is surrounded by floating ice shelves that buttress the continental ice mass – these are disintegrating at an accelerating rate, potentially further destabilizing the ice sheets (Fürst et al. 2016). The most rapid Antarctic changes are occurring in the Antarctic Peninsula and West Antarctica (The IMBIE Team 2018). This ice loss is altering the biogeochemical cycles and physical processes of the Southern Ocean and may be pushing Antarctic sea-ice levels into a new state of diminished ocean coverage (DeConto et al. 2021; Alley, Scambos and Alley 2023).

Globally, snow conditions are also changing. In some regions, such as the Alps, the length of snow cover has decreased by 36 days, mostly over the past century (Carrer et al. 2023). Every degree of warming lowers the proportion of precipitation falling as snow worldwide. Since snow is a critical source of water for agriculture worldwide, changes to snow cover are changing our global food security and economy.

5.2.1.4 Permafrost thawing

Polar ice includes sea ice floating on the ocean, lakes and rivers, continental ice sheets, high latitude glaciers and snow. All these components of the frozen Earth are changing (Druckenmiller et al. 2024, World Meteorological Organization, 2024, 2025).

Permafrost, the frozen ground that contains organic matter and stores large amounts of carbon, is warming at a global scale, both on land (Biskaborn et al. 2019) (4.3.3.3) and beneath the Arctic shelf seas. In the northern hemisphere, permafrost underlies almost 15 million km^2 of land, and thaw is driven by rapidly rising air temperatures and changes in snow cover, vegetation and hydrology (Ran et al. 2022). An additional estimated 2.5 million km^2 of permafrost lies beneath the Arctic Ocean (Sabino et al. 2024). This permafrost originated on land but was submerged following the last ice age and has been warming ever since (Overduin et al. 2019). As sea ice continues to disappear, the ocean water will warm, and this permafrost is expected to thaw more rapidly (Wilkenskjeld et al. 2022).

Permafrost thawing contributes to global warming in a positive feedback loop through the release of greenhouse gases. Land permafrost contains about

Credit: AlbertoCarrera/Envato

twice as much carbon as the atmosphere; even more is contained in submarine permafrost (Miesner et al. 2023). When this thaws, the organic matter trapped within it decomposes and releases carbon dioxide (CO_2) and methane into the atmosphere (Ramage et al. 2024; Wild et al. 2022). The permafrost region has already become a net greenhouse gas source (Hugelius et al. 2023), contributing further to global warming (Schuur and Mack 2018; Turetsky et al. 2019).

Permafrost thaw leads to coastal land loss, subsidence and flooding, creating risk for communities and infrastructure (Wang et al. 2023). Around coastal regions, permafrost thaw affects sea cliffs and beaches and, in combination with sea-ice push processes and wave action, increases coastal erosion (Lim et al. 2020). Permafrost compounds erosion and sea level rise with ground subsidence driven by ground-ice melt: by mid-century, more land will be submerged by seawater than will be eroded along the coast of the Alaska coastal plain (Creel et al. 2024). Ice melting in permafrost almost equals losses from the Antarctic Ice Sheet (Nitzbon et al. 2023) and may be contributing to sea level rise.

Permafrost thaw beneath the Arctic margins is associated with the release of CO_2 and methane into the water column (Wild et al. 2022). Subsea and coastal permafrost thaw may affect sediment and water-column ecosystems through gas release and altered biogeochemistry of the Arctic shelf seawater (Nielsen et al. 2024).

5.2.1.5 Ocean deoxygenation

Oxygen is essential for marine life and for many chemical processes in the ocean. Since 1970, the open ocean has lost 0.5–3.3 per cent of dissolved oxygen in the upper 1,000 metres, with the largest declines in the equatorial and North Pacific, Southern Ocean, and South Atlantic (Schmidtko, Stramma and Visbeck 2017; Canadell et al. 2021). More than 700 coastal areas have reported new or worsening low-oxygen conditions (Limburg et al. 2020). This process, known as ocean deoxygenation, is becoming more severe and is a serious concern due to its potentially large impacts on marine ecosystems at both global and local scales. This decline is mainly driven by ocean warming, which increases stratification, reduces ventilation, and lowers oxygen solubility (Schmidtko, Stramma and Visbeck 2017; Roach and Bindoff 2023; Portela et al. 2024).

Tropical oxygen-minimum areas, or hypoxia zones, are expanding (Stramma et al. 2008; Limburg et al. 2020). Over 700 coastal sites are now classified hypoxic due to eutrophication, warming, and circulation changes (Limburg et al. 2020). Models project subsurface oxygen losses of 32–71 per cent greater than previous estimates, with a total decline of 1–7 per cent by 2100, depending on emissions scenarios and relative to 1870–1899 (Kwiatkowski et al. 2020). Even if emissions cease today, deep ocean oxygen loss could exceed 10 per cent of pre-industrial levels (Oschlies 2021), highlighting the

Credit: wirestock/Envato

urgent need to reduce human-driven emissions to slow the process. Ocean deoxygenation, especially when combined with other environmental stressors, poses a major threat to organisms and is potentially related to strandings of sealife and thus affects the sustainable use of marine resources (Waller et al., 2024). These changes often occur in conjunction with ocean acidification (Section 5.2.1.6), and along with their extreme events, create compounding stresses on marine ecosystems (Ross et al. 2020; Wong et al. 2024).

5.2.1.6 Ocean acidification

Oceans absorb about 25 per cent of human CO_2 emissions, accelerating acidification (Canadell et al. 2021; Friedlingstein et al. 2022; Gruber et al. 2023). Since the 1750s, ocean acidity has increased 30 per cent, a rate unprecedented in at least 26,000 years (Gulev et al. 2021). Acidification affects all ocean basins, including subsurface waters (Fassbender et al. 2023), with vertical penetration occurring through ventilation processes (Iudicone et al. 2016).

The rate of acidification is slowest in the tropics and subtropics and fastest in the Arctic Ocean (Jiang et al. 2023). Tropical Pacific upwelling zones show acidity increases from both anthropogenic CO_2 and natural deep-water upwelling. Coastal waters are made more acidic through terrestrial inputs, eutrophication, and other human contributions (Canadell et al. 2021).

High emissions scenarios project global ocean absorption of CO_2 to increase by 2100, potentially increasing acidity by 150 per cent compared to pre-industrial levels (IPCC 2023), with the Arctic facing the most dramatic changes. However, even with aggressive atmospheric CO_2 removal, ocean acidification will persist for generations due to slow deep-ocean turnover (IPCC 2021; Jiang et al. 2023). The combined and interactive effects of acidification and deoxygenation (Section 5.2.1.5), along with their extreme events, present significant challenges for marine ecosystems and the communities that depend on them (Grix et al. 2025; Tai et al. 2021).

5.2.1.7 Sea level rise

Global mean sea level is rising at accelerating rates, increasing the frequency and severity of both minor and extreme coastal flooding events (IPCC 2021; IPCC 2023). The 20th-century rate of sea level rise is unprecedented in the past 3,000 years, with rapid acceleration since the 1960s–1970s (Gulev et al. 2021; Dangendorf et al. 2024; Wang et al. 2024). Satellite observations since 1993 reveal a 103 mm rise, at an average rate of 3.4 mm per year (Gulev et al; Guérou et al. 2023; National Aeronautics and Space Administration 2024).

Major drivers include the thermal expansion of warming oceans and land-based ice loss (Fox-Kemper et al. 2021). Ice-sheet meltwater contribution quadrupled from 1992–1999 to 2010–2019. Terrestrial

water storage plays a minor role globally but can have a significant impact regionally.

Regional and local sea levels often deviate from global averages (Hamlington et al. 2020; Cazenave and Moreira 2022; Woodworth 2022). Since the 1960s, ocean circulation and density changes in response to atmospheric forcing – including changes in radiation, temperature and precipitation – have dominated climate-driven coastal sea level rise, except where geological features near former ice sheets counteract this (Dangendorf et al. 2021; Wang et al. 2021a).

IPCC projections indicate continued acceleration throughout the 21st century under all emissions scenarios (**Figure 5.2**), with near-term mitigation resulting in smaller rises by 2100 (Fox-Kemper et al. 2021; IPCC 2023). Relative to 1995–2014, projections by 2100 range from 0.28–0.55 m at 1.5°C warming to 0.63–1.60 m with high emissions, and potentially higher considering ice sheet uncertainties (IPCC 2023).

Most non-polar coastlines will experience sea level rise within 20 per cent of the projected global mean by 2100, intensifying extreme events (Church et al. 2013; Fox-Kemper et al. 2021). Even with 1.5°C warming, by 2100, extreme events that used to occur once per century are projected to occur annually at over 50 per cent of tide-gauge locations, especially in the tropics (Tebaldi et al. 2021). Global models may underestimate these projections due to challenges in resolving fine-scale processes that they cannot capture directly (Hewitt et al. 2022; Slangen, Haasnoot and Winter 2022; Jevrejeva et al. 2023; Wickramage et al. 2023).

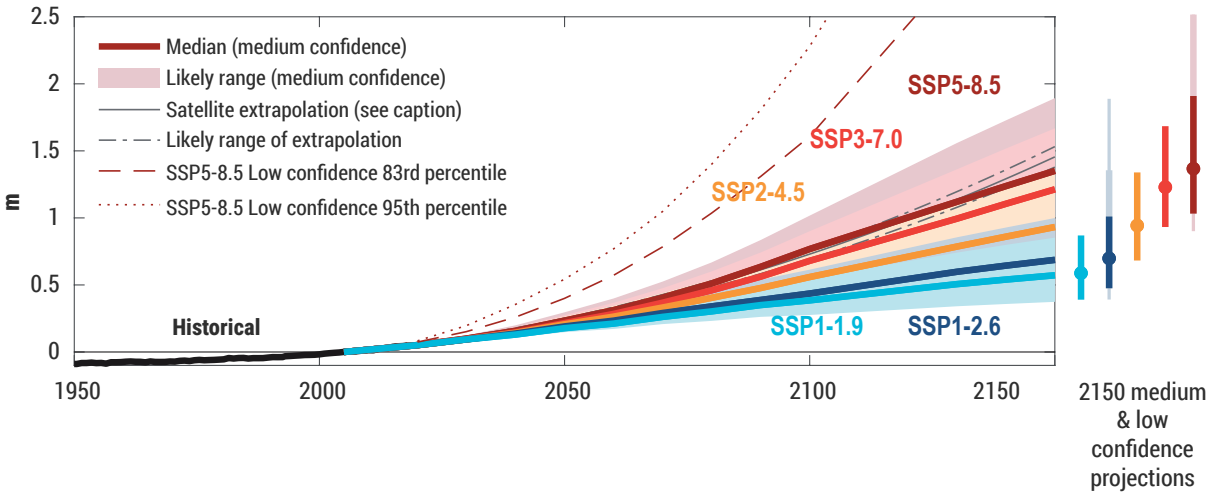
Sea level rise will continue for millenniums due to slow ocean warming and ice-sheet responses (Church et al. 2013; Fox-Kemper et al. 2021), which are effectively irreversible under high-emissions scenarios. Current emissions could trigger critical thresholds this century, resulting in metres of rise over coming centuries (IPCC 2023). While stopping emissions immediately would not halt sea level rise, it would dampen its acceleration and continuation over the long term (Church et al. 2013; Oppenheimer et al. 2019; Fox-Kemper et al. 2021; Turner et al. 2023; Palmer and Weeks 2024).

Climate change adaptation measures, such as the development of resilient coastal infrastructure, managed retreat, and ecosystem-based solutions like wetland restoration, are essential to mitigate the adverse effects of rising sea levels on vulnerable communities and ecosystems (IPCC 2023).

5.2.2 Pollution

Pollution from human sources is increasing in the global ocean, including from land-based industrial, agricultural and urban waste, as well as light and sound. Maritime activities – particularly from marine traffic, fisheries and aquaculture – also contribute to pollution in the global ocean (Joint

Figure 5.2: Projected global mean sea level rise under different warming scenarios



Source: IPCC (2021)

Credit: GreensandBlues/Envato

Group of Experts on the Scientific Aspects of Marine Environmental Protection 2015; Sheppard 2019; Micella et al. 2024). Pollution in coastal and marine environments harms marine ecosystem function and integrity, the health of organisms, and human livelihoods (Sheppard 2019).

Prominent pollutants include:

- **Plastics** – such as litter, breakdown particles and plasticizers
- **Nutrients** – such as nitrogen, phosphorus, and organic matter that cause eutrophication and deoxygenated areas (O'Boyle 2020; Devlin and Brodie 2023; Bhuiyan et al. 2024)
- **Noise pollution** – from point sources such as shipping, energy rigs, offshore prospecting including seismic surveys, and construction
- **Industrial pollutants** – such as persistent organic pollutants, oils, heavy metals, xenobiotics, mining waste, per- and polyfluoroalkyl substances, and thermal pollution from cooling waters

The increasing diversity of land- and sea-based industries and the corresponding introduction of new products and processes is increasing pollutant release to the oceans. Most of these emerging pollutants are unmonitored and unmanaged, and their consequences are poorly understood.

5.2.2.1 Plastic pollution

Plastic pollution is found in all areas of the ocean, from the depths of the Mariana Trench to the ocean's surface (Peng et al. 2020; Agnelli and Tortora 2022) and has been shown to interact with around 700 species and counting (Gall and Thompson 2015; International Union for the Conservation of Nature [IUCN] 2022; Section 5.2.3). As of 2010, an estimated 14 million metric tons of plastic enter the global ocean each year (Jambeck et al. 2015; IUCN 2022). The global abundance of floating plastic particles is estimated to weigh between 1.1 million and 4.9 million tons (Eriksen et al. 2023). Long-term data from multiple ocean basins have demonstrated an increasing trend of floating plastic debris (Wilcox, Hardesty and Law 2020; Isobe and Iwasaki 2022).

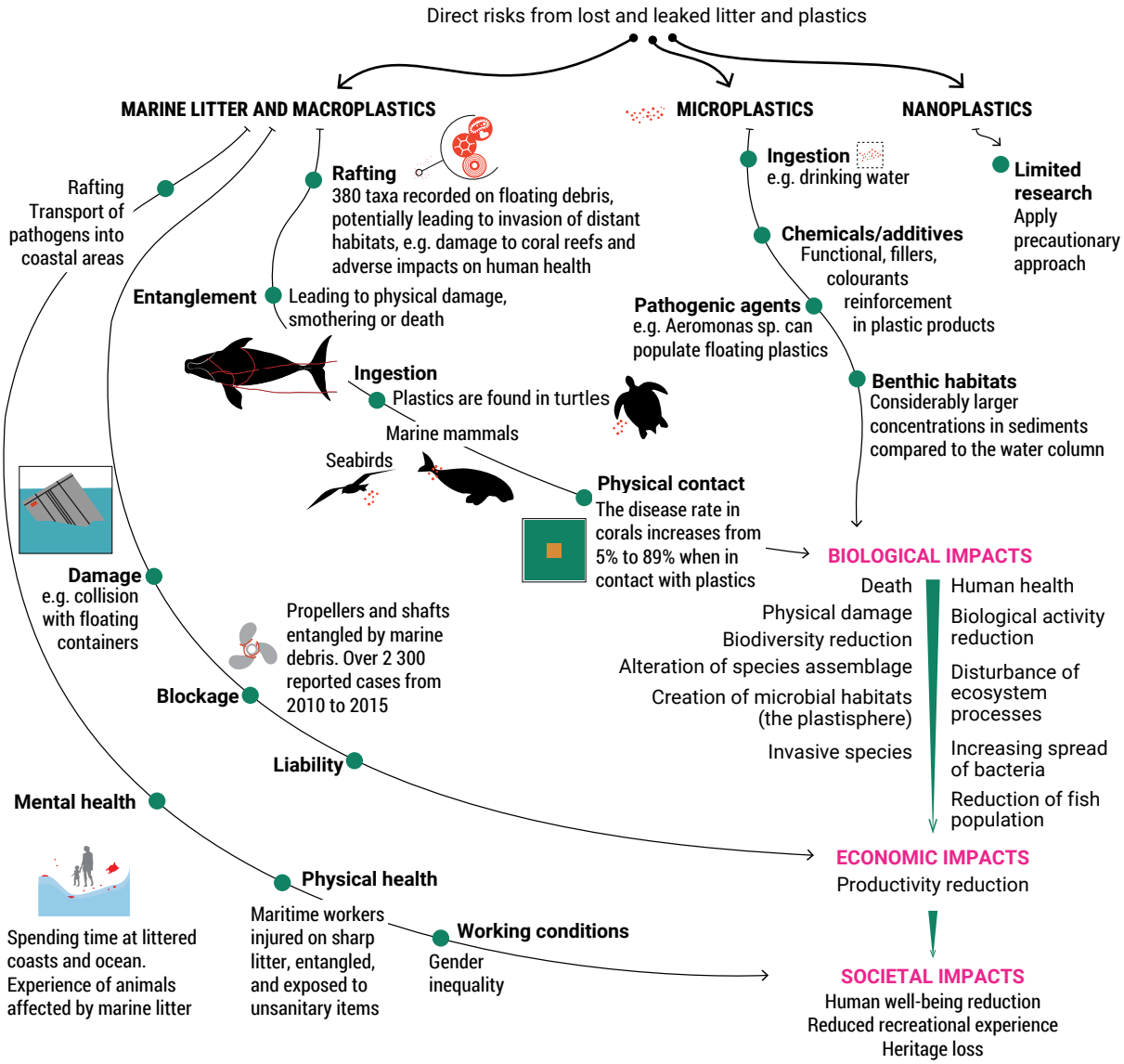
While approximately 80 per cent of marine litter comes from land-based sources, contributors

include wastewater treatment plants, fisheries estimated to lose 6 per cent of all nets and 29 per cent of all lines per year, maritime traffic, and rivers (UNEP 2021a; González-Fernández et al. 2021; Richardson, Hardesty and Wilcox 2019; **Figure 5.3**). Plastic in the environment varies considerably depending on waste-management practices, geographical regions, hydrography and topography. Water body connectivity and hydrography, such as in ocean gyres and medium-scale ocean characteristics, are pivotal to floating litter accumulation (UNEP 2021a; Strokal et al. 2023). The North Pacific Subtropical Gyre is responsible for the Great Pacific Garbage Patch, a 1.6 million km^2 North Pacific Ocean area with an accumulated 79,000 tons of mostly plastic debris (Lebreton et al. 2018).

5.2.2.2 Nutrient pollution

Nutrient input into coastal and marine systems occurs from both natural processes, such as rock weathering and ocean upwelling, and anthropogenic processes such as agricultural run-off, sewerage, and aquaculture (Chislock et al. 2013). With increasing human populations, particularly in coastal areas,

Figure 5.3: Direct risks and impacts of marine litter and plastics



Sources: UNEP 2021, adapted from Aliani and Molcard 2003; Boerger et al. 2010; Fossi et al. 2012; Fossi et al. 2014; Goldstein et al. 2014; Avio et al. 2015; Kiessling et al. 2015; Santos et al. 2015; Rech et al. 2016; Rochman et al. 2016b; Hong et al. 2017b; Lusher et al. 2017a; Sbrana et al. 2017; Steer et al. 2017; Anbumani and Kakkar 2018; Godoy and Stockin 2018; Duncan et al. 2018a; Duncan et al. 2018b Fossi et al. 2018; Lamb et al. 2018; Lavers et al. 2018; Schymanski et al. 2018; Waite et al. 2018; Akhbarizadeh et al. 2019; Alimba and Faggio 2019; Battisti et al. 2019; Besseling et al. 2019; Bucci et al. 2019; Koelmans et al. 2019; Li et al. 2019; Windsor et al. 2019; Woods et al. 2019; Zhu, C. et al. 2019; Zhu, L. et al. 2019; Amaral-Zettler et al. 2020; Harris 2020; Landrigan et al. 2020; Prata et al. 2020a. Illustrated by GRID-Arendal

and the intensification of farming practices, nutrient pollution – particularly of nitrogen and phosphorus – is increasing. Alongside direct input from rivers, marine nutrient balance may also be affected by factors such as alterations in ocean currents (Rogers et al. 2020), and inputs from dust storms (UNEP 2020) and wildfire smoke (Herbert-Read et al. 2022).

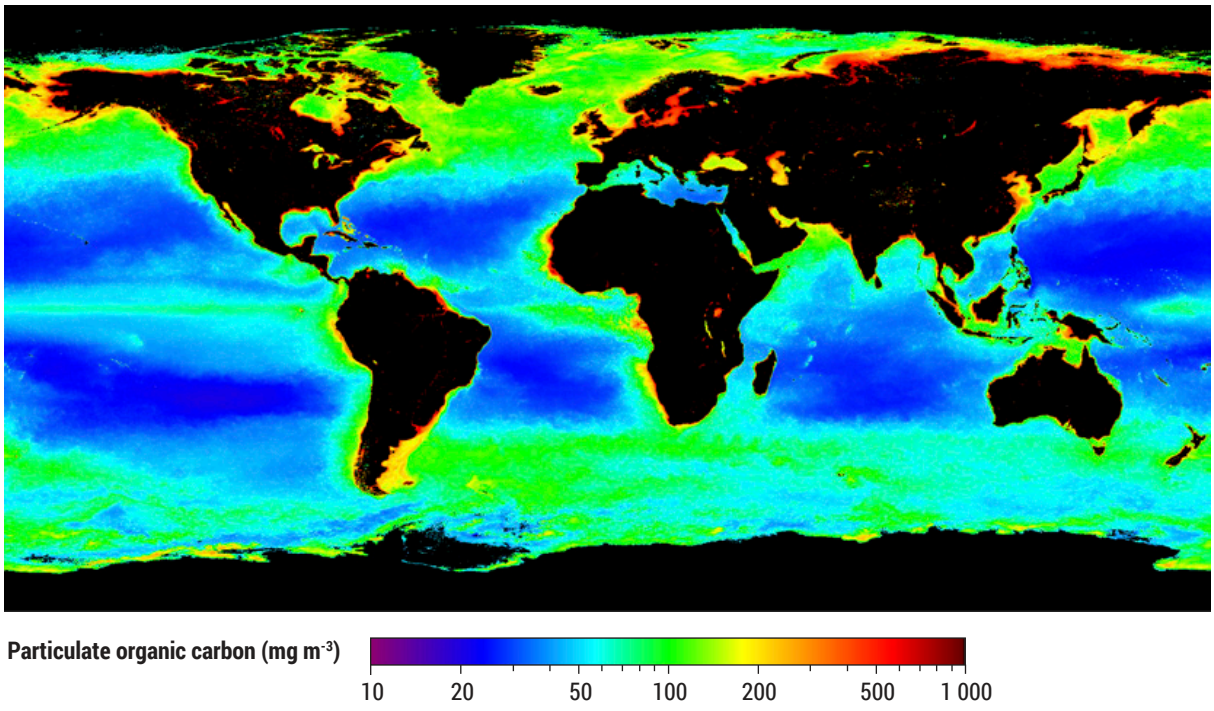
Excessive nitrogen and phosphorus in marine systems lead to excessive phytoplankton and algal growth, and to anoxic conditions which can kill all oxygen-breathing organisms, such as bivalves and fish, due to eutrophication. In the United States, 78 per cent of coastal waters and 65 per cent of European Atlantic coastal waters are eutrophic (Malone and Newton 2020; **Figure 5.4**), and over 20 per cent of coastal waters in China are now classified as "affected by eutrophication" (People's Republic of China, Ministry of Ecology and Environment 2024; Wang et al. 2021b). Statistics on eutrophication in other marine and coastal areas are difficult to find, intercalibrate and collate (Graves et al. 2021).

The resulting degradation leads to declines in ecosystem services, including aquaculture production, fish and shellfish stocks, and overall amenity value (Smith and Schindler 2009). The economic costs to fisheries, tourism and other coastal livelihoods are already in tens of billions of dollars annually. The importance of interconnecting some of the solutions with sustainable agriculture cannot be overemphasized, especially when watersheds drain directly into the seas and oceans.

5.2.2.3 Pollution from aquaculture

Aquaculture – the breeding, raising and harvesting of fish, shellfish and aquatic plants (National Oceanic and Atmospheric Agency 2023) – is one of the fastest-growing food sectors in the world (Organisation for Economic Co-operation and Development/FAO 2021; FAO 2022; **Figure 5.5**). The State of World Fisheries and Aquaculture reports that global fisheries and aquaculture production in 2022 surged to 223.2 million tons, a 4.4 per cent increase from the year 2020. Production comprised 185.4 million tons of aquatic animals and 37.8 million tons of algae (FAO 2024). Although aquaculture is accelerating to meet growing aquatic food demand, many current operations severely

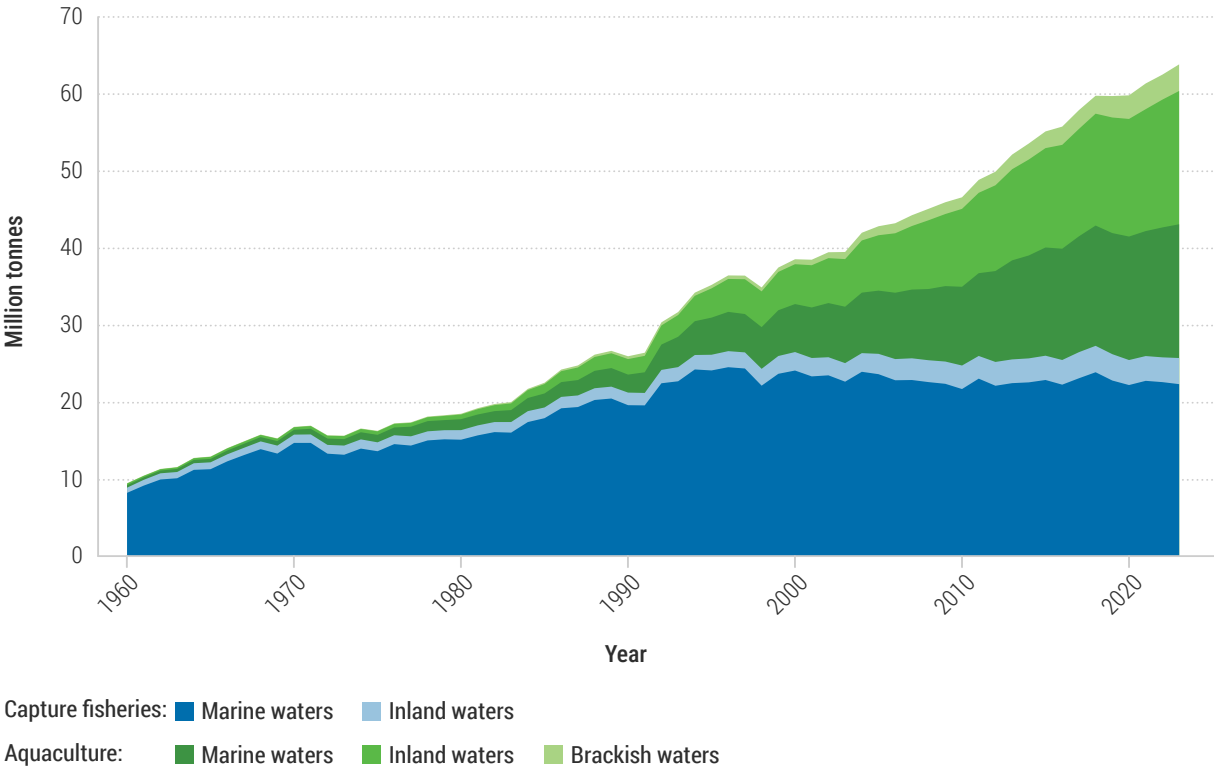
Figure 5.4: Global distribution of particulate organic carbon in seawater, implying marine eutrophication



Note: Elevated levels of particulate organic matter signal excessively nutrient-rich waters, which can lead to oxygen-depleted "dead zones" as a result of eutrophication

Source: National Aeronautics and Space Administration (2024)

Figure 5.5: Global fishery and aquaculture production from 1960 to 2023



Source: FAO (2025)

affect the marine environment and human health in the long term, for example, in sediments (Bergland et al. 2020; Stentiford et al. 2022). The waste generated by aquaculture farms includes animal and fish faeces, fertilizers, sediments, dead fish, pathogens, non-native species, therapeutic compounds such as antibiotics, feed additives and nutrients. These can have detrimental effects on water quality, biodiversity, ecosystem functioning, food webs and human health. Thus, this maritime industry increasingly contributes significantly to ocean pollution (Braithwaite, Carrascosa and McEvoy 2007; Amirkolaie 2011; Schar et al. 2020).

5.2.2.4 Oil pollution

Oil pollution in marine waters still happens anywhere crude oil is drilled, transported or used and may originate from tankers, rigs, wells and offshore platforms. Pollution from point-source oil spills has declined substantially in recent years, although the data available in some regions remains sparse. The reduction is due to the implementation of stricter regulations and the development of new shipping technologies (Jernelöv 2010). The average number of large oil spills – greater than 700 tons – per decade has decreased from 24.5 in the 1970s to 1.7 in the 2010s (International Tanker Owners Pollution Federation 2024). Similarly, the total amount of oil spilled from tankers per decade declined from 3.2 million tons in the 1970s to 138,000 tons in the 2010s. This decline in oil pollution has had a positive effect on the environment and human health.

5.2.2.5 Other prominent sources of industrial pollution

Chemical pollution of industrial origin in marine systems is a multifaceted issue, encompassing a variety of pollutants, including heavy metals, persistent organic pollutants, per- and polyfluoroalkyl substances, xenobiotics, and industrial solvents (Tornero and Hanke 2016), as well as pharmaceuticals (Mezzelani and Regoli 2022).

All synthetic compounds which are foreign to natural ecosystems, such as industrial chemicals, pharmaceuticals, pesticides, artificial fertilizers and plasticizers, pose a significant threat to all aquatic systems, particularly those near the shore

Credit: stockfilmstudio/Envato

(Piwowarska et al. 2024). These compounds have been reported in surface waters throughout the world (Kumar et al. 2012), including those in Europe (Sablayrolles et al. 2011; Milić et al. 2018), and even in the Arctic (Lehmann-Konera et al. 2020).

While most industrial contaminants enter the marine environment from land-based sources, they are increasingly emitted from point sources at sea such as rigs and offshore installations. These sea-based pollutants can also be recirculated in the marine environment and are difficult to assess, due to monitoring challenges offshore.

Some regions are more heavily affected by chemical pollution due to multiple rivers as sources and a long history of industry. Marine waters most seriously impaired by industrial pollutants are the North Sea, Mediterranean Sea, the Baltic Sea, and Asian estuaries (Joerss et al. 2020).

Heavy metals such as lead, mercury, cadmium, copper, and zinc can enter systems from various sources, including industrial emissions, mining operations, wastewater and riverine discharges, and from shipping and offshore sources. Direct inputs of metals via antifouling chemicals, mainly copper and tin, and corrosion anodes, mainly zinc, create hotspots in and around marinas, harbours and along shipping routes. The level of pollution by heavy metals varies regionally in coastal and shelf seas (Larsen and Hjermann 2022).

Comprehensive monitoring and comparison of the ocean and coastal seas are rare. Current protocols include stringent controls of heavy metal emissions and facilitate the assessment of countries in Eastern Europe, South-Eastern Europe, the Caucasus and Central Asia (United Nations Economic Commission for Europe 1998).

Persistent organic pollutants are a group of chemicals that resist degradation and can therefore accumulate in the environment (Wenning and Martello 2014). They include polychlorinated biphenyls, dioxins and furans, polycyclic aromatic hydrocarbons and many pesticides. They enter the global ocean from sources that include industrial emissions, agricultural run-off, and waste disposal. Persistent organic pollutants can accumulate in marine animals such

as shellfish, posing an additional risk to human health through consumption of contaminated seafoods (Camacho-Jiménez et al. 2023).

Per- and polyfluoroalkyl substances, encompassing thousands of compounds, are of increasing concern in human health and ecosystems due to their environmental persistence and toxicity. They have been detected in global surface waters since the early 2000s (Muir and Miaz 2021).

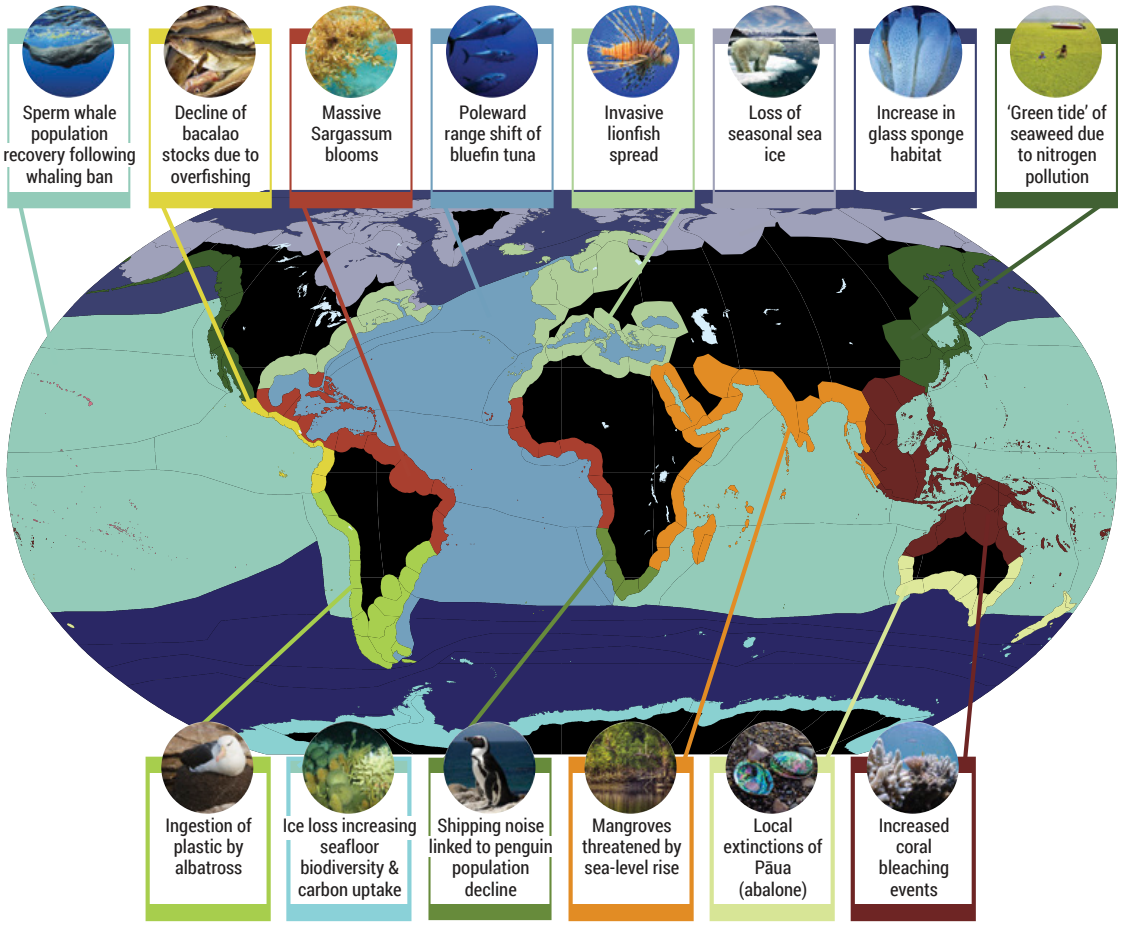
Industrial solvents are chemicals used in various industrial processes. They can enter the global ocean through industrial emissions, wastewater discharges and accidental spills.

5.2.3 Biodiversity

The oceans represent around 70 per cent of the Earth's surface and contain almost 245,000 known species (World Register of Marine Species 2023), with potentially 33–66 per cent of marine species yet to be discovered (Appeltans et al. 2012; Costello and Chaudhary 2017). Marine biodiversity patterns are undergoing significant shifts due to human influence. Around 59 per cent of the world's marine ecosystems are classified as experiencing significantly increasing human impacts and only 13 per cent are classified as wilderness with low human impacts (Jones et al. 2018; Halpern et al. 2019). These adverse effects include loss or decline of species, range shifts and introductions, and in some cases a disruptive increase in species abundance (Box 5.1; **Figure 5.6)**.

A major trend of ocean biodiversity is a poleward shift of species, with cold-water species being lost and warm-water species either being lost or migrating poleward. This decreases biodiversity in the tropics and increases biodiversity in temperate areas due to the arrival of new species (Chan and Briski 2017; IPCC

Figure 5.6: Examples of biodiversity changes within global marine regions demonstrating the variety of impacts and changes seen in marine ecosystems



Sources: Marine ecoregions taken from (Spalding et al. 2007) (coastal); (Spalding et al. 2012) (pelagic). Examples from (Godwin 2003; Jiménez et al. 2015; Ward et al. 2016; Andradi-Brown 2019; Pontón-Cevallos et al. 2020; Wang, Wang and Gu 2020; Bennett-Jones et al. 2021; Beazley et al. 2021; Steiner et al. 2021; Morley et al. 2022; Pichegru et al. 2022; Skliris et al. 2022; Whitehead and Shin 2022; Crear et al. 2023; Virgen-Urcelay and Donner 2023; Zhang et al. 2024

Box 5.1 Ecological and social consequences of shifts in Sargassum ecology

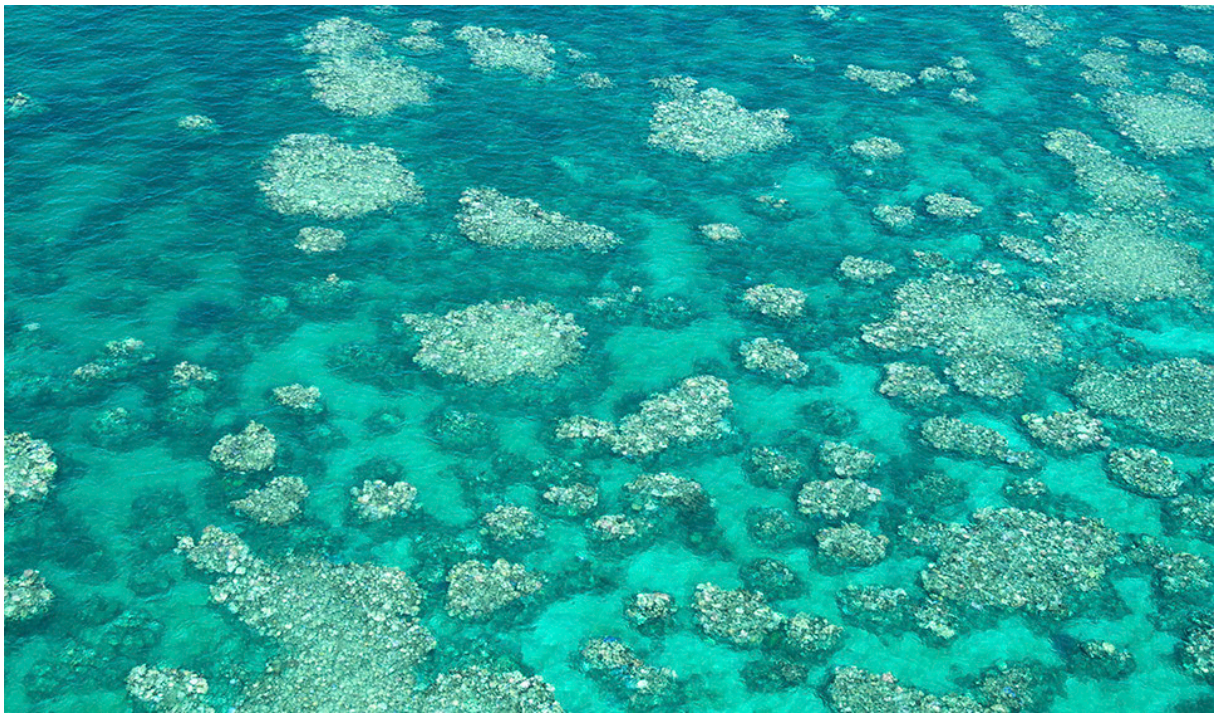
An extreme example of a highly habitat-disrupting organism class is the Sargassum seaweeds, encompassing 300 species. Since 2011, a floating aggregation of Sargassum known as the "Great Atlantic Sargassum Belt" has been recorded stretching nearly 9,000 km across and extending from West Africa into the Caribbean Sea and the Gulf of Mexico (Wang et al. 2019). This unusual abundance has been linked to global shifts in wind patterns, warming, increased nutrient input from rivers, and changed hydrography stemming from land degradation (Robledo et al. 2021). Although normal levels of Sargassum are beneficial as a habitat for fish and other species (Polte and Buschbaum 2008), the extreme proliferation has become problematic.

Credit: FabianMontano/Envato

For coastal Caribbean communities, such massive blooms and stranding of two pelagic species of this seaweed, *Sargassum fluitans* and *Sargassum natan*, have become an economic and social problem, meaning that they are now perceived to be invasive even where they are native to the area. Upon coastal stranding, Sargassum begins to rot, often releasing hydrogen sulfide and ammonia. These noxious gases travel long distances, affecting livelihoods, especially tourism, and both marine and human health, causing respiratory, eye, and possibly neurological effects. Caribbean countries are struggling to predict, prevent, contain, or utilize Sargassum blooms to limit the consequences for the economy, the environment, and health (Schmidt 2023).

2019; Antão et al. 2020; Benedetti et al. 2021; Boag, Gearty and Stockey 2021; Chaudhary et al. 2021).

Although relatively few marine extinctions have occurred in the last 500 years (del Monte-Luna et al. 2023; Nikolaou and Katsanevakis 2023), combined factors such as climate change, pollution, over-exploitation, and habitat destruction (Section 5.2.3.1) mean that many marine species' populations are declining (Pacoureau et al. 2021; Fortuna et al. 2024; Hendrix and Pérez-Espona 2024; Plön et al. 2024). The average global biomass of exploitable fish is predicted to decline by at least 5.3 per cent by 2050 as a result of climate change alone, even under low emissions scenarios (Blanchard and Novaglio 2024). However, 717 local extinctions have been recorded globally (Nikolaou and Katsanevakis 2023), with 26 per cent of cetacean species, 32 per cent of



Coral bleaching in the Great Barrier Reef, Australia. Credit: ARC CoE for Coral Reef Studies/Terry Hughes (via flickr) (CC BY-ND 2.0)

sharks, skates and rays, and estimates of up to 13 per cent of marine bony fish threatened with extinction (Dulvy et al. 2021; Braulik et al. 2023; Loiseau et al. 2024). Habitat loss is occurring for key marine and coastal ecosystems, such as seagrasses, coral reefs and mangroves (Dunic et al. 2021; Eddy et al. 2021; FAO 2023a). Ocean productivity is declining overall; the maximum sustainable yield of fisheries decreased by 4 per cent on average between 1930 and 2010, with some regions such as the Sea of Japan and Celtic Biscay Shelf decreasing by up to 35 per cent (Free et al. 2019). Overall biomass is predicted to decline on average by 5 per cent for every 1°C of warming (Lotze et al. 2019).

5.2.3.1 Causes of biodiversity change

While some stressors have specific and unique impacts on ecosystems as outlined in the following subsections, in many cases changes in biodiversity are the result of multiple interacting factors (Baag and Mandal 2022). Coral bleaching, for example, is caused by stress-induced expulsion of algae living in tissues and may be induced by high temperatures, salinity or light stress, pollution, and ocean acidification (IPCC 2019; Suggett and Smith 2020). The presence of marine litter may decrease ecosystem resilience to climate change (Lincoln et al. 2022); deoxygenated water may make blue sharks more likely to be caught by long-line fisheries (Vedor et al. 2021); and the vulnerability of organisms to metal pollution can be increased by ocean acidification and rising temperatures (Roberts et al. 2013; de Almeida Rodrigues et al. 2019).

Ocean Warming

Ocean warming affects the distribution, abundance, physiology, behaviour and life cycles of marine organisms (IPCC 2019), which may be more vulnerable than terrestrial species to extreme temperatures (Pinsky et al. 2019). Rising ocean temperatures are linked with a relative decrease of equatorial biodiversity and an increase in biodiversity at mid latitudes, as tropical species that are unable to tolerate higher temperatures die off or are forced to migrate polewards (IPCC 2019; Antão et al. 2020; Benedetti et al. 2021; Boag et al. 2021; Chaudhary et al. 2021). Warming also changes ocean current patterns, which may adversely affect ecosystems (Rogers et al. 2020). Warming-induced thinning and loss of Arctic and Antarctic sea ice, alongside contributing to sea level rise, directly threatens ice-dependent species such as polar bears, seals and seabirds (Lannuzel et al. 2020) and destabilizes food webs based on ice algae (Deb and Bailey 2023).

Both chronic and acute heat stress can cause damage and die-offs of marine species. Mass mortality events associated with heatwaves are

increasing globally (Garrabou et al. 2022) and adverse effects may be exacerbated by repeated exposures (Harris et al. 2018; Brown et al. 2023; Levitan et al. 2023). Coral bleaching events can also be triggered by heat stress; up to 91 per cent of the reefs surveyed on the Great Barrier Reef were affected by coral bleaching in 2022 (Great Barrier Reef Marine Park Authority 2022). Furthermore, 99 per cent of coral reefs are predicted to be lost worldwide if global temperatures rise by 2°C (IPCC 2018).

Acidification

Ocean acidification is particularly harmful to species with carbonate shells and exoskeletons – such as coral, crustaceans, urchins, starfish, some plankton species, oysters, clams and scallops – as it leaves them unable to form such structures (Figuerola et al. 2021). Global mean production of mollusks is predicted to decline by 7.7–12.8 per cent by 2100 under a high emissions scenario (IPCC 2019). Ocean acidification may also have physiological effects in organisms such as fish, particularly fish larvae, with growth, survival and metabolism affected by high CO_2 levels (Esbaugh 2018).

Sea level rise

Sea level rise negatively affects coastal ecosystems such as salt marshes, mangroves, reefs, and seagrass meadows through changes in light availability, sediment dynamics, salinity, mechanical wave action, and temperature (Trégarot et al. 2024; Saintilan et al. 2024). In some cases, these systems can adapt, migrate inland, or increase productivity and sedimentation to migrate vertically in response (Daru and Rock 2023). However, this may be constrained by high rates of sea level rise, human activities and other stressors that limit their resilience (Sadat-Noori et al. 2021; FAO 2023a; Saintilan et al. 2024).

Pollution

Plastic pollution accounts for around 85 per cent of total marine waste (UNEP 2021a) and significantly impinges on marine life and ecosystems globally, at all levels of food webs (Eriksen et al. 2014; Geyer, Jambeck and Law 2017; Choy et al. 2019; Omeyer et al. 2023; Vered et al. 2024). It causes harm to marine animals primarily through ingestion or entanglement, leading to injuries such as constriction or loss of limbs (Jepsen and de Bruyn 2019), digestive tract damage (Roman et al. 2019), and reduced fitness associated with ingestion of both macro- and microplastics (Al-Salem, Uddin and Al-Yamani 2020; López-Martínez et al. 2021; Pal et al. 2025).

Beyond direct impacts, plastic pollution affects marine habitats such as coral reefs, mangroves, and seagrass meadows (Ballesteros, Matthews and Hoeksema 2018; Harris, et al. 2021; Navarrete-Fernández et al. 2022) by smothering them, changing sediment composition, and preventing photosynthesis (Walther and Bergmann 2022). Movement of plastic in ocean currents may facilitate invasive species spread (García-Gómez et al. 2021; González-Ortegón et al. 2024), as well as movement of harmful chemicals or pathogens (Andrade et al. 2021; Bowley et al. 2021; Sanganyado et al. 2021) as plastic debris may act as substrates with the potential to absorb, accumulate or leach harmful substances.

Nutrient pollution or eutrophication may trigger algal blooms – reducing water clarity, producing toxins, and depleting water oxygen levels with a resulting die-off of marine life and destabilization of ecosystems (Fredston-Hermann et al. 2016; Mardones et al. 2023; Mack et al. 2024). In addition, sediment run-off associated with nutrient pollution may reduce water clarity, hindering photosynthesis or foraging behaviour. It may also physically bury marine habitats such as coral reefs and seagrass beds (Magris and Ban 2019).

Pollution from aquaculture, including the release of pathogens and parasites from farmed stock, can change the composition of ecosystems, alter behaviour and movement of wild fish stocks, and affect local water quality (Bergland et al. 2020; Casadevall et al. 2021). Some forms of aquaculture, particularly the "unfed" aquaculture of shellfish and algae, may have a large footprint and cause substantial hydrological and chemical changes in their local area (Harvey et al. 2024).

Exposure to chemical pollutants – including heavy metals, pharmaceuticals, sunscreen, and organic pollutants (petroleum products/oil pollution, pesticides, and industrial chemicals) – can cause direct physiological damage and the interruption of neurological, reproductive and immune function in

a wide range of marine organisms and shorebirds (Mayer-Pinto et al. 2020; National Academies of Sciences, Engineering and Medicine et al. 2022; Camacho-Jiménez et al.2023; Bielmyer-Fraser et al. 2024; Aarif et al. 2025). This represents a potential health hazard for human consumption. Muscle tissue of the Peruvian lorna drum *(Sciaena deliciosa)*, a fish eaten by coastal residents, has been found to exceed international standards for arsenic, mercury and lead (Gubloche et al. 2024). Persistent organic pollutants were detected in 100 per cent of samples of traditional marine food animals, including bowhead whale and various seal species, in a recent Alaskan study, although at lower concentrations than in previous assessments, possibly reflecting some global regulation success (Byrne, 2022).

Noise pollution affects animal communication and hearing, behaviour, navigation, foraging ability, and organ integrity and function (Middel and Verones 2017; Weilgart 2018; Duarte et al. 2021; ZoBell, Hildebrand and Frasier 2024).

Over-exploitation

Global sustainable exploitation of marine species is possible (Costello and Chaudhary 2017) and practised at local levels by Indigenous Peoples and local communities enforcing seasonal restrictions. Examples include the law enforcing fishing restrictions during turtle breeding seasons in the Niger Delta, no-take zones of Fijian tabu areas, and protection of spawning areas by the Haida Nation of British Columbia to preserve salmon habitats. However, an increasing proportion of fish stocks are currently fished beyond biologically sustainable levels, with 10 per cent in 1990 rising to 34.2 per cent exploited beyond sustainability in 2017 (FAO 2020) and over 37 per cent of fish stocks now classified as overfished (FAO 2024). In parallel, illegal, unreported and unregulated fishing continues to undermine effective fisheries management and poses a significant threat to marine biodiversity. It accelerates stock depletion, disrupts food webs, and erodes ecosystem resilience on a global scale (FAO 2024).

Fishing beyond a sustainable level causes a decline in stocks such that even with more than doubled effort, catch sizes have reduced since a maximum in 1994 (Worm et al. 2006), with catch per unit effort decreasing by over 80 per cent between 1950 and 2015 (Rousseau et al. 2019). Species with long generation times and low population growth rates, such as sharks and whales, are particularly vulnerable to the effects of over-exploitation. The global abundance of sharks has declined by 65 per cent between 1951 and 2021 (Dulvy et al. 2024), but relief of hunting pressure on whales since the 1980s means that populations are slowly beginning to recover (Calderan et al. 2020; Whitehead and Shin 2022). Particular fishing techniques may also adversely affect non-target species, such as the by-catch of marine mammals, birds and sea turtles in gillnet and long-line fisheries (Lewison et al. 2014), or disturbance to seabed communities from bottom trawling (Thrush, Ellingsen and Davis 2015; Eigaard et al. 2016).

Other forms of marine resource use or exploitation – including the construction of artificial structures such as marine platforms for oil and gas extraction, offshore wind turbines or desalination plants; laying of submarine cables; sand mining; and shipping – may also disrupt marine ecosystems. Disturbance or pollution including chemical, noise, light, and brine from desalination plants may occur during the installation, decommissioning and lifetime of artificial structures, but they may also function as new habitats or artificial reefs (Taormina et al. 2022; Stranddorf et al. 2024). The effects on biodiversity of novel forms of marine exploitation, such as deep-sea mining of metal nodules, are currently unclear (Katona et al. 2023). Such mining has the potential to cause mechanical damage to species and habitats, change local water chemistry, and result in the creation of smothering plumes of sediment (Filho et al. 2021).

Invasive species

The arrival of non-native species into marine habitats may occur due to shifts in species range or via the transport of species through human activities such as shipping ballast-water (de Souza et al. 2024), aquaculture (Chan and Briski 2017), and movement of plastic debris (García-Gómez et al. 2021). Incoming species may appear to bolster declining biodiversity within habitats but can also severely disrupt ecosystem dynamics and cause further decline of native species and ecosystem functioning (Occhipinti-Ambrogi 2021; Olenin et al. 2024), particularly in high latitudes, around islands, and in areas with low natural biodiversity (Alidoost Salimi et

Credit: © FAO/Veejay Villafranca

al. 2021; Gjedde et al. 2024). For example, the arrival of tropical herbivore species is increasing pressure on kelp forests (Zarco-Perello et al. 2021) and temperate seagrasses (Hyndes et al. 2016). However, the arrival of non-native species may also present opportunities for exploitation that relieve pressure on native stocks and can facilitate the maintenance of overall ecosystem function, despite loss of local native species (Kleitou et al. 2021).

5.2.3.2 Assessing biodiversity loss

As oceans are vast, international and typically remote and difficult to sample, monitoring their biodiversity is frequently challenging, and marine systems receive comparatively little conservation research effort (Caldwell et al. 2024). Marine biodiversity metrics are often patchy, both in terms of the areas studied – deep-sea, offshore, and tropical or polar regions are relatively under-studied (Menegotto and Rangel 2018; Danovaro 2024; Pertierra et al. 2025) – and in terms of the species assessed. The focus is usually on large, charismatic, or commercially important species (Troudet et al. 2017; Smith et al. 2021; Deb and Bailey 2023), however, recent advances in techniques such as DNA barcoding mean that species identification and biodiversity assessments are improving (Nguyen et al. 2020; Fan et al. 2023; Jiang et al. 2025). The influence of non-native species may be hard to assess due to long timescales and the complications of other sources of environmental degradation involved (Tiralongo et al. 2022).

Local community monitoring makes up a large part of marine biodiversity assessment; in particular, Indigenous coastal communities are among the first to experience the impacts of climate change on marine environments. Their detailed knowledge of local ecosystems allows them to observe and document changes such as rising sea levels, shifts in species distribution and alterations in water quality. This knowledge is essential to understanding the localized effects of climate change and for developing culturally appropriate adaptation strategies. For example, Inuit observations of sea ice and marine resource availability changes in the Canadian Arctic have been critical in both developing new hunting strategies and informing scientific research on the effects of climate change in the Arctic. There are several projects aggregating biodiversity metrics and data across the world's oceans, but differences in methods and reporting between studies and reports make comparison, and therefore global assessment, challenging (Katona et al. 2023).

5.2.3.3 Consequences of biodiversity change

Climate change

Biological marine carbon uptake and sequestration removes around 10 billion tons of carbon per year from the surface oceans (Siegel et al. 2023), which represents around 25 per cent of the excess CO_2 produced by human activities. CO_2 is absorbed by marine plants and phytoplankton before entering the food chain and being transported away from the ocean surface, with around 20–200 million tons per year sequestered in sediment (Siegel et al. 2023). Changes in phytoplankton communities affect this both positively and negatively; for example, blooms resulting from increased nutrient flow from melting glaciers may increase uptake (Hodson et al. 2017), while shifts in dominant species as a result of acidification and warming decrease it (Boot et al. 2023).

Blue carbon refers to the aspects of marine carbon uptake that may be managed or cultivated, such as tidal marshes, mangroves, and seagrass meadows (Macreadie et al. 2019), many of which are vulnerable to sea level rise, storm surges, heatwaves and elevated CO_2. These ecosystems sequester and store more carbon per unit area than terrestrial forests (UNEP 2021b; IPCC 2022); their loss releases sequestered CO_2 back into the atmosphere and exacerbates climate change. It is estimated that emissions from the destruction of these ecosystems account for 0.15–1.02 billion tons of CO_2 annually, amounting to between US$ 6 billion and US$ 42 billion in economic damages (Pendleton et al. 2012).

Pollution

Marine species may accumulate or ingest pollutants such as plastic or chemicals, enabling the substances' spread through the system. Some species act as reservoirs of pollutants. This could be due to a number of individuals each carrying small amounts, such as microplastics in marine copepods and persistent organic pollutants in deep-sea amphipods (Fagiano et al. 2024). Alternatively, it could result from bioaccumulation in top predators consuming many contaminated prey, such as mercury in predatory fish, persistent organic pollutants in orcas, and heavy metals in shorebirds (de Almeida Rodrigues et al. 2019; Atkinson et al. 2019; Desforges et al. 2024; Aarif et al. 2025). In other cases, coastal biological structures such as mangrove trees may trap floating debris, preventing dispersion into the ocean environment (Martin et al. 2019; Maghsodian et al. 2021).

Biodiversity loss

Loss of marine biodiversity causes a decrease in ecosystem productivity, stability, resilience to disturbances and water quality, with a higher probability of fisheries collapse and local extinction of species (Worm et al. 2006; Rastelli et al. 2020; Zerebecki et al. 2022). Some ecosystems also provide structural protection for neighbouring habitats: the degradation of coral reefs combined with sea level rise may lead to losses of seagrass and mangrove habitat in lagoons as wave action increases (Saunders et al. 2014).

Habitat degradation

Changes in ecosystem composition may cause shifts in ecosystem function, particularly when the affected species are responsible for physical or chemical alterations to the area. For example, reef-building species such as corals or shellfish on oyster reefs disrupt wave action and thereby contribute to natural coastal protection against storm surges and erosion (Saunders et al. 2014; Bitterwolf et al. 2024), as do mangroves and seagrass meadows (Ondiviela et al. 2014; De Dominicis et al. 2023; Veettil et al. 2024). The loss of these species or ecosystems removes this protection and leaves coastlines vulnerable.

Terrestrial ecosystems

The loss of coastal areas due to erosion and sea level rise will disrupt terrestrial biodiversity, particularly in islands, mangroves, wetlands and swamps, with a 1 m sea level rise predicted to cause the extinction of at least 100 endemic species globally (Menon, Soberón and Peterson 2010). Ecosystems in the Caribbean, Sundaland and Polynesia-Micronesian islands, as well as areas in northeastern South America, eastern North America, Southeast Asia, and

Credit: Image-Source/Envato

western Alaska will be most affected (Menon et al. 2010; Bellard et al. 2014).

Shifts in land–sea nutrient exchange as a result of a loss of marine species will also damage coastal terrestrial biodiversity. Species that move between marine and terrestrial environments – such as seabirds, penguins and seals – transfer nutrients between the two, increasing terrestrial biodiversity even beyond where those species are found (Bokhorst et al. 2019).

5.2.4 Land degradation

5.2.4.1 Coastal development

As of 2019, nearly 2.5 billion people live in coastal regions, with that number projected to increase disproportionately to other regions (UN 2021a). This poses significant challenges for ocean management, especially in the context of climate change. Key issues include sea level rise, safety, aquaculture, tourism, shipping, and sustainable ecosystems (Taherkhani et al. 2020).

While many studies have addressed these topics in relation to sustainable coastal zone management, comprehensive international cooperation and resource studies are urgently needed to develop effective global policies and avoid conflicts of interest (Jackson et al. 2001; Tõnisson et al. 2011; Vandenbruwaene et al. 2011; Lusher et al. 2013).

Coastal development can provide economic benefits and recreational opportunities, but it also poses significant environmental challenges, including habitat loss and degradation, pollution, erosion, sedimentation, and conflicts with other uses of the coastal zone.

Coastal fisheries and aquaculture, along with waste from inland fisheries, are major global management issues. The coastal environments in which aquaculture is practised, for example in the

mangroves of Indonesia, Brazil and Malaysia, and sensitive fjord ecosystems such as those of Norway and Chile, are increasingly threatened by overuse (FAO 2016; Bertram et al. 2021; de Lacerda et al. 2021). Globally, coastal development and associated pollutants threaten almost 25 per cent of the world's reefs; the largest proportion of threatened reefs are in Southeast Asia where small islands with densely populated coastlines put pressure on at least one-third of the region's corals (Burke et al. 2011; Dehm et al. 2024).

An increasing coastal environmental issue is the construction of artificial structures such as harbours, beaches and sea walls, especially in terms of land reclamation and artificial structures in the sea (Sengupta et al. 2023; Wang et al. 2023). This has become particularly pronounced in the Mediterranean, with over 8 per cent, and the North Sea with 16 per cent affected, where countries like Germany and the Kingdom of the Netherlands have the highest conversion of shorelines to man-made surfaces (European Environment Agency 2013).

Energy companies should design future facilities with nature-based ideas and decommissioning in mind. However, the renewable energy sector has not fully applied lessons from the offshore oil industry, and environmental legislation in Exclusive Economic Zones varies considerably. As renewable energy structures reach the end of their lifespan, decommissioning poses significant challenges, both financially and due to materials that may now be considered harmful (Kaiser and Snyder 2010).

Coastal ecosystems are increasingly shaped by these artificial structures, affecting sediment and geological processes. To reduce reliance on artificial surfaces, new strategies such as controlled flooding, innovative materials and structure recycling need further research. Nature-based solutions need to be increasingly utilized in new marine structures (Justine and Seenath 2025; Sakr and Altieri 2025).

Policies, regulations, incentives and governance arrangements at different levels also influence coastal development. In order to avoid conflicts of interest, multidimensional and international cooperation as well as resource studies, ending in globally useful legislation, are urgently required (European Environment Agency 2013). A renewed focus on sustainability and the implementation of strong joint governance is needed to address various conflicts of interest (FAO 2016).

5.2.4.2 Catchment run-off

When rainfall, irrigation or wind displaces topsoil, it may be transferred to nearby water bodies and rivers may carry it to the ocean (Borrelli et al. 2017). Such catchment run-off may discharge pesticides, nutrients, sediments and other contaminants such as industrial chemicals or plastic debris into the marine system, particularly from agricultural land, urban areas or waste disposal sites.

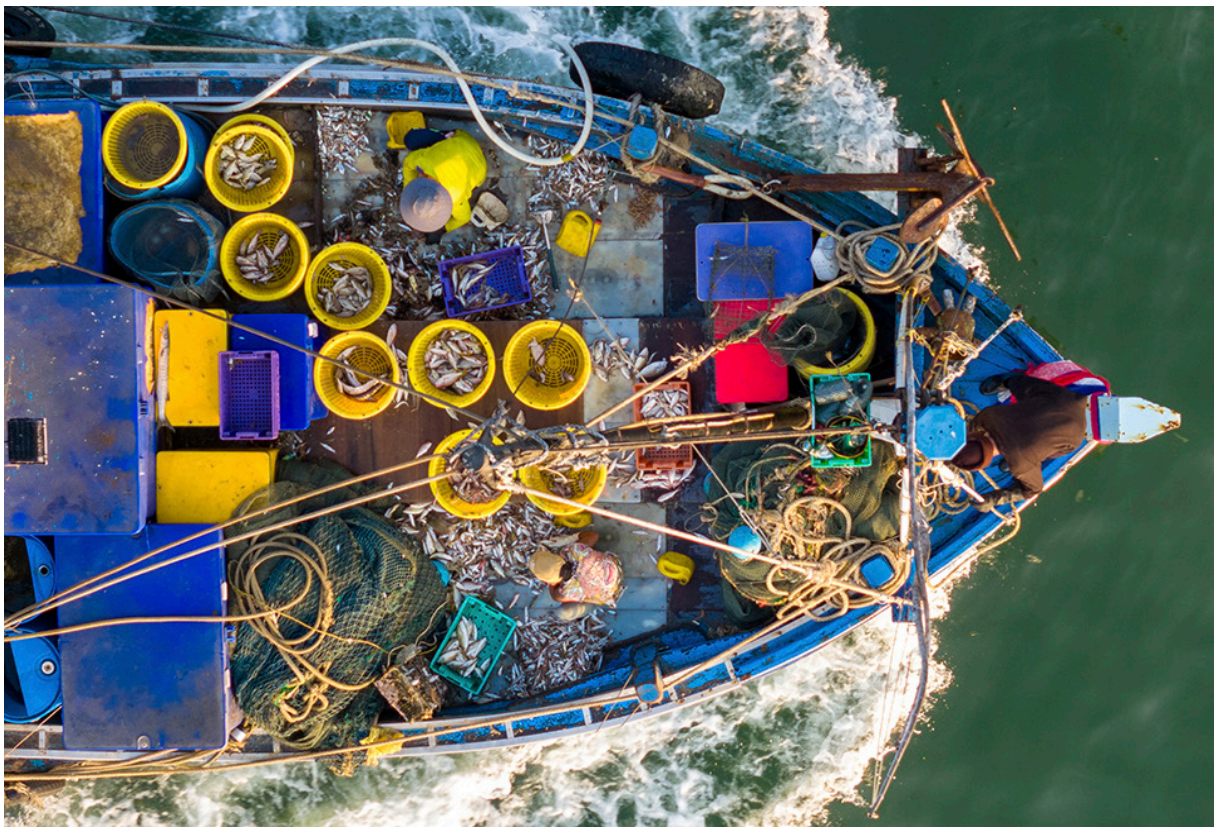
Although most pesticides are degraded by soil microorganisms or retained in terrestrial environments, around 760 metric tons of active ingredients from pesticides are discharged into oceans via rivers every year (Maggi et al. 2023). This can harm non-target organisms and disrupt food chains even in relatively small quantities. Increases in agriculture, animal waste, and use of fertilizers mean that inputs of nitrogen and phosphorus into the ocean have escalated over the 20th century (Beusen et al. 2016; Section 5.2.2.2).

Extensive nutrient-reduction efforts in the Chesapeake Bay watershed in the USA have yielded mixed results to date (Hyer et al. 2021). Other examples include the Baltic Sea, where biogeochemical functioning was affected by increasing nutrient loads in the second half of the 20th century, despite changes from the 1980s onwards (Kuliński et al. 2022). On the Great Barrier Reef, sediment loads from most catchment basins have increased substantially since European settlement, with negative implications for coral reefs and seagrass beds (Lewis, Bainbridge and Smithers et al. 2022).

5.3 Human systems

5.3.1 Economic benefits

The ocean is a rich source of resources, including food, fuel, fibre, biochemicals, pharmaceuticals, minerals and raw materials. These are essential for numerous industries and play a significant role in the global economy. According to the Food and Agriculture Organization, approximately 58.5 million people are



Credit: Bluesandisland/Envato

employed in primary fish production worldwide. Taking into account subsistence and secondary-sector workers and their dependants, an estimated 600 million people worldwide rely on fisheries and aquaculture for their livelihoods (FAO 2022).

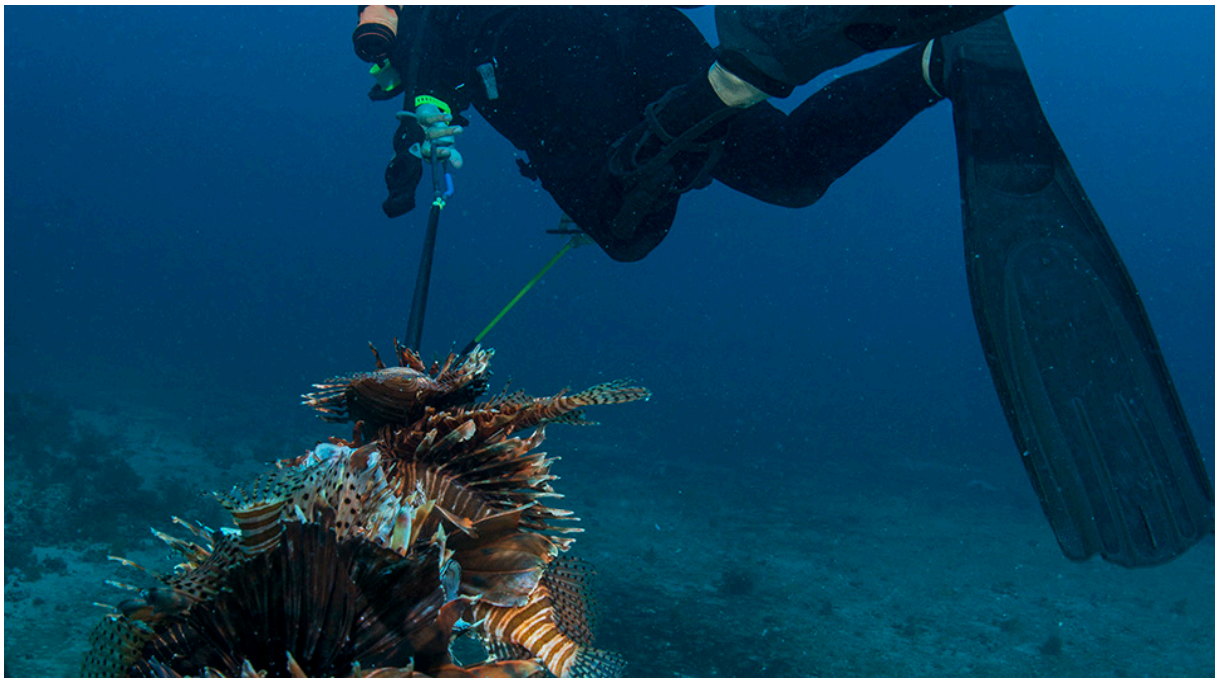
Marine recreational activities, such as fishing, whale watching and enjoying scenic coastal views, generate substantial revenue and benefit local coastal economies. Additionally, the spiritual, religious and cultural significance of ocean and coastal environments attracts cultural tourism, further contributing to both local and national economies (UNEP 2021b). In many Indigenous Peoples' communities, economic activities related to marine resources are closely linked to cultural practices and community well-being. These activities are managed in ways that ensure equitable distribution of benefits within the community and this holistic approach strengths social cohesion while promoting the sustainable use of marine resources.

Maritime industries are major contributors to global trade and the overall economy. For instance, shipping is responsible for transporting 80 per cent of the volume of international trade in goods, with this figure often even higher in many developing countries (UN 2024a).

Ocean energy – encompassing wind, wave, tidal and thermal energy – represents an important source of renewable energy and promotes sustainable development by reducing reliance on fossil fuels (Garavelli et al. 2024). Ocean energy has the potential to generate between 45,000 and 130,000 terawatt hours of electricity annually, which could theoretically meet the world's electricity needs more than twice over (International Renewable Energy Agency 2020).

Lastly, ocean processes have significant economic implications by mitigating potential costs associated with climate change impacts. The ocean acts as the planet's largest carbon sink, absorbing greenhouse gases and significantly reducing the effects of climate change (Sections 5.2.2.6 and 5.2.3.1). Additionally, photosynthesis by marine plants and algae contributes to oxygen production.

Alteration, degradation and loss of invaluable marine ecosystems and their biodiversity threatens many economic benefits associated with coastal and marine ecosystems. Similarly, changes associated with climate change have significant implications for the development of human settlements and activities in coastal areas. For example, under a high emissions scenario, sea levels are projected to rise by 0.63–1.01 metres by 2100, placing up to 630 million people living on land below the projected annual flood levels (Kulp and Strauss 2019). Storm surges, intensified by sea level rise and extreme weather events, can cause severe disruption to coastal infrastructure, displace



Credit: Image-Source/Envato

communities and result in significant economic losses in tourism, fisheries, transport and housing sectors, compounding the vulnerabilities of coastal development (IPCC 2019).

5.3.2 Food security

Food security means that all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs for an active and healthy life. Fisheries and aquaculture are essential for global food security, with production reaching an unprecedented 182 million tons of aquatic animals and 36 million tons of algae in 2021 (Intergovernmental Oceanographic Commission of United Nations Educational, Scientific and Cultural Organization [IOC-UNESCO] 2024). In numerous low-income food-deficit countries across Africa, Asia, Latin America and the Pacific Islands, small-scale fisheries contribute approximately 40 per cent of the global fisheries catch, sustaining the livelihoods of nearly 500 million people (FAO et al. 2023). While capture fisheries have remained relatively stable since the mid-1990s, averaging about 92.1 million tons, aquaculture has grown at an annual rate of 5.2 per cent during the same period (IOC-UNESCO 2024).

The apparent per capita consumption of aquatic food was estimated at 20.4 kg per year in 2021 (IOC-UNESCO 2024). Aquatic food consumption accounts for over 20 per cent of the average per capita animal protein intake for 3 billion people, and more than 50 per cent in some developing countries (UN 2021b). Seaweed farming and harvesting also contribute to food security and nutrition by providing edible seaweed, animal feed, fertilizers and biofuels (Nagula et al. 2022; Choulot et al. 2022), as well as absorption of CO_2 (UN 2021b).

Aquatic foods also offer greater sustainability, as the production of aquatic animal-source foods typically has a lower environmental impact than the production of most terrestrial animal-source foods (IOC-UNESCO 2024). However, overfishing has escalated in recent decades, with over 37 per cent of fish stocks now classified as overfished (FAO 2024). Furthermore, by 2100, global fish biomass production is projected to decline under both low and high emissions scenarios. Some of the largest declines are expected in countries that rely heavily on aquatic foods for protein – such as the Solomon Islands, Federated States of Micronesia, Nauru, Portugal, and Palau – or are major producers in global marine fisheries, including China and Peru (Blanchard et al. 2024).

5.3.3 Health

Health is a case of whole mental, physical and social well-being and is not restricted to the absence of disease or even infirmity (World Health Organization 1984). Living near the sea offers numerous benefits

for human health, including enhanced air quality, opportunities for exercise, and access to novel marine-derived pharmaceuticals (UNEP 2021a).

Human health is interconnected with a healthy environment and is defined as the ability to adapt to emerging threats (The Lancet 2009). Such threats arising from the marine environment include:

- The continuous rise in sea surface temperatures, coupled with pollution, is contributing to the increased abundance and wider geographical distribution of certain marine pathogens, particularly the Vibrio species. Among these, *Vibrio cholerae*, which is responsible for cholera, is of particular concern (Baker-Austin et al. 2024).

- Non-native species in marine environments are a growing concern as they can adversely affect the health of both humans and animals, which in turn can disrupt economic activities and livelihoods (Katsanevakis et al. 2014).

- Microplastics pose significant threats to marine life, particularly through the transmission of pathogens. They can act as carriers for a variety of bacteria, viruses and other pathogenic organisms, representing a risk for both marine ecosystems and the broader marine environment (Zhong et al. 2023). Notably, zoonotic human pathogens, including *Escherichia coli,* Salmonella, Cryptosporidium, and rotavirus, can adhere to microplastics (Metcalf et al. 2022; Moresco et al. 2022).

- Risks arise from antimicrobial-resistant bacteria and genes in estuarine and coastal waters, driven by antibiotic use in agriculture and aquaculture. These residues enter coastal areas via run-off and wastewater, posing risks to human health through contaminated seafood and recreational water use, while also reducing the effectiveness of antibiotics (Salma et al. 2025).

5.3.4 Equity/distributional effects

The ocean provides a multitude of benefits to humans, from food and raw materials to climate regulation and recreational opportunities. However, the distribution of these benefits is not uniform across different regions, countries and groups of people. Certain regions and countries are more exposed and sensitive to adverse environmental changes due to their geographical location, socioeconomic status, governance capacity and dependence on marine resources. For instance, Small Island Developing States and coastal communities in developing countries often rely heavily on fisheries and tourism for their livelihoods, making them particularly vulnerable to changes in marine ecosystems (UNEP 2021a).

Similarly, some groups of people are more vulnerable and marginalized than others due to factors such as gender, age, ethnicity, culture or occupation. Women, for example, often play crucial roles in small-scale fisheries and seaweed farming but may lack access to resources, rights and decision-making power. They constitute a significant portion of the workforce in processing and trading fish; however, they frequently engage in low-paid, informal jobs without adequate protection (IOC-UNESCO 2024). Indigenous Peoples also have deep cultural connections to the ocean but may face threats to their traditional territories, knowledge systems, and food sovereignty (UNEP 2021a). These inequities can exacerbate existing social and environmental injustices by disproportionately affecting those who are already disadvantaged or marginalized.

Equitable access to marine resources is paramount, particularly for small-scale fisheries. Climate change, pollution and other human activities disproportionately affect marginalized communities, highlighting the need for relevant policies that promote justice and sustainability in ocean governance (IOC-UNESCO 2024).

Addressing these inequities is essential to ensure a fair and sustainable future for all, as they can undermine human rights and dignity by limiting people's access to resources, opportunities, and justice (UNEP 2021a).

5.3.5 Indigenous Peoples

Coastal Indigenous communities are especially vulnerable to the effects of rising ocean temperatures, acidification, sea level rise and pollution. Projections show that increased ocean hypoxia, combined with acidification and marine heatwaves, will lead to significant declines in Dungeness crab populations,

resulting in economic losses for the Hoh, Makah, Quileute, and Quinault Indian Nation tribes along Washington State's Olympic coast (Alin et al. 2023). Similarly, the depletion of shellfish populations due to ocean acidification adversely affects the livelihoods of Indigenous communities in Alaska and along the West and Gulf Coasts of the United States of America (Environmental Protection Agency 2024)

In Tasmania, Aboriginal communities on the east coast, one of the world's fastest-warming marine areas, face climate-driven challenges such as the decline of giant kelp and the increasing prevalence of urchin barrens, which are overgrazed areas in kelp forests. These changes complicate adaptation efforts, leading to cultural losses related to governance and connections to the coastlines where they have lived for countless generations and the resources they have adapted with over that time, their sea country (Pecl et al. 2019). Additionally, Māori communities in New Zealand are experiencing a decline in their cultural functioning capacity due to similar environmental changes (New Zealand, Ministry for the Environment and Stats NZ 2022). Arctic Indigenous communities such as the Russian Sakha, Evenkis and Evens peoples have their ways of life threatened by thawing permafrost and ice that cause coastal erosion and reduce ice road availability, intensification of winter storms, and changes in the seasonality and abundance of fish stocks (Povoroznyuk et al. 2023).

In response to the challenges posed by climate change, many Indigenous communities have adapted their marine resource management practices. These adaptations are often based on traditional knowledge, which is continuously updated to reflect new environmental realities. Indigenous strategies for coping with environmental change emphasize resilience, the sustainable use of marine resources, and the protection of biodiversity. Examples include the people of the Pacific island of Kiribati adapting traditional practices in fish-trap construction in response to rising sea levels and the preservation of native wetland species and sustainable management of water resources by the Lafkenche in Chile. Further examples can be found in mangrove restoration projects by Indigenous communities in the Sundarbans of India and Bangladesh and Ogoni people in the Niger Delta.

5.4 Progress towards internationally agreed goals

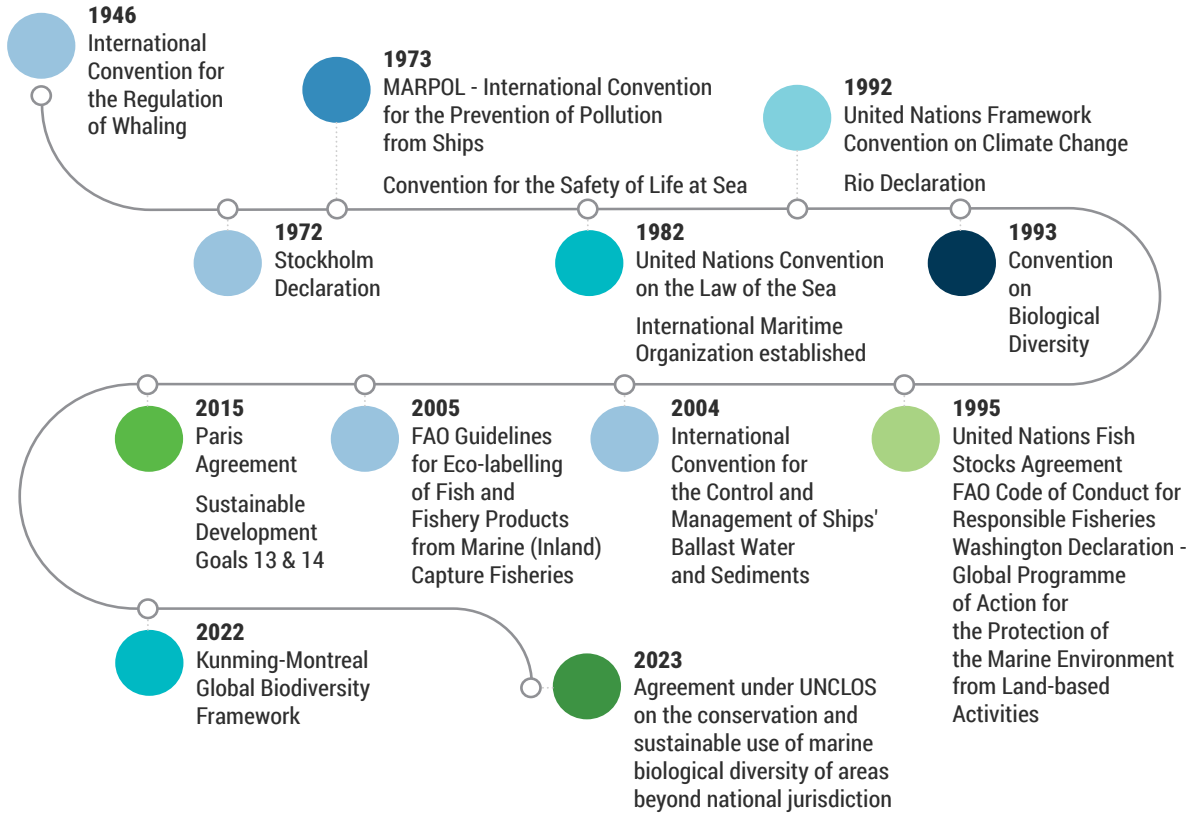
Many international agreements, conventions and treaties exist to protect and conserve ocean resources and regulate their use, including those aimed at improving specific aspects of ocean management (**Figure 5.7**). These cover various topics, including climate change, pollution, energy, fisheries, mining, and transport (**Box 5.2**). This section examines progress towards selected internationally agreed goals, particularly biodiversity targets and Sustainable Development Goal (SDG) 14. It also addresses progress and ongoing negotiations towards establishing new agreements addressing emerging issues such as biodiversity in areas beyond national jurisdiction, plastic pollution and deep-sea mining.

5.4.1 Aichi Biodiversity Target 11

Aichi Biodiversity Target 11, set by the Convention on Biological Diversity (CBD), aimed to conserve at least 17 per cent of terrestrial and inland water areas and 10 per cent of coastal and marine areas by 2020. These areas, important for biodiversity and ecosystem services, were to be conserved through well-managed, ecologically representative and connected protected areas, along with other effective area-based conservation measures.

The Aichi Biodiversity Target 11 was assessed as partially achieved, contributing to the greatest global Marine Protected Area (MPA) network growth since 2000 (Secretariat of the CBD 2020). Nevertheless, the total protected area fell short of the 10 per cent goal, with 7.74 per cent of coastal waters and oceans protected (The United Nations Environment Programme World Conservation Monitoring Centre [UNEP-WCMC] 2021). Some progress was made towards covering areas of ecological and biodiversity importance, for example, 46.1 per cent of marine ecoregions had at least 10 per cent coverage, and an additional 9.1 per cent had at least 5 per cent coverage (Secretariat of the CBD 2020; European Commission Joint Research Centre 2020). Questions remain about ecological representation due to the generally low coverage (Carr et al. 2020). As of March 2025, 8.34 per cent – 16,503 MPAs – of marine areas within national waters were under protection (**Figure 5.10**) (UNEP-WCMC and IUCN 2024).

Figure 5.7: International treaties on marine law and management



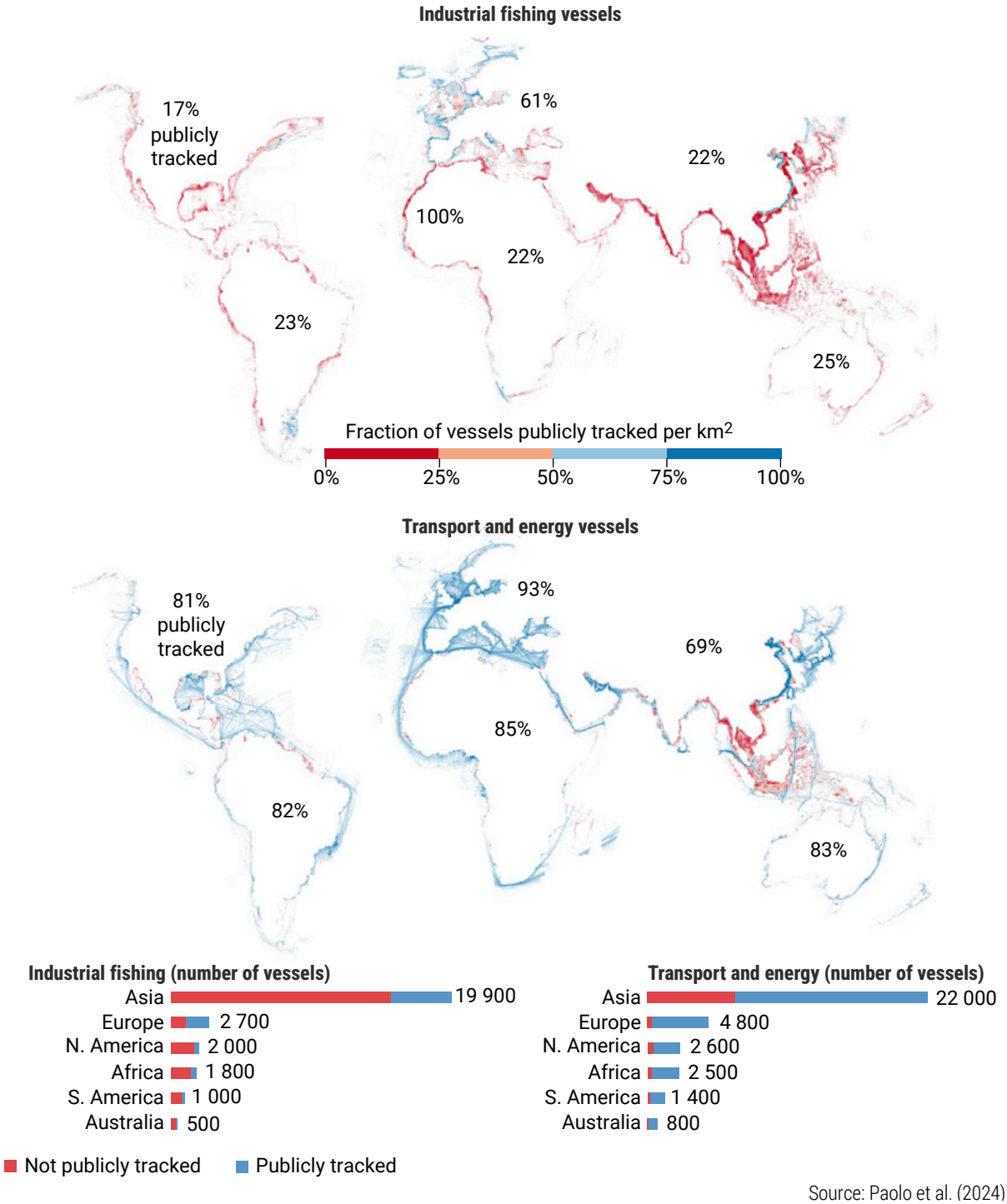
Box 5.2 Example of how selected international agreements apply to different sectors and activities

Human activity is rapidly expanding ocean infrastructure, including offshore energy, artificial islands, submarine cables, and mining operations. These developments impact land–ocean interfaces, cause substrate change, hydrography shifts, affect biodiversity and ecosystem structures, and increase maritime logistic and security pressures. Unregulated fishing persists alongside these increased pressures (**Figure 5.8**) (Paolo et al. 2024).

The UN Sustainable Development Goals 13 and 14 emphasize the need for sustainable ocean use under the United Nations Convention on the Law of the Sea (UNCLOS) framework. While UNCLOS regulates seafloor mining and high seas freedoms such as fishing and navigation, it lacks specifics on renewable resource collection and carbon sequestration. Mining of polymetallic nodules from the seafloor, a controversial activity, is regulated under UNCLOS by the International Seabed Authority. The freedom to utilize renewable resources – for example, wind, light, heat and currents – is, however, not explicitly dealt with (Soria-Rodríguez 2022).

The High Seas Treaty addresses some gaps by promoting ocean heritage, biodiversity loss, and ecosystem sustainability. However, for all marine industry and urbanization and especially in the case of the Offshore Renewable Industry international environmental agreements, standards and best practices must be applied and reported, both within jurisdictional areas in national or international waters (United Nations 2024b). As is clear from the evaluation of shipping trends by the International Maritime Organization (IMO), there is an urgent need to reduce emissions, such as carbon dioxide, and noise from shipping. Indeed, the role of other bodies such as the IMO, International Renewable Energy Agency, OSPAR Commission, International Council for the Exploration of the Sea and Baltic Marine Environment Protection Commission in reducing ocean and coastal industrialization and urbanization impacts cannot be overemphasized. As an example of progress, the IMO's revised GHG Strategy, adopted at the 80th session of its Marine Environment Protection Committee, targets net-zero emissions for international shipping by 2050, with interim goals of reducing emissions by 20 per cent by 2030 and 70 per cent by 2040 (IMO 2023a) (**Figure 5.9**).

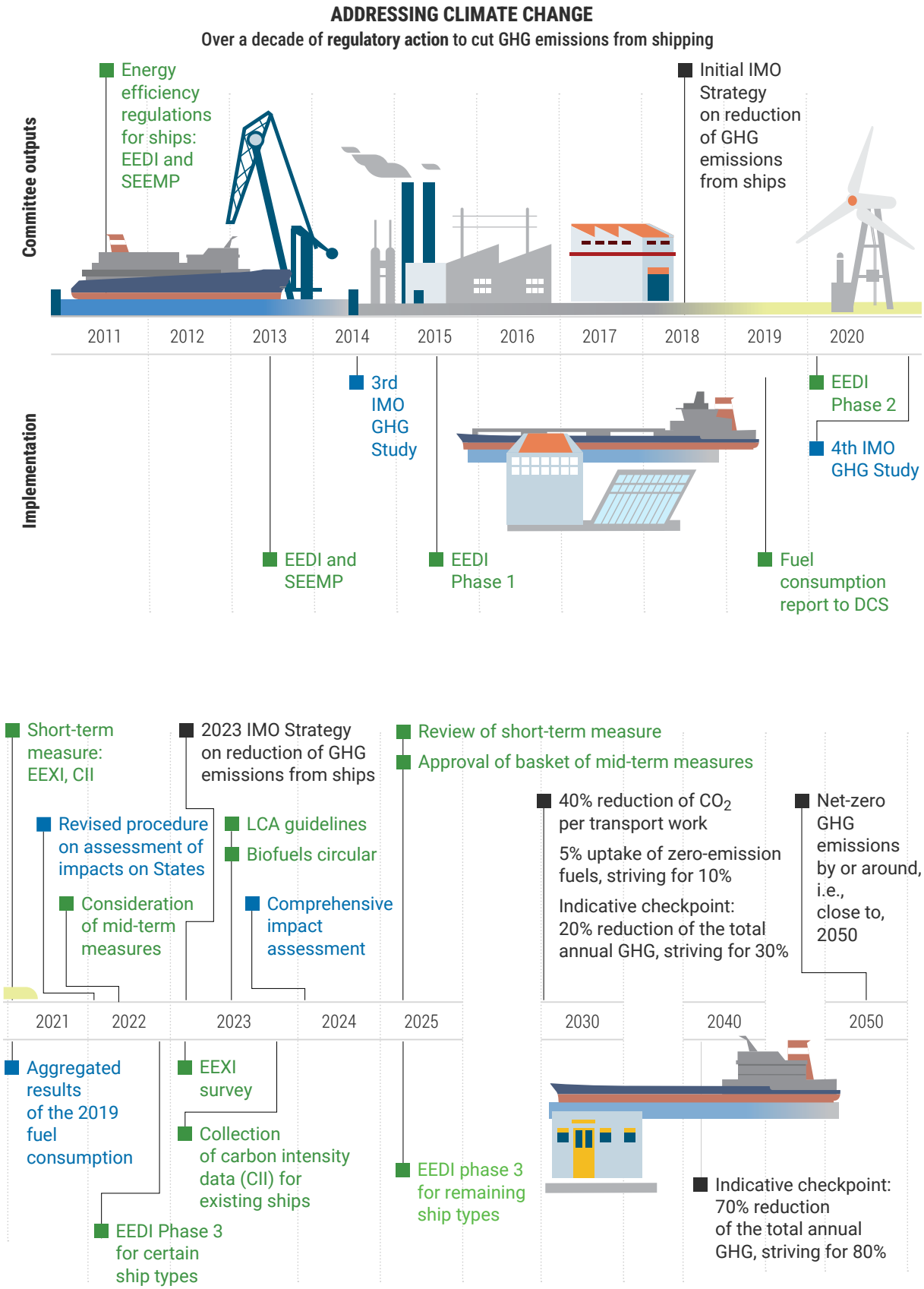
Figure 5.8: Industrial fishing and other uses of oceans and coasts, 2017–2021



Source: Paolo et al. (2024)

Area-based measurements have been criticized for falling short of adequately protecting threatened areas (Kuempel et al. 2019) and the diversity of marine habitats (Fischer et al. 2019; Carr et al. 2020). The level of protection varies within MPAs, and in 2023 only 2.9 per cent of such areas were classed as fully or highly protected from extractive activities (Marine Conservation Institute 2023). In addition, one-quarter of the 100 largest MPAs, which cover 90 per cent of the world's total, are not implemented, and one-third allow high-impact activities. Fully protected MPAs make up one-third of the area but are unevenly distributed, often in remote territories (Pike et al. 2024). A further limitation is that data on the effectiveness of governance and management in existing protected areas remains poor (Carr et al. 2020; UNEP-WCMC 2021). The Global Database on Management Effectiveness of Protected Areas has only conducted

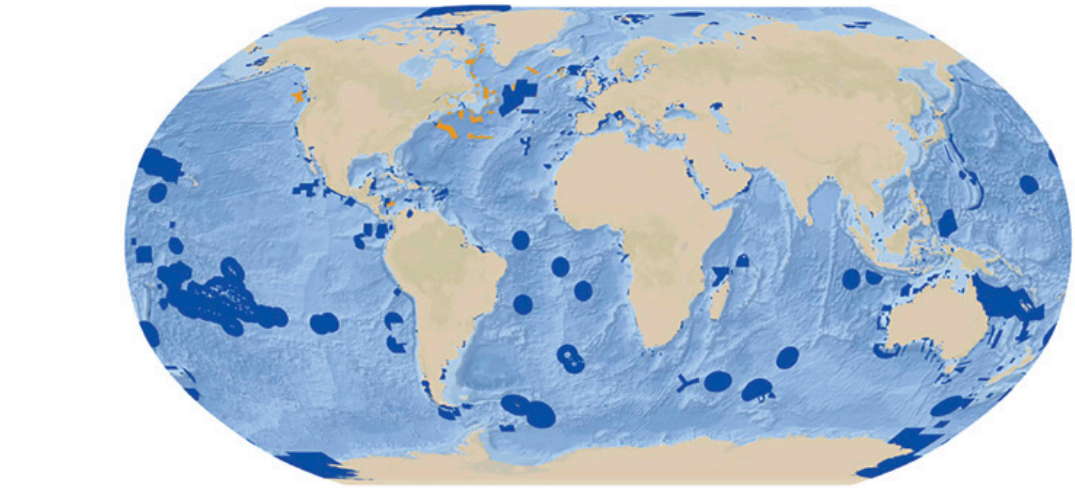
Figure 5.9: Timeline of regulatory action to cut shipping emissions



Note: DCS: Data collection System; CII: Carbon Intensity Indicator; EEDI: Energy Efficiency Design Index; EEXI - Energy Efficiency Existing Ship Index; LCA – Life Cycle Analysis; SEEMP - Ship Energy Efficiency Management Plan

Source: IMO (2023)

Figure 5.10: Growth in marine protected area coverage



Marine and coastal protected areas OECMs

Source: UNEP-WCMC and IUCN 2025

assessments covering approximately 1 per cent of coastal and marine areas (Secretariat of the CBD 2020).

5.4.2 Kunming-Montreal Global Biodiversity Framework

The Aichi Biodiversity Targets (2011–2020) have been replaced by the Kunming-Montreal Global Biodiversity Framework (GBF), which will guide actions through to 2030. These include restoring at least 30 per cent of degraded ecosystems and protecting at least 30 per cent of terrestrial, marine, and coastal areas by 2030 (Secretariat of the CBD 2022).

Achieving the new goals may be challenging, particularly in implementing the framework at the national level, as the Aichi national indicators showed inconsistent alignment with global targets (Secretariat of the CBD 2020). Nationally differentiated targets have been identified as more effective for meeting global conservation goals (UNEP-WCMC 2021). The new framework includes indicators for parties to report and monitor progress (Secretariat of the CBD 2022). The Kunming-Montreal GBF's interim goals and targets are more specific than previous Convention on Biological Diversity iterations (Streck 2023), moving away from a set-and-forget approach to international agreements of 2002 and 2010 (Phang et al. 2020).

Nevertheless, questions about the Kunming-Montreal GBF targets' measurability arise from a lack of clear metrics, limited data availability and the complexity of biodiversity itself. Tracking is further complicated by the variability in national capacities to monitor progress, especially in resource-limited regions. Ecological changes often occur over long time frames, making short-term measurement difficult, and cross-sectoral impacts from industries such as agriculture and fisheries can distort progress assessments (Hughes et al. 2023). Addressing these issues is critical in ensuring effective monitoring and reporting of the Kunming-Montreal GBF's ambitious goals.

5.4.3 Sustainable Development Goal 14

While some regions and countries have made advances, overall progress towards achieving SDG 14: Life Below Water is insubstantial and inadequate in pace and scale (UNEP 2019; Andriamahefazafy et al. 2022; Haas 2023).

A key barrier to accurately measuring SDG targets is the lack of specific and quantifiable metrics common to many such targets (McArthur et al. 2019; UNEP 2019). For Target 14.1, which aims to prevent and reduce all forms of marine pollution by 2025, progress can be inferred by tracking trends in different types of pollution. One key indicator is plastic pollution, with the volume of plastic entering the ocean expected to triple by 2040. Another is Chlorophyll-a levels in Exclusive Economic Zones, which serve as an indicator of the risk of algal blooms and eutrophication. These levels decreased by 20 per

cent from 2018 to 2020 (UN 2022a). However, despite this decline, hypoxic zones caused by fertilizer run-off and untreated wastewater remain widespread (Section 5.2.2.2). Insufficient data on plastic pollution at regional and global levels, and the lack of globally comparable nitrogen and phosphorus measurements for coastal areas (IOC-UNESCO 2022), pose significant challenges to measuring progress on Target 14.1.

Progress towards SDG 14 Targets including 14.2, 14.4, 14.5 and 14.6, set to be achieved by 2020, varied. For Target 14.2, 53 countries or 34.8 per cent, made good progress in sustainably protecting and managing marine and coastal ecosystems, (Andriamahefazafy et al. 2022). The number of countries using marine spatial planning – an approach that analyzes and allocates human activities in marine areas to achieve ecological, economic and social objectives – surged from a few before 2006 to 100 in 2022 (UN 2022b).

For Target 14.4, over 61 per cent of countries have made only "low progress" in sustainable fishing through regulation of "fish harvesting, elimination of illegal, unreported, and unregulated fishing" and implementation of science-based management plans. In 2019, 35.4 per cent of global fish stocks were overfished, up from 34.2 per cent in 2017 and significantly higher than the 10 per cent recorded in 1974 (UN 2021c). Contributing factors to overfishing include the illegal, unreported, and unregulated fishing; advances in fishing technology; population growth; and a rising demand for fish. Global aquatic fish consumption increased by 3 per cent annually since 1961, compared to a population growth rate of 1.6 per cent (Bardey 2020; FAO 2022). At the same time, the rate of underfished stocks has decreased, showing slight recovery in 2018 and 2019 (FAO 2022). Despite prevalent reports of low progress, a notable lack of data on sustainable fishing practices remains.

Target 14.6 aims to prohibit specific fisheries subsidies that contribute to overcapacity and overfishing; eliminate subsidies that support illegal, unreported, and unregulated fishing; and prevent the introduction of new harmful subsidies. This target also highlights the importance of special and differential treatment for developing and least developed countries in the World Trade Organization's fisheries subsidies negotiations.

Target 14.5, conserving at least 10 per cent of coastal and marine areas, is classified as "met or almost met" at a global level; even though only 55 countries achieved it by 2018 (Mustajoki et al. 2022). Pacific island nations, along with regions in Central and Southern Asia and Northern and Western Africa, are categorized as "far from target" (UN 2022c). Furthermore, despite Target 14.3's goal to minimize ocean acidification by 2030, acidification is expected to worsen (UN 2022a). Notably, there are significant data gaps regarding coastal waters near Asia and Africa, as well as in open waters such as the South Atlantic, Pacific, Indian, and Southern Oceans (UN 2021c).

Lastly, achieving SDG 14 is as significant for Indigenous Peoples as it is for other communities. However, except for a few countries, actions have not sufficiently addressed Indigenous rights to fisheries and ocean and coastal resources, nor adequately incorporated Indigenous opinions and perspectives (Yap et al. 2019). Encouragingly, Australia's Great Barrier Reef Marine Park Authority has been increasingly working with Aboriginal and Torres Strait Islander peoples to ensure the health of both marine life and Indigenous communities (Great Barrier Reef Marine Park Authority 2019). Similarly, Canada's national approach to SDG 14 acknowledges Indigenous rights to the ocean and its resources and includes Indigenous-led marine and coastal initiatives, such as establishing Indigenous Protected Areas. In New Zealand, traditional Māori knowledge has benefited the management of coastal and ocean resources, as seen in the restoration of mussel populations in Ōhiwa Harbour through the use of Mātauranga Māori, alongside other knowledge sources (Clapcott et al. 2018).

In the Arctic, the traditional knowledge of Indigenous Peoples such as the Inuit and Sámi is crucial for monitoring climate change and managing marine resources sustainably. Indigenous-led conservation efforts, such as those in Canada and Greenland, help safeguard biodiversity and food security while fostering co-productive governance approaches (Buschman 2022; Buschman et al. 2023).

Indigenous communities in Fiji have established MPAs that contribute to the country's efforts to meet the SDGs. These protected areas are managed using traditional knowledge, which ensures the sustainable use of marine resources and the protection of biodiversity. However, research remains limited on

Credit: Image-Source/Envato

Indigenous communities in coastal ecosystems in the Global South (Loch and Riechers 2021).

5.4.1 Emerging international agreements

5.4.4.1 Agreement on Marine Biodiversity of Areas Beyond National Jurisdiction

On 19 June 2023, the United Nations adopted the Agreement on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction under the United Nations Convention on the Law of the Sea (UNCLOS). This Agreement, which encompasses the high seas and the international seabed area, covers over two-thirds of the ocean (UN 2024b)and aims to enhance the scope and specificity of the Convention (Harden-Davies et al. 2024).

The Agreement addresses marine genetic resources and fair and equitable sharing of benefits, alongside measures such as area-based management tools, including MPAs, environmental impact assessments, capacity-building and the transfer of marine technology (UN 2023). It contributes to marine biodiversity protection beyond national borders, cleaner oceans through pollution control, sustainable fish stock management, ecosystem resilience to climate change effects, and the achievement of the 2030 Agenda, including SDG 14, by enabling marine conservation and equitable resource management. The Agreement is not yet in force and has been ratified by 15 states as of December 2024 (United Nations Treaty Collection 2025).

5.4.4.2 International Legally Binding Instrument on Plastic Pollution

In March 2022, the United Nations Environment Assembly adopted resolution 5/14, mandating the creation of a new international legally binding instrument to combat plastic pollution, including in the marine environment. This process involves five negotiation rounds over two years, facilitated by an Intergovernmental Negotiating Committee established

by the Executive Director of the United Nations Environment Programme. The instrument aims to address plastic waste comprehensively, covering its entire life cycle from production to disposal, which is crucial for preventing marine plastic pollution by reducing waste leakage into the ocean. The target completion date for this instrument was set for the end of 2024 (UNEP 2024). However, negotiators failed to reach an agreement, and negotiations are scheduled to resume during the second part of the fifth session in August 2025.

5.4.4.3 International Seabed Authority – Exploitation Regulations

Since 2014, the International Seabed Authority (ISA) has been developing regulations for the exploitation of mineral resources in the international seabed area, known as "the Area" (Pickens et al. 2024). These regulations include legally binding standards for contractors and the ISA, along with supplementary guidelines (International Seabed Authority 2022). The ISA did not meet the 9 July 2023 deadline, which was triggered in 2021 when the Republic of Nauru invoked a provision of the UNCLOS. Instead, at the second part of its 28th session in 2023, the ISA outlined a road map to adopt regulations during its 30th session in 2025. The negotiation process is supported by four working groups focusing on financial terms, environmental protection, compliance and enforcement, and institutional matters, as well as additional informal discussions (International Seabed Authority 2023).

This underscores the crucial role of the ISA's regulations in shaping the future of deep-sea mining, which according to Article 145 of UNCLOS must ensure effective protection of the marine environment from the industry's harmful effects (UN 1982). The delay in finalizing these rules highlights the complexity and importance of getting them right for effective ocean governance. Without clear and enforceable regulations, deep-sea mining could proceed without adequate safeguards, potentially leading to habitat destruction, biodiversity loss and harm to deep-sea species that are not yet fully understood. Metal contamination from mining activities could disrupt marine food webs (Martins et al. 2023), and interactions between deep-sea mining and fisheries may significantly affect the economies, livelihoods and well-being of coastal communities, particularly in Pacific Small Island Developing States and coastal States (Amon et al. 2023).

References

Aarif, K.M., Rubeena, K.A., Nefla, A., Musilova, Z., Musil, P. and Bin Muzaffar, S. (2025). Bio-concentration of hazardous metals in migrant shorebirds in a key conservation reserve and adjoining areas on the west coast of India. Ecotoxicology and Environmental Safety 289, 117690. https://doi.org/10.1016/j.ecoenv.2025.117690

Agnelli, A. and Tortora, P. (2022). The Role of Development Co-operation in Tackling Plastic Pollution: Key Trends, Instruments, and Opportunities to Scale up Action. OECD Environment Working Papers, 207. https://doi.org/10.1787/721355cb-en

Al-Salem, S.M., Uddin, S. and Al-Yamani, F. (2020). An assessment of microplastics threat to the marine environment: A short review in context of the Arabian/Persian Gulf. Marine Environmental Research 159, 104961. https://doi.org/10.1016/j.marenvres.2020.104961.

Alidoost Salimi, P., Creed, J.C., Esch, M.M., Fenner, D., Jaafar, Z., Levesque, J.C. et al. (2021). A review of the diversity and impact of invasive non-native species in tropical marine ecosystems. Marine Biodiversity Records 14(1), 11. https://doi.org/10.1186/s41200-021-00206-8

Alin, S.R., Siedlecki, S.A., Berger, H., Feely, R.A., Waddell, J.E., Carter, B.R. et al. (2023). Evaluating the evolving ocean acidification risk to Dungeness crab. Oceanography 36(2/3), 138-147. https://www.jstor.org/stable/27257892

Alley, K.E., Scambos, T.A. and Alley, R.B. (2023). The role of channelized basal melt in ice-shelf stability: Recent progress and future priorities. Annals of Glaciology, 1-5. https://doi.org/10.1017/aog.2023.5

Amirkolaie, A.K. (2011). Reduction in the environmental impact of waste discharged by fish farms through feed and feeding. Reviews in Aquaculture 3(1), 19-26. https://doi.org/10.1111/j.1753-5131.2010.01040.x

Amon, D.J., Palacios-Abrantes, J., Drazen, J.C., Lily, H., Nathan, N., van der Grient, J.M.A. et al. (2023). Climate change to drive increasing overlap between Pacific tuna fisheries and emerging deep-sea mining industry. npj Ocean Sustainability 2(1), 9. https://doi.org/10.1038/s44183-023-00016-8

Andrade, H., Glüge, J., Herzke, D., Ashta, N.M., Nayagar, S.M. and Scheringer, M. (2021). Oceanic long-range transport of organic additives present in plastic products: an overview. Environmental Sciences Europe 33(1). https://doi.org/10.1186/s12302-021-00522-x

Andradi-Brown, D.A. (2019). Invasive Lionfish (Pterois volitans and P. miles): Distribution, Impact, and Management. In Mesophotic Coral Ecosystems. Loya, Y., Puglise, K.A. and Bridge, T.C.L. (eds.). Cham: Springer International Publishing. 931-941. https://doi.org/10.1007/978-3-319-92735-0_48

Andriamahefazafy, M., Touron-Gardic, G., March, A., Hosch, G., Palomares, M. and Failler, P. (2022). Sustainable development goal 14: To what degree have we achieved the 2020 targets for our oceans? Ocean & Coastal Management 227, 106273. https://doi.org/10.1016/j.ocecoaman.2022.106273

Antão, L.H., Bates, A.E., Blowes, S.A., Waldock, C., Supp, S.R., Magurran, A.E. et al. (2020). Temperature-related biodiversity change across temperate marine and terrestrial systems. Nature Ecology & Evolution 4(7), 927-933. https://doi.org/10.1038/s41559-020-1185-7

Appeltans, W., Ahyong, S.T., Anderson, G., Angel, M.V., Artois, T., Bailly, N. et al. (2012). The magnitude of global marine species diversity. Current biology 22(23), 2189-2202. https://doi.org/10.1016/j.cub.2012.09.036

Atkinson, S., Branson, M., Burdin, A., Boyd, D. and Ylitalo, G.M. (2019). Persistent organic pollutants in killer whales (Orcinus orca) of the Russian Far East. Marine Pollution Bulletin 149, 110593. https://doi.org/10.1016/j.marpolbul.2019.110593

Baag, S. and Mandal, S. (2022). Combined effects of ocean warming and acidification on marine fish and shellfish: A molecule to ecosystem perspective. Science of the Total Environment 802, 149807. https://doi.org/10.1016/j.scitotenv.2021.149807

Baker, E.K., Thygesen, K. and Harris, P.T. (2024). Increase in Oxygen Depletion in the Marine Environment: Drivers and Recommendations. Arendal: GRID-Arendal. https://grid-arendal.herokuapp.com/publications/1034

Baker, J., Bell, M., Jackson, L., Vallis, G., Watson, A. and Wood, R. (2025). Continued Atlantic overturning circulation even under climate extremes. Nature 638(8052), 987-994. https://doi.org/10.1038/s41586-024-08544-0

Baker-Austin, C., Lake, I., Archer, E., Hartnell, R., Trinanes, J. and Martinez-Urtaza, J. (2024). Stemming the rising tide of Vibrio disease. The Lancet Planetary Health 8(7), e515-e520. https://doi.org/10.1016/S2542-5196(24)00124-4

Ballesteros, L.V., Matthews, J.L. and Hoeksema, B.W. (2018). Pollution and coral damage caused by derelict fishing gear on coral reefs around Koh Tao, Gulf of Thailand. Marine Pollution Bulletin 135, 1107-1116. https://doi.org/10.1016/j.marpolbul.2018.08.033

Bardey, D. (2020). Overfishing: pressure on our oceans. Research in Agriculture Livestock and Fisheries. 6 (3), 397-404. https://doi.org/10.3329/ralf.v6i3.44805

Beazley, L., Kenchington, E., Murillo, F.J., Brickman, D., Wang, Z., Davies, A.J. et al. (2021). Climate change winner in the deep sea? Predicting the impacts of climate change on the distribution of the glass sponge Vazella pourtalesii. Marine Ecology Progress Series 657, 1-23. https://doi.org/10.3354/meps13566

Bellard, C., Leclerc, C. and Courchamp, F. (2014). Impact of sea level rise on the 10 insular biodiversity hotspots. Global Ecology and Biogeography 23(2), 203-212. https://doi.org/10.1111/geb.12093

Ben-Yami, M., Morr, A., Bathiany, S. and Boers, N. (2024). Uncertainties too large to predict tipping times of major Earth system components from historical data. Science advances 10(31), eadl4841. https://doi.org/10.1126/sciadv.adl4841

Benedetti, F., Vogt, M., Elizondo, U.H., Righetti, D., Zimmermann, N.E. and Gruber, N. (2021). Major restructuring of marine plankton assemblages under global warming. Nature Communications 12(1), 5226. https://doi.org/10.1038/s41467-021-25385-x

Bennett-Jones, L., Gnanalingam, G., Flack, B., Scott, N., Pritchard, D., Moller, H. et al. (2021). Translocation of black foot pāua (Haliotis iris) in a customary fishery management area: transformation from top-down management to kaitiakitanga (local guardianship) of a cultural keystone. Pacific Conservation Biology 27(4), 402-417. https://doi.org/10.1071/PC20058

Bergland, H., Burlakov, E., Pedersen, P.A. and Wyller, J. (2020). Aquaculture, pollution and fishery-dynamics of marine industrial interactions. Ecological Complexity 43, 100853. https://doi.org/10.1016/j.ecocom.2020.100853

Bertram, C., Quaas, M., Reusch, T.B., Vafeidis, A.T., Wolff, C. and Rickels, W. (2021). The blue carbon wealth of nations. Nature Climate Change 11(8), 704-709. https://doi.org/10.1038/s41558-021-01089-4

Beusen, A.H., Bouwman, A.F., Van Beek, L.P., Mogollón, J.M. and Middelburg, J.J. (2016). Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum. Biogeosciences 13(8), 2441-2451. https://doi.org/10.5194/bg-13-2441-2016

Bhuiyan, M.M.U., Rahman, M., Naher, S., Shahed, Z.H., Ali, M.M. and Islam, A.R.M.T. (2024). Oxygen declination in the coastal ocean over the twenty-first century: Driving forces, trends, and impacts. Case Studies in Chemical and Environmental Engineering 9, 100621. https://doi.org/10.1016/j.cscee.2024.100621

Biskaborn, B.K., Smith, S.L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D.A. et al. (2019). Permafrost is warming at a global scale. Nature Communications 10 (1), 264. https://doi.org/10.1038/s41467-018-08240-4

Bielmyer-Fraser, G.K., Courville, J.M., Ward, A. and Hardie, M.M. (2024). Mercury and Selenium Accumulation in the Tissues of Stranded Bottlenose

Dolphins (Tursiops truncatus) in Northeast Florida, 2013–2021. Animals, 14(11), 1571. https://doi.org/10.3390/ani14111571

Bitterwolf, S.A., Reguero, B.G., Storlazzi, C.D. and Beck, M.W. (2024). Shifting sands: The influence of coral reefs on shoreline erosion from short-term storm protection to long-term disequilibrium. Nature-Based Solutions 6, 100174. https://doi.org/10.1016/j.nbsj.2024.100174

Blanchard, J.L. and Novaglio, C. (2024). Climate change risks to marine ecosystems and fisheries – Projections to 2100 from the Fisheries and Marine Ecosystem Model Intercomparison Project., FAO Fisheries and Aquaculture Technical Paper 707. https://doi.org/10.4060/cd1379en

Boag, T.H., Gearty, W. and Stockey, R.G. (2021). Metabolic trade-offs control biodiversity gradients through geological time. Current Biology 31(13), 2906-2913. e2903. https://doi.org/10.1016/j.cub.2021.04.021

Bokhorst, S., Convey, P. and Aerts, R. (2019). Nitrogen Inputs by Marine Vertebrates Drive Abundance and Richness in Antarctic Terrestrial Ecosystems. Current Biology 29(10), 1721-1727.e1723. https://doi.org/10.1016/j.cub.2019.04.038

Boot, A., von der Heydt, A.S. and Dijkstra, H.A. (2023). Effect of Plankton Composition Shifts in the North Atlantic on Atmospheric pCO_2. Geophysical Research Letters 50(2), e2022GL100230. https://doi.org/10.1029/2022GL100230

Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C. et al. (2017). An assessment of the global impact of 21st century land use change on soil erosion. Nature Communications 8(1), 2013. https://doi.org/10.1038/s41467-017-02142-7

Bosson, J.-B., Huss, M., Cauvy-Fraunié, S., Clément, J.-C., Costes, G., Fischer, M. et al. (2023). Future emergence of new ecosystems caused by glacial retreat. Nature 620(7974), 562-569. https://doi.org/10.1038/s41586-023-06302-2

Bowley, J., Baker-Austin, C., Porter, A., Hartnell, R. and Lewis, C. (2021). Oceanic hitchhikers–assessing pathogen risks from marine microplastic. Trends in Microbiology 29(2), 107-116. https://doi.org/10.1016/j.tim.2020.06.011

Braithwaite, R.A., Carrascosa, M.C.C. and McEvoy, L.A. (2007). Biofouling of salmon cage netting and the efficacy of a typical copper-based antifoulant. Aquaculture 262(2-4), 219-226. https://doi.org/10.1016/j.aquaculture.2006.11.027

Braulik, G.T., Taylor, B.L., Minton, G., Notarbartolo di Sciara, G., Collins, T., Rojas-Bracho, L. et al. (2023). Red-list status and extinction risk of the world's whales, dolphins, and porpoises. Conservation Biology 37(5), e14090. https://doi.org/10.1111/cobi.14090

Brown, K.T., Lenz, E.A., Glass, B.H., Kruse, E., McClintock, R., Drury, C. et al. (2023). Divergent bleaching and recovery trajectories in reef-building corals following a decade of successive marine heatwaves. Proceedings of the National Academy of Sciences of the United States of America 120(52), e2312104120. https://doi.org/10.1073/pnas.2312104120

Burke, L., Reytar, K., Spalding, M. and Perry, A. (2011). Reefs at Risk Revisited. Washington, DC: World Resources Institute. https://www.wri.org/research/reefs-risk-revisited

Buschman, V.Q. (2022). Framing co-productive conservation in partnership with Arctic Indigenous peoples. Conservation Biology 36(6), e13972. https://doi.org/10.1111/cobi.13972

Buschman, V.Q. and Sudlovenick, E. (2023). Indigenous-led conservation in the Arctic supports global conservation practices. Arctic Science 9(3), 714-719. https://doi.org/10.1139/as-2022-0025

Caesar, L., McCarthy, G.D., Thornalley, D.J.R., Cahill, N. and Rahmstorf, S. (2021). Current Atlantic Meridional Overturning Circulation weakest in last millennium. Nature Geoscience 14(3), 118-120. https://doi.org/10.1038/s41561-021-00699-z

Calderan, S.V., Black, A., Branch, T.A., Collins, M.A., Kelly, N., Leaper, R. et al. (2020). South Georgia blue whales five decades after the end of whaling. Endangered Species Research 43, 359-373. https://doi.org/10.3354/esr01077

Caldwell, I.R., Hobbs, J.-P.A., Bowen, B.W., Cowman, P.F., Dibattista, J.D., Whitney, J.L. et al. (2024). Global trends and biases in biodiversity conservation research. Cell Reports Sustainability, 100082. https://doi.org/10.1016/j.crsus.2024.100082

Camacho-Jiménez, L., González-Ruiz, R. and Yepiz-Plascencia, G. (2023). Persistent organic pollutants (POPs) in marine crustaceans: Bioaccumulation, physiological and cellular responses. Marine Environmental Research 192, 106184. https://doi.org/10.1016/j.marenvres.2023.106184

Canadell, J.G., Monteiro, P.M., Costa, M.H., Da Cunha, L.C., Cox, P.M., Eliseev, A.V. et al. (2021). Global carbon and other biogeochemical cycles and feedbacks. IPCC AR6 WGI, final government distribution, chapter 5. https://hal.science/hal-03336145/

Carr, H., Abas, M., Boutahar, L., Caretti, O.N., Chan, W.Y., Chapman, A.S.A. et al. (2020). The Aichi Biodiversity Targets: Achievements for marine conservation and priorities beyond 2020. PeerJ 8(e9743). https://doi.org/10.7717/peerj.9743

Carrer, M., Dibona, R., Prendin, A.L. and Brunetti, M. (2023). Recent waning snowpack in the Alps is unprecedented in the last six centuries. Nature Climate Change 13(2), 155-160. https://doi.org/10.1038/s41558-022-01575-3

Casadevall, M., Rodríguez-Prieto, C., Torres, J., Eira, C., Marengo, M., Lejeune, P. et al. (2021). Editorial: Marine aquaculture impacts on marine biota. Frontiers in Marine Science 8. https://doi.org/10.3389/fmars.2021.615267

Cazenave, A. and Moreira, L. (2022). Contemporary sea-level changes from global to local scales: A review. Proceedings of the Royal Society A 478(2261), 20220049. https://doi.org/10.1098/rspa.2022.0049

Chan, F.T. and Briski, E. (2017). An overview of recent research in marine biological invasions. Marine Biology 164(6), 121. https://doi.org/10.1007/s00227-017-3155-4

Chaudhary, C., Richardson, A.J., Schoeman, D.S. and Costello, M.J. (2021). Global warming is causing a more pronounced dip in marine species richness around the equator. Proceedings of the National Academy of Sciences 118(15), e2015094118. https://doi.org/10.1073/pnas.2015094118

Chislock, M.F., Doster, E., Zitomer, R.A. and Wilson, A.E. (2013). Eutrophication: causes, consequences, and controls in aquatic ecosystems. Nature Education Knowledge 4(4), 10. https://www.wilsonlab.com/wp-content/uploads/2021/05/2013_NE_Chislock_et_al.pdf

Choulot, M., Le Guillard, C., Bourgougnon, N. and Michalak, I. (2022). Seaweed-based fertilizing products. In Algae and Aquatic Macrophytes in Cities. Elsevier. 271-313. https://doi.org/10.1016/B978-0-12-824270-4.00012-2

Choy, C.A., Robison, B.H., Gagne, T.O., Erwin, B., Firl, E., Halden, R.U. et al. (2019). The vertical distribution and biological transport of marine microplastics across the epipelagic and mesopelagic water column. Scientific Reports 9(1), 7843. https://doi.org/10.1038/s41598-019-44117-2

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S., Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan (2013). Sea Level Change. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (ed.). Cambridge, United Kingdom and New York, USA. https://doi.org/10.1017/CBO9781107415324.026

Clapcott, J., Ataria, J., Hepburn, C., Hikuroa, D., Jackson, A.-M., Kirikiri, R. et al. 52 (2018). Mātauranga Māori: Shaping marine and freshwater futures. Taylor & Francis, 457-466. https://doi.org/10.1080/00288330.2018.1539404

Copernicus (2025a). Monthly Climate Bulletin: February 2025: Record Low Global Sea Ice Cover. https://climate.copernicus.eu/february-2025-record-low-global-sea-ice-cover#:~:text=Arctic%20sea%20ice%20saw%20its,February%202024%20and%20February%202016. Accessed 29 March 2025

Copernicus (2025b). Global Ocean Colour (Copernicus-GlobColour), Bio-Geo-Chemical, L4 (monthly and interpolated) from Satellite Observations (Near Real Time). E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS). https://data.marine.copernicus.eu/product/OCEANCOLOUR_GLO_BGC_L4_NRT_009_102/description. Accessed 22 March 2025

Cosby, A.G., Lebakula, V., Smith, C.N., Wanik, D.W., Bergene, K., Rose, A.N. et al. (2024). Accelerating growth of human coastal populations at the global and continent levels: 2000–2018. Scientific Reports 14(1), 22489. https://doi.org/10.1038/s41598-024-73287-x

Costello, M.J. and Chaudhary, C. (2017). Marine biodiversity, biogeography, deep-sea gradients, and conservation. Current Biology 27(11), R511-R527. https://doi.org/10.1016/j.cub.2017.04.060

Crear, D.P., Curtis, T.H., Hutt, C.P. and Lee, Y.-W. (2023). Climate-influenced shifts in a highly migratory species recreational fishery. Fisheries Oceanography 32(4), 327-340. https://doi.org/10.1111/fog.12632

Creel, R.C., Guimond, J., Jones, B., Nielsen, D.M., Bristol, E.M., Tweedie, C.E. et al. (2024). Permafrost thaw subsidence, sea-level rise, and erosion are transforming Alaska's Arctic coastal zone. Proceedings of the National Academy of Sciences of the United States of America 121 (50) e2409411121, https://doi.org/10.1073/pnas.240941112.

Dangendorf, S., Frederikse, T., Chafik, L., Klinck, J.M., Ezer, T. and Hamlington, B.D. (2021). Data-driven reconstruction reveals large-scale ocean circulation control on coastal sea level. Nature Climate Change 11(6), 514-520. https://doi.org/10.1038/s41558-021-01046-1

Dangendorf, S., Sun, Q., Wahl, T., Thompson, P., Mitrovica, J.X. and Hamlington, B. (2024). Probabilistic reconstruction of sea-level changes and their causes since 1900. Earth System Science Data Discussions 2024, 1-37. https://doi.org/10.5194/essd-16-3471-2024

Danovaro, R. (2024). Understanding marine biodiversity patterns and drivers: The fall of Icarus. Marine Ecology, e12814. https://doi.org/10.1111/maec.12814

Daru, B.H. and Rock, B.M. (2023). Reorganization of seagrass communities in a changing climate. Nature Plants, 1-10. https://doi.org/10.1038/s41477-023-01445-6

de Almeida Rodrigues, P., Ferrari, R.G., dos Santos, L.N. and Conte Junior, C.A. (2019). Mercury in aquatic fauna contamination: A systematic review on its dynamics and potential health risks. Journal of Environmental Sciences 84, 205-218. https://doi.org/10.1016/j.jes.2019.02.018

de Amorim, F.d.L.L., Wiltshire, K.H., Lemke, P., Carstens, K., Peters, S., Rick, J. et al. (2023). Investigation of marine temperature changes across temporal and spatial gradients: providing a fundament for studies on the effects of warming on marine ecosystem function and biodiversity. Progress in Oceanography 216, 103080. https://doi.org/10.1016/j.pocean.2023.103080

de Dominicis, M., Wolf, J., van Hespen, R., Zheng, P. and Hu, Z. (2023). Mangrove forests can be an effective coastal defence in the Pearl River Delta, China. Communications Earth & Environment 4(1), 13. https://doi.org/10.1038/s43247-022-00672-7

de Lacerda, L.D., Ward, R.D., Godoy, M.D.P., de Andrade Meireles, A.J., Borges, R. and Ferreira, A.C. (2021). 20-Years Cumulative Impact from Shrimp Farming on Mangroves of Northeast Brazil. Frontiers in Forests and Global Change 4. https://doi.org/10.3389/ffgc.2021.653096

de Souza, J.S., Franco, A.C.S., Tavares, M.R., Guimarães, T.d.F.R. and dos Santos, L.N. (2024). Shipping traffic, salinity and temperature shape non-native fish richness in estuaries worldwide. Science of The Total Environment 908, 168218. https://doi.org/10.1016/j.scitotenv.2023.168218

Deb, J.C. and Bailey, S.A. (2023). Arctic marine ecosystems face increasing climate stress. Environmental Reviews 31(3), 403-451. https://doi.org/10.1139/er-2022-0101

DeConto, R.M., Pollard, D., Alley, R.B., Velicogna, I., Gasson, E., Gomez, N. et al. (2021). The Paris climate agreement and future sea-level rise from Antarctica. Nature 593(7857), 83-89. https://doi.org/10.1038/s41586-021-03427-0

Dehm, J., Singh, A., Le Gendre, R. and Menkes, C. (2024). Suva Urban Reefs: An ecological history of the coral reefs of the Greater Suva Urban Area, Fiji. Regional Studies in Marine Science 80, 103894. https://doi.org/10.1016/j.rsma.2024.103894

del Monte-Luna, P., Nakamura, M., Vicente, A., Pérez-Sosa, L., Yáñez-Arenas, A., Trites, A.W. et al. (2023). A review of recent and future marine extinctions. Cambridge Prisms: Extinction, 1-17. https://doi.org/10.1017/ext.2023.11.

Desforges, J.-P., Ferguson, S.H., Remili, A., McKinney, M.A., Watt, C.A. and Matthews, C.J.D. (2024). Assessment of persistent organic pollutants in killer whales (Orcinus orca) of the Canadian Arctic: Implications for subsistence consumption and conservation strategies. Environmental Research 244, 117992. https://doi.org/10.1016/j.envres.2023.117992

Devlin, M. and Brodie, J. (2023). Nutrients and Eutrophication. In Marine Pollution – Monitoring, Management and Mitigation. Reichelt-Brushett, A. (ed.). Cham: Springer Nature Switzerland. 75-100. https://doi.org/10.1007/978-3-031-10127-4_4

Druckenmiller, M.L., Thoman, R.L., Moon, T.A., Andreassen, L.M., Ballinger, T.J., Berner, L.T. et al. (2024). The arctic. Bulletin of the American Meteorological Society, 105(8), S277-S330. https://doi.org/10.1175/BAMS-D-24-0101.1

Duarte, C., Chapuis, L., Collin, S., Costa, D., Devassy, R., Eguiluz, V. et al. (2021). The soundscape of the Anthropocene ocean. Science 371. https://doi.org/10.1126/science.aba4658

Dulvy, N.K., Pacoureau, N., Matsushiba, J.H., Yan, H.F., VanderWright, W.J., Rigby, C.L. et al. (2024). Ecological erosion and expanding extinction risk of sharks and rays. Science 386(6726), eadn1477. https://doi.org/10.1126/science.adn1477

Dulvy, N.K., Pacoureau, N., Rigby, C.L., Pollom, R.A., Jabado, R.W., Ebert, D.A. et al. (2021). Overfishing drives over one-third of all sharks and rays toward a global extinction crisis. Current biology 31(21), 4773-4787.e4778. https://doi.org/10.1016/j.cub.2021.08.062

Dunic, J.C., Brown, C.J., Connolly, R.M., Turschwell, M.P. and Côté, I.M. (2021). Long-term declines and recovery of meadow area across the world's seagrass bioregions. Global Change Biology 27(17), 4096-4109. https://doi.org/10.1111/gcb.15684

Dussaillant, I., Hugonnet, R., Huss, M., Berthier, E., Bannwart, J., Paul, F. et al. (2024). Annual mass changes for each glacier in the world from 1976 to 2023. Earth System Science Data Discussions 2024, 1-41. https://doi.org/10.5194/essd-2024-323

Eddy, T.D., Lam, V.W., Reygondeau, G., Cisneros-Montemayor, A.M., Greer, K., Palomares, M.L.D. et al. (2021). Global decline in capacity of coral reefs to provide ecosystem services. One Earth 4(9), 1278-1285. https://doi.org/10.1016/j.oneear.2021.08.016

Eigaard, O.R., Bastardie, F., Hintzen, N.T., Buhl-Mortensen, L., Buhl-Mortensen, P., Catarino, R. et al. (2016). The footprint of bottom trawling in European waters: distribution, intensity, and seabed integrity. ICES Journal of Marine Science 74(3), 847-865. https://doi.org/10.1093/icesjms/fsw194

Eriksen, M., Cowger, W., Erdle, L.M., Coffin, S., Villarrubia-Gómez, P., Moore, C.J. et al. (2023). A growing plastic smog, now estimated to be over 170 trillion plastic particles afloat in the world's oceans—Urgent solutions required. Plos one 18(3), e0281596. https://doi.org/10.1371/journal.pone.0281596

Eriksen, M., Lebreton, L.C., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C. et al. (2014). Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. Plos one 9(12), e111913. https://doi.org/10.1371/journal.pone.0111913

Esbaugh, A.J. (2018). Physiological implications of ocean acidification for marine fish: emerging patterns and new insights. Journal of Comparative Physiology B 188(1), 1-13. https://doi.org/10.1007/s00360-017-1105-6

European Commission Joint Research Centre (2020). The Digital Observatory for Protected Areas, Ecoregion Protection Statistics. Commission, E., Ispra, Italy https://dopa.jrc.ec.europa.eu/dopa/ (Accessed March 2020)

European Environment Agency (2013). Balancing the future of Europe's coasts - Knowledge base for integrated management. https://www.eea.europa.eu/publications/balancing-the-future-of-europes

Fagiano, V., Compa, M., Alomar, C. and Deudero, S. (2024). Global Meta-Analysis and Review of Microplastic in Marine Copepods. Environmental Pollution 351, 124092. https://doi.org/10.1016/j.envpol.2024.124092

Fan, H., Huang, M., Chen, Y., Zhou, W., Hu, Y. and Wei, F. (2023). Conservation priorities for global marine biodiversity across multiple dimensions. Natl Sci Rev 10(6), nwac241. https://doi.org/10.1093/nsr/nwac241

Fassbender, A.J., Carter, B.R., Sharp, J.D., Huang, Y., Arroyo, M.C. and Frenzel, H. (2023). Amplified subsurface signals of ocean acidification. Global Biogeochemical Cycles 37(12), e2023GB007843. https://doi.org/10.1029/2023GB007843

Fetterer, F., Knowles, K., Meier, W.N., Savoie, M. and Windnagel, A.K. (2017). Sea Ice Index, 3. Center, National Snow and Ice Data Center, Boulder: CO. https://nsidc.org/data/g02135/versions/3. Accessed 4 February 2023

Figuerola, B., Hancock, A.M., Bax, N., Cummings, V.J., Downey, R., Griffiths, H.J. et al. (2021). A review and meta-analysis of potential impacts of ocean acidification on marine calcifiers from the Southern Ocean. Frontiers in Marine Science 8, 584445. https://doi.org/10.3389/fmars.2021.584445

Filho, L., Abubakar, W.I.R., Nunes, C., Platje, J., Ozuyar, P.G., Will, M. et al. (2021). Deep Seabed Mining: A Note on Some Potentials and Risks to the Sustainable Mineral Extraction from the Oceans. Journal of Marine Science and Engineering 9(5), 521https://www.mdpi.com/2077-1312/9/5/521

Fischer, A., Bhakta, D., Macmillan-Lawler, M. and Harris, P. (2019). Existing global marine protected area network is not representative or comprehensive

measured against seafloor geomorphic features and benthic habitats. Ocean & Coastal Management 167, 176-187. https://doi.org/10.1016/j.ocecoaman.2018.10.001

Food and Agriculture Organization (2016). The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all. Rome. https://doi.org/10.18356/8e4e0ebf-en

Food and Agriculture Organization (2020). The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome. https://doi.org/10.4060/ca9229en

Food and Agriculture Organization (2022). The state of world fisheries and aquaculture 2022. Towards Blue Transformation. Rome. https://doi.org/10.4060/cc0461en

Food and Agriculture Organization (2023). The world's mangroves 2000-2020. Rome. https://doi.org/10.4060/cc7044en

Food and Agriculture Organization (2024). The State of World Fisheries and Aquaculture 2024 – Blue Transformation in action. Rome. https://doi.org/10.4060/cd0683en

Food and Agriculture Organization, Duke University and WorldFish (2023). Illuminating Hidden Harvests–The contributions of small-scale fisheries to sustainable development. Franz, N., Smith, S., Gutiérrez, N., Vannuccini, S., Westlund, L., Basurto, X. et al. (eds.). Rome, Italy. https://doi.org/10.4060/cc4576en

Fortuna, C.M., Fortibuoni, T., Bueno-Pardo, J., Coll, M., Franco, A., Giménez, J. et al. (2024). Top predator status and trends: ecological implications, monitoring and mitigation strategies to promote ecosystem-based management. Frontiers in Marine Science 11. https://doi.org/10.3389/fmars.2024.1282091

Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, (2021). Ocean, Cryosphere and Sea Level Change. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (ed.). Cambridge, United Kingdom and New York, USA

Frajka-Williams, E., Foukal, N. and Danabasoglu, G. (2023). Should AMOC observations continue: how and why? Philosophical Transactions of the Royal Society A 381(2262), 20220195. https://doi.org/10.1098/rsta.2022.0195

Fredston-Hermann, A., Brown, C.J., Albert, S., Klein, C.J., Mangubhai, S., Nelson, J.L. et al. (2016). Where does river runoff matter for coastal marine conservation? Frontiers in Marine Science 3, 273. https://doi.org/10.3389/fmars.2016.00273

Free, C.M., Thorson, J.T., Pinsky, M.L., Oken, K.L., Wiedenmann, J. and Jensen, O.P. (2019). Impacts of historical warming on marine fisheries production. Science 363(6430), 979-983. https://doi.org/10.1126/science.aau1758

Friedlingstein, P., O'sullivan, M., Jones, M.W., Andrew, R.M., Gregor, L., Hauck, J. et al. (2022). Global carbon budget 2022. Earth system science data 14(11), 4811-4900. https://doi.org/10.5194/essd-14-4811-2022

Fürst, J.J., Durand, G., Gillet-Chaulet, F., Tavard, L., Rankl, M., Braun, M. et al. (2016). The safety band of Antarctic ice shelves. Nature Climate Change 6(5), 479-482. https://doi.org/10.1038/nclimate2912

Gall, S.C. and Thompson, R.C. (2015). The impact of debris on marine life. Marine Pollution Bulletin 92(1), 170-179. https://doi.org/10.1016/j.marpolbul.2014.12.041

Garavelli, L., Copping, A. E., Hemery, L. G., Freeman M. C., (eds.) (2024). OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). https://tethys.pnnl.gov/sites/default/files/publications/OES-Environmental-2024-State-of-the-Science-Report_1_0.pdf

Great Barrier Reef Marine Park Authority (2022). Synopsis of the 2022 mass bleaching event. https://www2.gbrmpa.gov.au/learn/reef-health/past-reef-health-updates. Accessed: 7 February 2024

Grix, N., Burger, F.A. and Frölicher, T.L. (2025). Surface and subsurface compound marine heatwave and biogeochemical extremes under Climate change. Global Biogeochemical Cycles, 39(5), 2025GB008514. https://doi.org/10.1029/2025GB008514

Gruber, N., Bakker, D.C., DeVries, T., Gregor, L., Hauck, J., Landschützer, P. et al. (2023). Trends and variability in the ocean carbon sink. Nature Reviews Earth & Environment 4(2), 119-134. https://doi.org/10.1038/s43017-022-00381-x

Guérou, A., Meyssignac, B., Prandi, P., Ablain, M., Ribes, A. and Bignalet-Cazalet, F. (2023). Current observed global mean sea level rise and acceleration estimated from satellite altimetry and the associated measurement uncertainty. Ocean Science 19(2), 431-451. https://doi.org/10.5194/os-19-431-2023

Gulev, S.K., P.W. Thorne, J. Ahn, F.J. Dentener, C.M. Domingues, S. Gerland, D. Gong, D.S. Kaufman, H.C. Nnamchi, J. Quaas, J.A. Rivera, S. Sathyendranath, S.L. Smith, B. Trewin, K. von Schuckmann, and R.S. Vose (2021). Changing State of the Climate System. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (ed.). Chapter 2. Cambridge. https://www.ipcc.ch/report/ar6/wg1/

Haas, B. (2023). Achieving SDG 14 in an equitable and just way. International Environmental Agreements: Politics, Law and Economics, 1-7. https://doi.org/10.1007/s10784-023-09603-z

Halpern, B.S., Frazier, M., Afflerbach, J., Lowndes, J.S., Micheli, F., O'Hara, C. et al. (2019). Recent pace of change in human impact on the world's ocean. Scientific Reports 9(1), 11609. https://doi.org/10.1038/s41598-019-47201-9

Hamlington, B.D., Gardner, A.S., Ivins, E., Lenaerts, J.T., Reager, J., Trossman, D.S. et al. (2020). Understanding of contemporary regional sea-level change and the implications for the future. Reviews of Geophysics 58(3), e2019RG000672. https://doi.org/10.1029/2019RG000672

Hampton, S.E., Powers, S.M., Dugan, H.A., Knoll, L.B., McMeans, B.C., Meyer, M.F. et al. (2024). Environmental and societal consequences of winter ice loss from lakes. Science 386(6718), eadl3211. https://doi.org/10.1126/science.adl3211

Hanna, E., Topál, D., Box, J.E., Buzzard, S., Christie, F.D., Hvidberg, C. et al. (2024). Short-and long-term variability of the Antarctic and Greenland ice sheets. Nature Reviews Earth & Environment 5(3), 193-210. https://doi.org/10.1038/s43017-023-00509-7

Harden-Davies, H., Lopes, V.F., Coelho, L.F., Nelson, G., Veiga, J.S., Talma, S. et al. (2024). First to finish, what comes next? Putting Capacity Building and the Transfer of Marine Technology under the BBNJ Agreement into practice. npj Ocean Sustainability 3(1), 3. https://doi.org/10.1038/s44183-023-00039-1

Harris, P.T., Westerveld, L., Nyberg, B., Maes, T., Macmillan-Lawler, M. and Appelquist, L.R. (2021). Exposure of coastal environments to river-sourced plastic pollution. Science of the Total Environment 769, 145222. https://doi.org/10.1016/j.scitotenv.2021.145222

Harris, R.M., Beaumont, L.J., Vance, T.R., Tozer, C.R., Remenyi, T.A., Perkins-Kirkpatrick, S.E. et al. (2018). Biological responses to the press and pulse of climate trends and extreme events. Nature Climate Change 8(7), 579-587. https://doi.org/10.1038/s41558-018-0187-9

Harvey, M., Barrett, L.T., Morris, R.L., Swearer, S.E. and Dempster, T. (2024). Ocean sprawl: The global footprint of shellfish and algae aquaculture and its implications for production, environmental impact, and biosecurity. Aquaculture 586, 740747. https://doi.org/10.1016/j.aquaculture.2024.740747

Hendrix, H. and Pérez-Espona, S. (2024). A Systematic Review of Population Monitoring Studies of Sea Turtles and Its Application to Conservation. Diversity 16(3), 177. https://doi.org/10.3390/d16030177

Herbert-Read, J.E., Thornton, A., Amon, D.J., Birchenough, S.N.R., Côté, I.M., Dias, M.P. et al. (2022). A global horizon scan of issues impacting marine and coastal biodiversity conservation. Nature Ecology & Evolution 6(9), 1262-1270. https://doi.org/10.1038/s41559-022-01812-0

Hewitt, H., Fox-Kemper, B., Pearson, B., Roberts, M. and Klocke, D. (2022). The small scales of the ocean may hold the key to surprises. Nature Climate Change 12(6), 496-499. https://doi.org/10.1038/s41558-022-01386-6

Hobday, A.J., Burrows, M.T., Filbee-Dexter, K., Holbrook, N.J., Sen Gupta, A., Smale, D.A. et al. (2023). With the arrival of El Niño, prepare for stronger marine heatwaves. Nature 621(7977), 38-41. https://go.nature.com/45UXWBP

Hodson, A., Nowak, A., Sabacka, M., Jungblut, A., Navarro, F., Pearce, D. et al. (2017). Climatically sensitive transfer of iron to maritime Antarctic ecosystems by surface runoff. Nature Communications 8(1), 14499. https://doi.org/10.1038/ncomms14499

Hugelius, G., Ramage, J.L., Burke, E.J., Chatterjee, A., Smallman, T.L., Aalto, T. et al. (2023). Two decades of permafrost region CO2, CH4, and N2O budgets suggest a small net greenhouse gas source to the atmosphere. Authorea Preprints. https://10.22541/essoar.169444320.01914726/v1

Hughes, A.C. and Grumbine, R.E. (2023). The Kunming-Montreal Global Biodiversity Framework: what it does and does not do, and how to improve it. Frontiers in Environmental Science 11. https://doi.org/10.3389/fenvs.2023.1281536

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L. et al. (2021). Accelerated global glacier mass loss in the early twenty-first century. Nature 592(7856), 726-731. https://doi.org/10.1038/s41586-021-03436-z

Hyer, K.E., Phillips, S.W., Ator, S.W., Moyer, D.L., Webber, J.S., Felver, R., , Keisman, J.L., McDonnell, L.A., Murphy, R., Trentacoste, E.M., Zhang, Q., and Dennison, W.C., Swanson, S., Walsh, B., Hawkey, J., and Taillie, D. (2021). Nutrient trends and drivers in the Chesapeake Bay Watershed: US Geological Survey Fact Sheet 2020-3069. https://doi.org/10.3133/fs20203069

Hyndes, G.A., Heck, K.L.J., Vergés, A., Harvey, E.S., Kendrick, G.A., Lavery, P.S. et al. (2016). Accelerating Tropicalization and the Transformation of Temperate Seagrass Meadows. BioScience 66(11), 938-948. https://doi.org/10.1093/biosci/biw111

International Maritime Organization (2023a). 2023 IMO Strategy on Reduction of GHG Emissions from Ships. https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx

International Maritime Organization (2023b). IMO's work to cut GHG emissions from ships. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx

International Renewable Energy Agency (2020). Renewable capacity statistics 2020. Abu Dhabi. http://www.irena.org/Publications

International Seabed Authority (2022). The Mining Code. https://www.isa.org.jm/the-mining-code/standards-and-guidelines/

International Seabed Authority (2023). Decision of the Council of the International Seabed Authority on a timeline following the expiration of the two-year period pursuant to section 1, paragraph 15, of the annex to the Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea. https://www.isa.org.jm/wp-content/uploads/2023/07/2314552E.pdf

International Union for Conservation of Nature (2022). Issues Brief: Post-2020 Global Biodiversity Framework. https://www.iucn.org/resources/issues-brief/post-2020-global-biodiversity-framework. Accessed: 12 September 2023

IOC-UNESCO (2022). State of the Ocean Report, Pilot Edition. United Nations Educational, Scientific and Cultural Organization: Paris. https://unesdoc.unesco.org/ark:/48223/pf0000381921

IOC-UNESCO (2024). State of the Ocean Report 2024. United Nations Educational, Scientific and Cultural Organization: Paris. https://unesdoc.unesco.org/ark:/48223/pf0000390054.locale=en

Intergovernmental Panel on Climate Change (2018). Global warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D. C., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, Y., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M. & Waterfield, T. (ed.). Cambridge. https://www.ipcc.ch/sr15/

Intergovernmental Panel on Climate Change (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Pörtner, H.-O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B. & Weyer, N. M. (eds.). Cambridge. https://www.ipcc.ch/srocc/

Intergovernmental Panel on Climate Change (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (eds.)

Intergovernmental Panel on Climate Change (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Pörtner, H.-O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A. & Rama, B. (eds.). Cambridge. https://www.ipcc.ch/report/ar6/wg2/

Intergovernmental Panel on Climate Change (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva. https://doi.org/10.59327/IPCC/AR6-9789291691647

Isobe, A. and Iwasaki, S. (2022). The fate of missing ocean plastics: Are they just a marine environmental problem? Science of the Total Environment 825, 153935. https://doi.org/10.1016/j.scitotenv.2022.153935

ITOPF (2024). Oil Tanker Spill Statistics 2023. London. https://www.itopf.org/fileadmin/uploads/itopf/data/Documents/Company_Lit/Oil_Tanker_Spill_Statistics_2023

Iudicone, D., Rodgers, K.B., Plancherel, Y., Aumont, O., Ito, T., Key, R.M. et al. (2016). The formation of the ocean's anthropogenic carbon reservoir. Scientific Reports 6(1), 35473. https://doi.org/10.1038/srep35473

Jackson, J.B.C., Kirby, M.X., Berger, W.H., Bjorndal, K.A., Botsford, L.W., Bourque, B.J. et al. (2001). Historical Overfishing and the recent collapse of coastal ecosystems. Science 293(5530), 629-637. https://doi.org/10.1126/science.1059199

Jackson, L.C., Hewitt, H.T., Bruciaferri, D., Calvert, D., Graham, T., Guiavarc'h, C. et al. (2023). Challenges simulating the AMOC in climate models. Philosophical Transactions of the Royal Society A 381(2262), 20220187. https://doi.org/10.1098/rsta.2022.0187

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A. et al. (2015). Plastic waste inputs from land into the ocean. Science 347(6223), 768-771. https://doi.org/10.1126/science.1260352

Jepsen, E.M. and de Bruyn, P.N. (2019). Pinniped entanglement in oceanic plastic pollution: A global review. Marine Pollution Bulletin 145, 295-305. https://doi.org/10.1016/j.marpolbul.2019.05.042

Jernelöv, A. (2010). The threats from oil spills: now, then, and in the future. Ambio 39(5-6), 353-366. https://doi.org/10.1007%2Fs13280-010-0085-5

Jevrejeva, S., Williams, J., Vousdoukas, M.I. and Jackson, L.P. (2023). Future sea level rise dominates changes in worst case extreme sea levels along the global coastline by 2100. Environmental Research Letters 18(2), 024037. https://doi.org/10.1088/1748-9326/acb504

Jiang, L.q., Dunne, J., Carter, B.R., Tjiputra, J.F., Terhaar, J., Sharp, J.D. et al. (2023). Global surface ocean acidification indicators from 1750 to 2100. Journal of Advances in Modelling Earth Systems 15(3), e2022MS003563. https://doi.org/10.1029/2022MS003563

Jiang, Y., Zhao, W., Zhu, Y., Ma, S., Li, M., Zhang, S. et al. (2025). An innovative approach for marine macro-organism monitoring: methodology and future perspectives of environmental DNA (eDNA) technology. Marine Biology 172(3), 52. https://doi.org/10.1007/s00227-025-04609-4

Jiménez, S., Domingo, A., Brazeiro, A., Defeo, O. and Phillips, R.A. (2015). Marine debris ingestion by albatrosses in the southwest Atlantic Ocean. Marine Pollution Bulletin 96(1), 149-154. https://doi.org/10.1016/j.marpolbul.2015.05.034

Joerss, H., Xie, Z., Wagner, C.C., Von Appen, W.-J., Sunderland, E.M. and Ebinghaus, R. (2020). Transport of legacy perfluoroalkyl substances and the replacement compound HFPO-DA through the Atlantic Gateway to the Arctic Ocean—is the Arctic a sink or a source? Environmental Science & Technology 54(16), 9958-9967. https://doi.org/10.1021/acs.est.0c00228

Joint Group of Experts on the Scientific Experts of Marine Environmental Protection (GESAMP) (2015). Sources, Fate and Effects of Microplastics in the Marine Environment: A global Assessment. Kershaw, P.J. (ed.) London. http://www.gesamp.org/publications/reports-and-studies-no-90

Jones, K.R., Klein, C.J., Halpern, B.S., Venter, O., Grantham, H., Kuempel, C.D. et al. (2018). The location and protection status of earth's diminishing marine wilderness. Current biology 28(15), 2506-2512.e2503. https://doi.org/10.1016/j.cub.2018.06.010

Justine, Y.E.D. and Seenath, A. (2025). Vegetative nature-based solutions for coastal flood risk management: Benefits, challenges, and uncertainties. Ocean & Coastal Management 261, 107520. https://doi.org/10.1016/j.ocecoaman.2024.107520

Kaiser, M.J. and Snyder, B. (2010). Offshore Wind Energy Installation and Decommissioning Cost Estimation in the US Outer Continental Shelf. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Regulation and

Enforcement, Herndon, VA. https://www.bsee.gov/sites/bsee.gov/files/tap-technical-assessment-program/648aa.pdf

Katona, S., Paulikas, D., Ali, S., Clarke, M., Ilves, E., Lovejoy, T.E. et al. (2023). Land and deep-sea mining: the challenges of comparing biodiversity impacts. Biodiversity and Conservation 32(4), 1125-1164. https://doi.org/10.1007/s10531-023-02558-2

Katsanevakis, S., Coll, M., Piroddi, C., Steenbeek, J., Ben Rais Lasram, F., Zenetos, A. et al. (2014). Invading the Mediterranean Sea: Biodiversity patterns shaped by human activities. Frontiers in Marine Science 1, 32. https://doi.org/10.3389/fmars.2014.00032

Kleitou, P., Crocetta, F., Giakoumi, S., Giovos, I., Hall-Spencer, J.M., Kalogirou, S. et al. (2021). Fishery reforms for the management of non-indigenous species. Journal of Environmental Management 280, 111690. https://doi.org/10.1016/j.jenvman.2020.111690

Kuempel, C.D., Jones, K.R., Watson, J.E. and Possingham, H.P. (2019). Quantifying biases in marine-protected-area placement relative to abatable threats. Conservation Biology 33(6), 1350-1359. https://doi.org/10.1111/cobi.13340

Kuliński, K., Rehder, G., Asmala, E., Bartosova, A., Carstensen, J., Gustafsson, B. et al. (2022). Biogeochemical functioning of the Baltic Sea. Earth Systems Dynamics 13(1), 633-685. https://doi.org/10.5194/esd-13-633-2022

Kulp, S.A. and Strauss, B.H. (2019). New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nature Communications 10(1), 1-12. https://doi.org/10.1038/s41467-019-12808-z

Kumar, B., Singh, S.K., Mishra, M., Kumar, S. and Sharma, C.S. (2012). Assessment of polychlorinated biphenyls and organochlorine pesticides in water samples from the Yamuna River. Journal of Xenobiotics 2(1), e6. https://doi.org/10.4081/xeno.2012.e6

Kwiatkowski, L., Torres, O., Bopp, L., Aumont, O., Chamberlain, M., Christian, J.R. et al. (2020). Twenty-first century ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production decline from CMIP6 model projections. Biogeosciences 17(13), 3439-3470. https://doi.org/10.5194/bg-17-3439-2020

Lannuzel, D., Tedesco, L., Van Leeuwe, M., Campbell, K., Flores, H., Delille, B. et al. (2020). The future of Arctic sea-ice biogeochemistry and ice-associated ecosystems. Nature Climate Change 10(11), 983-992. https://doi.org/10.1038/s41558-020-00940-4

Larsen, M. and Hjermann, D. (2022). Status and Trend for Heavy Metals (Mercury, Cadmium and Lead) in Fish, Shellfish and Sediment. In OSPAR, 2023: The 2023 Quality Status Report for the Northeast Atlantic. OSPAR Commission, London. https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/indicator-assessments/heavy-metals-biota-sediment

Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R. et al. (2018). Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. Scientific Reports 8(1), 1-15. https://doi.org/10.1371/journal.pone.0281596

Lee, Y.-C., Liu, W., Fedorov, A.V., Feldl, N. and Taylor, P.C. (2024). Impacts of Atlantic meridional overturning circulation weakening on Arctic amplification. Proceedings of the National Academy of Sciences 121(39), e2402322121. https://doi.org/10.1073/pnas.2402322121

Lehmann-Konera, S., Ruman, M., Franczak, Ł. and Polkowska, Ż. (2020). Contamination of arctic lakes with persistent toxic PAH substances in the NW part of Wedel Jarlsberg Land (Bellsund, Svalbard). Water 12(2), 411. https://doi.org/10.3390/w12020411

Levitan, D.R., Best, R.M. and Edmunds, P.J. (2023). Sea urchin mass mortalities 40 y apart further threaten Caribbean coral reefs. Proceedings of the National Academy of Sciences 120(10), e2218901120. https://doi.org/10.1073/pnas.2218901120

Lewis, S., Bainbridge, Z. and Smithers, S. (2024). Question 2.3 What evidence is there for changes in land-based runoff from pre-development estimates in the Great Barrier Reef. In 2022, the Scientific Consensus Statement on land-based impacts on Great Barrier Reef water quality and ecosystem condition. Waterhouse J, Pineda M-C, Sambrook K., (eds.) Commonwealth of Australia and Queensland Government. https://reefwqconsensus.com.au/wp-content/uploads/2024/06/2022-SCS-Q2.3_Evidence-Summary_Final.pdf

Lewison, R.L., Crowder, L.B., Wallace, B.P., Moore, J.E., Cox, T., Zydelis, R. et al. (2014). Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. Proceedings of the National Academy of Sciences 111(14), 5271-5276. https://doi.org/10.1073/pnas.1318960111

Lim, M., Whalen, D., Martin, J., Mann, P., Hayes, S., Fraser, P. et al. (2020). Massive ice control on permafrost coast erosion and sensitivity. Geophysical Research Letters 47(17), e2020GL087917. https://doi.org/10.1029/2020GL087917

Limburg, K.E., Breitburg, D., Swaney, D.P. and Jacinto, G. (2020). Ocean deoxygenation: a primer. One Earth 2(1), 24-29. https://doi.org/10.1016/j.oneear.2020.01.001

Lincoln, S., Andrews, B., Birchenough, S.N.R., Chowdhury, P., Engelhard, G.H., Harrod, O. et al. (2022). Marine litter and climate change: Inextricably connected threats to the world's oceans. Science of the Total Environment 837, 155709. https://doi.org/10.1016/j.scitotenv.2022.155709

Loch, T.K. and Riechers, M. (2021). Integrating indigenous and local knowledge in management and research on coastal ecosystems in the Global South: A literature review. Ocean & Coastal Management 212, 105821. https://doi.org/10.1016/j.ocecoaman.2021.105821

Loiseau, N., Mouillot, D., Velez, L., Seguin, R., Casajus, N., Coux, C. et al. (2024). Inferring the extinction risk of marine fish to inform global conservation priorities. PLOS Biology 22(8), e3002773. https://doi.org/10.1371/journal.pbio.3002773

López-Martínez, S., Morales-Caselles, C., Kadar, J. and Rivas, M.L. (2021). Overview of global status of plastic presence in marine vertebrates. Global Change Biology 27(4), 728-737. https://doi.org/10.1111/gcb.15416

Lotze, H.K., Tittensor, D.P., Bryndum-Buchholz, A., Eddy, T.D., Cheung, W.W., Galbraith, E.D. et al. (2019). Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. Proceedings of the National Academy of Sciences 116(26), 12907-12912. https://doi.org/10.1073/pnas.1900194116

Lusher, A.L., McHugh, M. and Thompson, R.C. (2013). Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. Marine Pollution Bulletin 67(1), 94-99. https://doi.org/10.1016/j.marpolbul.2012.11.028

Mack, M.R., Langley, J.A., Feller, I.C. and Chapman, S.K. (2024). The ecological consequences of nutrient enrichment in mangroves. Estuarine, Coastal and Shelf Science 300, 108690. https://doi.org/10.1016/j.ecss.2024.108690

Macreadie, P.I., Anton, A., Raven, J.A., Beaumont, N., Connolly, R.M., Friess, D.A. et al. (2019). The future of Blue Carbon science. Nature Communications 10(1). https://doi.org/10.1038/s41467-019-11693-w

Maggi, F., Tang, F.H. and Tubiello, F.N. (2023). Agricultural pesticide land budget and river discharge to oceans. Nature 620(7976), 1013-1017. https://doi.org/10.1038/s41586-023-06296-x

Maghsodian, Z., Sanati, A.M., Ramavandi, B., Ghasemi, A. and Sorial, G.A. (2021). Microplastics accumulation in sediments and Periophthalmus waltoni fish, mangrove forests in southern Iran. Chemosphere 264, 128543. https://doi.org/10.1016/j.chemosphere.2020.128543

Magris, R.A. and Ban, N.C. (2019). A meta-analysis reveals global patterns of sediment effects on marine biodiversity. Global Ecology and Biogeography 28(12), 1879-1898. https://doi.org/10.1111/geb.12990

Malone, T.C. and Newton, A. (2020). The Globalization of Cultural Eutrophication in the Coastal Ocean: Causes and Consequences. Frontiers in Marine Science 7. https://doi.org/10.3389/fmars.2020.00670

Mardones, J.I., Paredes-Mella, J., Flores-Leñero, A., Yarimizu, K., Godoy, M., Artal, O. et al. (2023). Extreme harmful algal blooms, climate change, and potential risk of eutrophication in Patagonian fjords: Insights from an exceptional Heterosigma akashiwo fish-killing event. Progress in Oceanography 210, 102921. https://doi.org/10.1016/j.pocean.2022.102921

Marine Conservation Institute (2023). Marine protection atlas - Global marine fishing protection. https://mpatlas.org/zones/ Accessed 16 January 2024

Martin, C., Almahasheer, H. and Duarte, C.M. (2019). Mangrove forests as traps for marine litter. Environmental Pollution 247, 499-508. https://doi.org/10.1016/j.envpol.2019.01.067

Martins, I., Guerra, A., Azevedo, A., Harasse, O., Colaço, A., Xavier, J. et al. (2023). A modelling framework to assess multiple metals impacts on marine food webs: Relevance for assessing the ecological implications of deep-sea mining based on a systematic review. Marine Pollution Bulletin 191, 114902. https://doi.org/10.1016/j.marpolbul.2023.114902

Marzeion, B., Cogley, J.G., Richter, K. and Parkes, D. (2014). Attribution of global glacier mass loss to anthropogenic and natural causes. Science 345(6199), 919-921. https://doi.org/10.1126/science.1254702

Mayer-Pinto, M., Ledet, J., Crowe, T.P. and Johnston, E.L. (2020). Sublethal effects of contaminants on marine habitat-forming species: a review and meta-analysis. Biological Reviews 95(6), 1554-1573. https://doi.org/10.1111/brv.12630

McArthur, J.W. and Rasmussen, K. (2019). Classifying Sustainable Development Goal trajectories: A country-level methodology for identifying which issues and people are getting left behind. World Development 123, 104608. https://doi.org/10.1016/j.worlddev.2019.06.031

Menary, M.B., Robson, J., Allan, R.P., Booth, B.B.B., Cassou, C., Gastineau, G. et al. (2020). Aerosol-Forced AMOC Changes in CMIP6 Historical Simulations. Geophysical Research Letters 47(14), e2020GL088166. https://doi.org/10.1029/2020GL088166

Menegotto, A. and Rangel, T.F. (2018). Mapping knowledge gaps in marine diversity reveals a latitudinal gradient of missing species richness. Nature Communications 9(1). https://doi.org/10.1038/s41467-018-07217-7

Menon, S., Soberón, J., Li, X. and Peterson, A.T. (2010). Preliminary global assessment of terrestrial biodiversity consequences of sea-level rise mediated by climate change. Biodiversity and Conservation 19(6), 1599-1609. https://doi.org/10.1007/s10531-010-9790-4

Merchant, C.J., Allan, R.P. and Embury, O. (2025). Quantifying the acceleration of multidecadal global sea surface warming driven by Earth's energy imbalance. Environmental Research Letters 20(2), 024037. https://doi.org/10.1088/1748-9326/adaa8a

Metcalf, R., Oliver, D.M., Moresco, V. and Quilliam, R.S. (2022). Quantifying the importance of plastic pollution for the dissemination of human pathogens: The challenges of choosing an appropriate 'control' material. Science of the Total Environment 810, 152292. https://doi.org/10.1016/j.scitotenv.2021.152292

Mezzelani, M. and Regoli, F. (2022). The Biological Effects of Pharmaceuticals in the Marine Environment. Annual Review of Marine Science 14, 105-128. https://doi.org/10.1146/annurev-marine-040821-075606

Micella, I., Kroeze, C., Bak, M.P. and Strokal, M. (2024). Causes of coastal waters pollution with nutrients, chemicals and plastics worldwide. Marine Pollution Bulletin 198, 115902. https://doi.org/10.1016/j.marpolbul.2023.115902

Middel, H. and Verones, F. (2017). Making Marine Noise Pollution Impacts Heard: The Case of Cetaceans in the North Sea within Life Cycle Impact Assessment. Sustainability 9(7), 1138. https://doi.org/10.3390/su9071138

Miesner, F., Overduin, P.P., Grosse, G., Strauss, J., Langer, M., Westermann, S. et al. (2023). Subsea permafrost organic carbon stocks are large and of dominantly low reactivity. Scientific Reports 13(1), 9425. https://doi.org/10.1038/s41598-023-36471-z

Milić, N., Milanović, M., Radonić, J., Turk Sekulić, M., Mandić, A., Orčić, D. et al. (2018). The occurrence of selected xenobiotics in the Danube River via LC-MS/MS. Environmental Science and Pollution Research 25, 11074-11083. https://doi.org/10.1007/s11356-018-1401-z

Moresco, V., Charatzidou, A., Oliver, D.M., Weidmann, M., Matallana-Surget, S. and Quilliam, R.S. (2022). Binding, recovery, and infectiousness of enveloped and non-enveloped viruses associated with plastic pollution in surface water. Environmental Pollution 308, 119594. https://doi.org/10.1016/j.envpol.2022.119594

Morley, S.A., Souster, T.A., Vause, B.J., Gerrish, L., Peck, L.S. and Barnes, D.K. (2022). Benthic biodiversity, carbon storage and the potential for increasing negative feedbacks on climate change in shallow waters of the Antarctic Peninsula. Biology 11(2), 320. https://doi.org/10.3390/biology11020320

Muir, D. and Miaz, L.T. (2021). Spatial and temporal trends of perfluoroalkyl substances in global ocean and coastal waters. Environmental Science & Technology 55(14), 9527-9537. https://doi.org/10.1021/acs.est.0c08035

Mustajoki, J., Borchardt, S., Büttner, L., Köhler, B., Lepenies, R., Lyytimäki, J. et al. (2022). Ambitiousness of Sustainable Development Goal (SDG) targets: classification and implications for policy making. Discover Sustainability 3(1), 36. https://doi.org/10.1007/s43621-022-00104-8

Nagula, K., Sati, H., Trivedi, N. and Reddy, C.R.K. (2022). Biofuels and bioproducts from seaweeds. In Advanced Biofuel Technologies. Tuli, D., Kasture, S. and Kuila, A. (eds.). Elsevier. Chapter 17. 431-455. https://www.sciencedirect.com/science/article/pii/B978032388427300012X

National Aeronautics and Space Administration (2024). Sea Level: Satellite Data 1993 - Present. https://climate.nasa.gov/vital-signs/sea-level/?intent=121

National Academies of Sciences, Engineering, and Medicine; Health and Medicine Division; Division on Earth and Life Studies; Board on Health Sciences Policy; Board on Environmental Studies and Toxicology; Ocean Studies Board; Committee on Environmental Impact of Currently Marketed Sunscreens and Potential Human Impacts of Changes in Sunscreen Usage (2022). Review of Fate, Exposure, and Effects of Sunscreens in Aquatic Environments and Implications for Sunscreen Usage and Human Health. Washington (DC): National Academies Press. https://pubmed.ncbi.nlm.nih.gov/36479751/

National Snow and Ice Data Center (2024). The new abnormal. https://nsidc.org/sea-ice-today/analyses/new-abnormal

Navarrete-Fernández, T., Bermejo, R., Hernández, I., Deidun, A., Andreu-Cazenave, M. and Cózar, A. (2022). The role of seagrass meadows in the coastal trapping of litter. Marine Pollution Bulletin 174, 113299. https://doi.org/10.1016/j.marpolbul.2021.113299

Newton, A.M. and Mullan, D.J. (2021). Climate change and Northern Hemisphere Lake and river ice phenology from 1931–2005. The Cryosphere 15(5), 2211-2234. https://doi.org/10.5194/tc-15-2211-2021

Nguyen, H.M., Kim, M., Ralph, P.J., Marín-Guirao, L., Pernice, M. and Procaccini, G. (2020). Stress Memory in Seagrasses: First Insight Into the Effects of Thermal Priming and the Role of Epigenetic Modifications. Frontiers in Plant Science 11. https://doi.org/10.3389/fpls.2020.00494

Nielsen, D.M., Chegini, F., Maerz, J., Brune, S., Mathis, M., Dobrynin, M. et al. (2024). Reduced Arctic Ocean CO2 uptake due to coastal permafrost erosion. Nature Climate Change, 1-8. https://doi.org/10.1038/s41558-024-02074-3

Nikolaou, A. and Katsanevakis, S. (2023). Marine extinctions and their drivers. Regional environmental change 23(3), 88. https://doi.org/10.1007/s10113-023-02081-8

Nitzbon, J., Krinner, G., Schneider von Deimling, T., Werner, M. and Langer, M. (2023). First quantification of the permafrost heat sink in the Earth's climate system. Geophysical Research Letters 50(12), e2022GL102053. https://doi.org/10.1029/2022GL102053

National Oceanic and Atmospheric Agency (2023). Aquaculture. https://www.fisheries.noaa.gov/topic/aquaculture

National Oceanic and Atmospheric Agency (2025). Annual 2024 Global Climate Report. https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202413

New Zealand, Ministry for the Environment and Stats NZ (2022). New Zealand's Reporting Series: Environment Aotearoa 2022. https://environment.govt.nz/assets/publications/Environmental-Reporting/environment-aotearoa-2022.pdf

O'Boyle, S. (2020). Oxygen depletion in coastal waters and the open ocean. In Coastal and Deep Ocean Pollution. https://doi.org/10.1201/b22488-3

Occhipinti-Ambrogi, A. (2021). Bio pollution by invasive marine non-indigenous species: a review of potential adverse ecological effects in a changing climate. International Journal of Environmental Research and Public Health 18(8), 4268. https://doi.org/10.3390/ijerph18084268

OECD-FAO (2021). OECD-FAO Agricultural Outlook 2021-2030. Paris. https://doi.org/10.1787/19428846-en

Olenin, S., Elliott, M., Minchin, D. and Katsanevakis, S. (2024). Marine ecosystem health and biological pollution: Reconsidering the paradigm. Marine Pollution Bulletin 200, 116054. https://doi.org/10.1016/j.marpolbul.2024.116054

Omeyer, L.C.M., Duncan, E.M., Abreo, N.A.S., Acebes, J.M.V., AngSinco-Jimenez, L.A., Anuar, S.T. et al. (2023). Interactions between marine megafauna and plastic pollution in Southeast Asia. Science of the Total Environment 874, 162502. https://doi.org/10.1016/j.scitotenv.2023.162502

Ondiviela, B., Losada, I.J., Lara, J.L., Maza, M., Galván, C., Bouma, T.J. et al. (2014). The role of seagrasses in coastal protection in a changing climate. Coastal Engineering 87, 158-168. https://doi.org/10.1016/j.coastaleng.2013.11.005

Oppenheimer, M., B.C. Glavovic , J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari (2019). Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In IPCC

Special Report on the Ocean and Cryosphere in a Changing Climate. H.-O. Pörtner, D.C.R., V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (ed.). Cambridge, United Kingdom and NY, USA. https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/08_SROCC_Ch04_FINAL.pdf

Orcutt, B.N., Bradley, J.A., Brazelton, W.J., Estes, E.R., Goordial, J.M., Huber, J.A. et al. (2020). Impacts of deep-sea mining on microbial ecosystem services. Limnology and Oceanography 65(7), 1489-1510. https://doi.org/10.1002/lno.11403

Oschlies, A. (2021). A committed fourfold increase in ocean oxygen loss. Nature Communications 12(1), 2307. https://doi.org/10.1038/s41467-021-22584-4

Otosaka, I.N., Shepherd, A., Ivins, E.R., Schlegel, N.-J., Amory, C., van den Broeke, M. et al. (2023). Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. Earth System Science Data Discussions 2022, 1-33. https://doi.org/10.5194/essd-15-1597-2023

Overduin, P., Schneider von Deimling, T., Miesner, F., Grigoriev, M., Ruppel, C., Vasiliev, A. et al. (2019). Submarine permafrost map in the Arctic modelled using 1-D transient heat flux (SuPerMAP). Journal of Geophysical Research: Oceans 124(6), 3490-3507. https://doi.org/10.1029/2018JC014675

Pacoureau, N., Rigby, C.L., Kyne, P.M., Sherley, R.B., Winker, H., Carlson, J.K. et al. (2021). Half a century of global decline in oceanic sharks and rays. Nature 589(7843), 567-571. https://doi.org/10.1038/s41586-020-03173-9

Pal, D., Prabhakar, R., Barua, V.B., Zekker, I., Burlakovs, J., Krauklis, A. et al. (2025). Microplastics in aquatic systems: A comprehensive review of its distribution, environmental interactions, and health risks. Environmental Science and Pollution Research 32(1), 56-88. https://doi.org/10.1007/s11356-024-35741-1

Palmer, M.D. and Weeks, J.H. (2024). The need for multi-century projections of sea level rise. Earth's Future 12(2), e2023EF004403. https://doi.org/10.1029/2023EF004403

Paolo, F.S., Kroodsma, D., Raynor, J., Hochberg, T., Davis, P., Cleary, J. et al. (2024). Satellite mapping reveals extensive industrial activity at sea. Nature 625(7993), 85-91. https://doi.org/10.1038/s41586-023-06825-8

Pecl, G.T., Alexander, K.A., Melbourne-Thomas, J., Novaglio, C., Villanueva, C. and Nash, K.L. (2022). Future Seas 2030: pathways to sustainability for the UN Ocean Decade and beyond. Reviews in Fish Biology and Fisheries 32(1), 1-7. https://doi.org/10.1007/s11160-022-09705-y

Pecl, G.T., Ogier, E., Jennings, S., van Putten, I., Crawford, C., Fogarty, H. et al. (2019). Autonomous adaptation to climate-driven change in marine biodiversity in a global marine hotspot. Ambio 48, 1498-1515. https://doi.org/10.1007/s13280-019-01186-x

Pendleton, L., Donato, D.C., Murray, B.C., Crooks, S., Jenkins, W.A., Sifleet, S. et al. (2012). Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. Plos one 7(9), e43542. https://doi.org/10.1371/journal.pone.0043542

Peng, G., Bellerby, R., Zhang, F., Sun, X. and Li, D. (2020). The ocean's ultimate trashcan: Hadal trenches as major depositories for plastic pollution. Water Research 168, 115121. https://doi.org/10.1016/j.watres.2019.115121

People's Republic of China, Ministry of Ecology and Environment (2024). Bulletin of Marine Ecology and Environment Status of China in 2019. https://www.mee.gov.cn/hjzl/sthjzk/jagb/

Pertierra, L.R., Convey, P., Barbosa, A., Biersma, E.M., Cowan, D., Diniz-Filho, J.A.F. et al. (2025). Advances and shortfalls in knowledge of Antarctic terrestrial and freshwater biodiversity. Science 387(6734), 609-615. https://doi.org/10.1126/science.adk2118

Phang, S.C., Failler, P. and Bridgewater, P. (2020). Addressing the implementation challenge of the global biodiversity framework. Biodiversity and Conservation 29(9-10), 3061-3066. https://doi.org/10.1007/s10531-020-02009-2

Pichegru, L., Vibert, L., Thiebault, A., Charrier, I., Stander, N., Ludynia, K. et al. (2022). Maritime traffic trends around the southern tip of Africa–Did marine noise pollution contribute to the local penguins' collapse? Science of The Total Environment 849, 157878. https://doi.org/10.1016/j.scitotenv.2022.157878

Pickens, C., Lily, H., Harrould-Kolieb, E., Blanchard, C. and Chakraborty, A. (2024). From what-if to what-now: Status of the deep-sea mining regulations and underlying drivers for outstanding issues. Marine Policy, 105967. https://doi.org/10.1016/j.marpol.2023.105967

Pike, E.P., MacCarthy, J.M.C., Hameed, S.O., Harasta, N., Grorud-Colvert, K., Sullivan-Stack, J. et al. (2024). Ocean protection quality is lagging behind quantity: Applying a scientific framework to assess real marine protected area progress against the 30 by 30 target. Conservation Letters 17(3), e13020. https://doi.org/10.1111/conl.13020

Pinsky, M.L., Eikeset, A.M., McCauley, D.J., Payne, J.L. and Sunday, J.M. (2019). Greater vulnerability to warming of marine versus terrestrial ectotherms. Nature 569(7754), 108-111. https://doi.org/10.1038/s41586-019-1132-4

Piwowarska, D., Kiedrzyńska, E. and Jaszczyszyn, K. (2024). A global perspective on the nature and fate of heavy metals polluting water ecosystems, and their impact and remediation. Critical Reviews in Environmental Science and Technology 54(19), 1436-1458. https://doi.org/10.1080/10643389.2024.2317112

Plön, S., Andra, K., Auditore, L., Gegout, C., Hale, P.J., Hampe, O. et al. (2024). Marine mammals as indicators of Anthropocene Ocean Health. npj Biodiversity 3(1), 24. https://doi.org/10.1038/s44185-024-00055-5

Polte, P. and Buschbaum, C. (2008). Native pipefish Entelurus aequoreus are promoted by the introduced seaweed Sargassum muticum in the northern Wadden Sea, North Sea. Aquatic Biology 3(1), 11-18. https://doi.org/10.3354/ab00071

Pontón-Cevallos, J.F., Bruneel, S., Marín Jarrín, J.R., Ramírez-González, J., Bermúdez-Monsalve, J.R. and Goethals, P.L. (2020). Vulnerability and decision-making in multispecies fisheries: a risk assessment of bacalao (mycteroperca olfax) and related species in the Galapagos' handline fishery. Sustainability 12(17), 6931. https://doi.org/10.3390/su12176931

Portela, E., Kolodziejczyk, N., Gorgues, T., Zika, J., Perruche, C. and Mignot, A. (2024). The Ocean's Meridional oxygen transport. Journal of Geophysical Research: Oceans 129(3), e2023JC020259. https://doi.org/10.1029/2023JC020259

Povoroznyuk, O. and Schweitzer, P. (2023). Ignoring environmental change? On fishing quotas and collapsing coastlines in Bykovskiy, Northern Sakha (Yakutiya). Ambio 52(7), 1211-1220. https://doi.org/10.1007/s13280-023-01874-9

Purich, A. and Doddridge, E.W. (2023). Record low Antarctic Sea ice coverage indicates a new sea ice state. Communications Earth & Environment 4(1), 314. https://doi.org/10.1038/s43247-023-00961-9

Rahmstorf, S. (2024). Is the Atlantic overturning circulation approaching a tipping point? Oceanography 37(3), 16-29. https://www.jstor.org/stable/27333920

Ramage, J., Kuhn, M., Virkkala, A.m., Voigt, C., Marushchak, M.E., Bastos, A. et al. (2024). The net GHG balance and budget of the permafrost region (2000–2020) from ecosystem flux upscaling. Global Biogeochemical Cycles 38(4), e2023GB007953. https://doi.org/10.1029/2023GB007953

Ran, Y., Li, X., Cheng, G., Che, J., Aalto, J., Karjalainen, O. et al. (2022). New high-resolution estimates of the permafrost thermal state and hydrothermal conditions over the Northern Hemisphere. Earth System Science Data 14(2), 865-884. https://doi.org/10.5194/essd-14-865-2022

Rantanen, M., Karpechko, A.Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K. et al. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment 3(1), 168. https://doi.org/10.1038/s43247-022-00498-3

Rastelli, E., Petani, B., Corinaldesi, C., Dell'Anno, A., Lo Martire, M., Cerrano, C. et al. (2020). A high biodiversity mitigates the impact of ocean acidification on hard-bottom ecosystems. Scientific Reports 10(1), 2948. https://doi.org/10.1038/s41598-020-59886-4

Richardson, K., Hardesty, B.D. and Wilcox, C. (2019). Estimates of fishing gear loss rates at a global scale: A literature review and meta-analysis. Fish and Fisheries 20(6), 1218-1231. https://doi.org/10.1111/faf.12407

Roach, C.J. and Bindoff, N.L. (2023). Developing a new oxygen atlas of the world's oceans using data interpolating variational analysis. Journal of Atmospheric and Oceanic Technology 40(11), 1475-1491. https://doi.org/10.1175/JTECH-D-23-0007.1

Roberts, D.A., Birchenough, S.N., Lewis, C., Sanders, M.B., Bolam, T. and Sheahan, D. (2013). Ocean acidification increases the toxicity of contaminated sediments. Global Change Biology 19(2), 340-351. https://doi.org/10.1111/gcb.12048

Robledo, D., Vázquez-Delfín, E., Freile-Pelegrín, Y., Vásquez-Elizondo, R.M., Qui-Minet, Z.N. and Salazar-Garibay, A. (2021). Challenges and opportunities

in relation to Sargassum events along the Caribbean Sea. Frontiers in Marine Science 8, 699664. https://doi.org/10.3389/fmars.2021.699664

Rogers, A.D., Frinault, B.A.V., Barnes, D.K.A., Bindoff, N.L., Downie, R., Ducklow, H.W. et al. (2020). Antarctic Futures: An Assessment of Climate-Driven Changes in Ecosystem Structure, Function, and Service Provisioning in the Southern Ocean. Annual Review of Marine Science 12(Volume 12, 2020), 87-120. https://doi.org/10.1146/annurev-marine-010419-011028

Roman, L., Hardesty, B.D., Hindell, M.A. and Wilcox, C. (2019). A quantitative analysis linking seabird mortality and marine debris ingestion. Scientific Reports 9(1), 3202. https://doi.org/10.1038/s41598-018-36585-9

Romanou, A., Hegerl, G.C., Seneviratne, S.I., Abis, B., Bastos, A., Conversi, A. et al. (2024). Extreme Events Contributing to Tipping Elements and Tipping Points. Surveys in Geophysics, 1-46. https://doi.org/10.1007/s10712-024-09863-7

Ross, T., Du Preez, C. and Ianson, D. (2020). Rapid deep ocean deoxygenation and acidification threaten life on Northeast Pacific seamounts. Global Change Biology, 26(11), 6424-6444.https://doi.org/10.1111/gcb.15307

Rousseau, Y., Watson, R.A., Blanchard, J.L. and Fulton, E.A. (2019). Evolution of global marine fishing fleets and the response of fished resources. Proceedings of the National Academy of Sciences 116(25), 12238-12243. https://doi.org/10.1073/pnas.1820344116

Sabino, M., Gustafsson, Ö., Wild, B., Semiletov, I.P., Dudarev, O.V., Ingrosso, G. et al. (2024). Feedbacks From Young Permafrost Carbon Remobilization to the Deglacial Methane Rise. Global Biogeochemical Cycles 38(10). https://doi.org/10.1029/2024gb008164

Sablayrolles, C., Breton, A., Vialle, C., Vignoles, C. and Montréjaud-Vignoles, M. (2011). Priority organic pollutants in the urban water cycle (Toulouse, France). Water Science and Technology 64(3), 541-556. https://doi.org/10.2166/wst.2011.580

Sadat-Noori, M., Rankin, C., Rayner, D., Heimhuber, V., Gaston, T., Drummond, C. et al. (2021). Coastal wetlands can be saved from sea level rise by recreating past tidal regimes. Scientific Reports 11(1). https://doi.org/10.1038/s41598-021-80977-3

Saintilan, N., Horton, B., Törnqvist, T.E., Ashe, E.L., Khan, N.S., Schuerch, M. et al. (2023). Widespread retreat of coastal habitat is likely at warming levels above 1.5 C. Nature 621(7977), 112-119. https://doi.org/10.1038/s41586-023-06448-z

Sakr, A. and Altieri, A.H. (2025). Living in a material world: Support for the use of natural and alternative materials in coastal restoration and living shorelines. Ecological Engineering 211, 107462. https://doi.org/10.1016/j.ecoleng.2024.107462

Salma, U., Hossain, A., Shafiujjaman, M., Nishimura, Y., Tokumura, M., Tanoue, R. et al. (2025). Occurrence, risks, and mitigation of antibiotic pollution in Bangladeshi aquaculture systems. Environmental Chemistry and Ecotoxicology 7, 351-363. https://doi.org/10.1016/j.enceco.2025.01.007

Sanganyado, E., Chingono, K.E., Gwenzi, W., Chaukura, N. and Liu, W. (2021). Organic pollutants in deep sea: Occurrence, fate, and ecological implications. Water Research 205, 117658. https://doi.org/10.1016/j.watres.2021.117658

Saunders, M.I., Leon, J.X., Callaghan, D.P., Roelfsema, C.M., Hamylton, S., Brown, C.J. et al. (2014). Interdependency of tropical marine ecosystems in response to climate change. Nature Climate Change 4(8), 724-729. https://doi.org/10.1038/nclimate2274

Schar, D., Klein, E.Y., Laxminarayan, R., Gilbert, M. and Van Boeckel, T.P. (2020). Global trends in antimicrobial use in aquaculture. Scientific Reports 10(1), 21878. https://doi.org/10.1038/s41598-020-78849-3

Schmidt, C. (2023). Escape from Sargasso Sea: Tremendous Sargassum Blooms Challenge Caribbean and Atlantic Communities. Environmental Health Perspectives 131 (9) 92001. https://doi.org/10.1289/EHP13418

Schmidtko, S., Stramma, L. and Visbeck, M. (2017). Decline in global oceanic oxygen content during the past five decades. Nature 542(7641), 335-339. https://doi.org/10.1038/nature21399

Schuur, E.A. and Mack, M.C. (2018). Ecological response to permafrost thaw and consequences for local and global ecosystem services. Annual review of ecology, evolution, and systematics 49, 279-301. https://doi.org/10.1146/annurev-ecolsys-121415-032349.

Secretariat of the Convention on Biological Diversity (2020). Global Biodiversity Outlook 5. Montreal. https://www.cbd.int/gbo/gbo5/publication/gbo-5-en.pdf

Secretariat of the Convention on Biological Diversity (2022). Decision adopted by the Conference of the Parties to the Convention on Biological Diversity: 15/4. Kunming-Montreal Global Biodiversity Framework, 2022. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf

Sengupta, D., Choi, Y.R., Tian, B., Brown, S., Meadows, M., Hackney, C.R. et al. (2023). Mapping 21st century global coastal land reclamation. Earth's Future 11(2). https://doi.org/10.1029/2022ef002927

Sharma, S., Richardson, D.C., Woolway, R.I., Imrit, M.A., Bouffard, D., Blagrave, K. et al. (2021). Loss of ice cover, shifting phenology, and more extreme events in Northern Hemisphere lakes. Journal of Geophysical Research: Biogeosciences 126(10), e2021JG006348. https://doi.org/10.1029/2021JG006348

Sheppard, C. (2019). III: Ecological Issues and Environmental Impacts. In World Seas: An Environmental Evaluation. Sheppard, C. (ed.). Elsevier Ltd. https://www.sciencedirect.com/book/9780128050521/world-seas-an-environmental-evaluation?via=ihub=

Siegel, D.A., DeVries, T., Cetinić, I. and Bisson, K.M. (2023). Quantifying the ocean's biological pump and its carbon cycle impacts on global scales. Annual Review of Marine Science 15(2023), 329-356. https://doi.org/10.1146/annurev-marine-040722-115226

Skliris, N., Marsh, R., Appeaning Addo, K. and Oxenford, H. (2022). Physical drivers of pelagic Sargassum bloom interannual variability in the Central West Atlantic over 2010–2020. Ocean Dynamics 72(6), 383-404. https://doi.org/10.1007/s10236-022-01511-1

Slangen, A., Haasnoot, M. and Winter, G. (2022). Rethinking sea-level projections using families and timing differences. Earth's Future 10(4), e2021EF002576. https://doi.org/10.1029/2021EF002576

Smith, H., Garcia Lozano, A., Baker, D., Blondin, H., Hamilton, J., Choi, J. et al. (2021). Ecology and the science of small-scale fisheries: A synthetic review of research effort for the Anthropocene. Biological Conservation 254, 108895. https://doi.org/10.1016/j.biocon.2020.108895

Smith, V.H. and Schindler, D.W. (2009). Eutrophication science: where do we go from here? Trends in ecology & evolution 24(4), 201-207. https://doi.org/10.1016/j.tree.2008.11.009

Soria-Rodríguez, C. (2022). Marine renewable energy technologies on the high seas: challenges and opportunities to strengthen international environmental and renewable energy governance. Cambridge International Law Journal 11(2), 202-219. https://doi.org/10.4337/cilj.2022.02.03

Spalding, M.D., Agostini, V.N., Rice, J. and Grant, S.M. (2012). Pelagic provinces of the world: A biogeographic classification of the world's surface pelagic waters. Ocean & Coastal Management 60, 19-30. https://doi.org/10.1016/j.ocecoaman.2011.12.016

Spalding, M.D., Fox, H.E., Allen, G.R., Davidson, N., Ferdaña, Z.A., Finlayson, M. et al. (2007). Marine Ecoregions of the World: A Bioregionalization of Coastal and Shelf Areas. BioScience 57(7), 573-583. https://doi.org/10.1641/b570707

Srokosz, M.A., Holliday, N.P. and Bryden, H.L. 381 (2023). Atlantic overturning: New observations and challenges. Philosophical Transactions of the Royal Society A, 20220196 2262. https://doi.org/10.1098/rsta.2022.0196

Steiner, N.S., Bowman, J., Campbell, K., Chierici, M., Eronen-Rasimus, E., Falardeau, M. et al. (2021). Climate change impacts on sea-ice ecosystems and associated ecosystem services. Elementa: Science of the Anthropocene 9(1), 00007. https://doi.org/10.1525/elementa.2021.00007

Stentiford, G.D., Peeler, E.J., Tyler, C.R., Bickley, L.K., Holt, C.C., Bass, D. et al. (2022). A seafood risk tool for assessing and mitigating chemical and pathogen hazards in the aquaculture supply chain. Nature Food 3(2), 169-178. https://doi.org/10.1038/s43016-022-00465-3

Storto, A. and Yang, C. (2024). Acceleration of the ocean warming from 1961 to 2022 unveiled by large-ensemble reanalyses. Nature Communications 15(1), 545. https://doi.org/10.1038/s41467-024-44749-7

Stramma, L., Johnson, G.C., Sprintall, J. and Mohrholz, V. (2008). Expanding oxygen-minimum zones in the tropical oceans. Science 320(5876), 655-658. https://doi.org/10.1126/science.1153847

Stranddorf, L., Colley, T., Delefosse, M., Svendsen, J.C. and Irving Olsen, S. (2024). Marine biodiversity impact pathways for offshore wind farm

decommissioning: Implications for Life Cycle impact assessment development. Ecological Indicators 167, 112613. https://doi.org/10.1016/j.ecolind.2024.112613

Streck, C. (2023). Synergies between the Kunming-Montreal Global Biodiversity Framework and the Paris Agreement: The role of policy milestones, monitoring frameworks and safeguards. Climate Policy 23(6), 800-811. https://doi.org/10.1080/14693062.2023.2230940

Strokal, M., Vriend, P., Bak, M.P., Kroeze, C., Van Wijnen, J. and Van Emmerik, T. (2023). River export of macro- and microplastics to seas by sources worldwide. Nature Communications 14(1). https://doi.org/10.1038/s41467-023-40501-9

Suggett, D.J. and Smith, D.J. (2020). Coral bleaching patterns are the outcome of complex biological and environmental networking. Global Change Biology 26(1), 68-79. https://doi.org/10.1111/gcb.14871

Tai, T.C., Sumaila, U.R. and Cheung, W.W. (2021). Ocean acidification amplifies multi-stressor impacts on global marine invertebrate fisheries. Frontiers in Marine Science, 8, 596644. https://doi.org/10.3389/fmars.2021.596644

Taherkhani, M., Vitousek, S., Barnard, P.L., Frazer, N., Anderson, T.R. and Fletcher, C.H. (2020). Sea-level rise exponentially increases coastal flood frequency. Scientific Reports 10(1), 6466. https://doi.org/10.1038/s41598-020-62188-4

Taormina, B., Claquin, P., Vivier, B., Navon, M., Pezy, J.-P., Raoux, A. et al. (2022). A review of methods and indicators used to evaluate the ecological modifications generated by artificial structures on marine ecosystems. Journal of Environmental Management 310, 114646. https://doi.org/10.1016/j.jenvman.2022.114646

Tebaldi, C., Ranasinghe, R., Vousdoukas, M., Rasmussen, D., Vega-Westhoff, B., Kirezci, E. et al. (2021). Extreme sea levels at different global warming levels. Nature Climate Change 11(9), 746-751. https://doi.org/10.1038/s41558-021-01127-1

The IMBIE Team (2018). Mass balance of the Antarctic Ice Sheet from 1992 to 2017. Nature 558(7709), 219-222. https://doi.org/10.1038/s41586-018-0179-y

The Lancet (2009). What is health? The ability to adapt. The Lancet Editorial 373(9666), 781. https://doi.org/10.1016/S0140-6736(09)60456-6

Thrush, S.F., Ellingsen, K.E. and Davis, K. (2015). Implications of fisheries impacts to seabed biodiversity and ecosystem-based management. ICES Journal of Marine Science 73(suppl_1), i44-i50. https://doi.org/10.1093/icesjms/fsv114

Tiralongo, F., Hall-Spencer, J.M., Giovos, I. and Kleitou, P. (2022). Editorial: Biological invasions in the Mediterranean Sea. Frontiers in Marine Science 9. https://doi.org/10.3389/fmars.2022.1016168

Tõnisson, H., Suursaar, Ü., Orviku, K., Jaagus, J., Kont, A., Willis, D.A. et al. (2011). Changes in coastal processes in relation to changes in large-scale atmospheric circulation, wave parameters and sea levels in Estonia. Journal of Coastal Research, 701-705. http://www.jstor.org/stable/26482262

Tornero, V. and Hanke, G. (2016). Chemical contaminants entering the marine environment from sea-based sources: A review with a focus on European seas. Marine Pollution Bulletin 112(1-2), 17-38. https://doi.org/10.1016/j.marpolbul.2016.06.091

Trégarot, E., D'Olivo, J.P., Botelho, A.Z., Cabrito, A., Cardoso, G.O., Casal, G. et al. (2024). Effects of climate change on marine coastal ecosystems – A review to guide research and management. Biological Conservation 289. https://doi.org/10.1016/j.biocon.2023.110394

Troudet, J., Grandcolas, P., Blin, A., Vignes-Lebbe, R. and Legendre, F. (2017). Taxonomic bias in biodiversity data and societal preferences. Scientific Reports 7(1). https://doi.org/10.1038/s41598-017-09084-6

Turetsky, M.R., Abbott, B.W., Jones, M.C., Walter Anthony, K., Olefeldt, D., Schuur, E.A. et al. (2019). Permafrost collapse is accelerating carbon release. Nature 569, 32-34. https://www.nature.com/articles/d41586-019-01313-4

Turner, F.E., Malagon Santos, V., Edwards, T.L., Slangen, A.B., Nicholls, R.J., Le Cozannet, G. et al. (2023). Illustrative multi-centennial projections of global mean sea-level rise and their application. Earth's Future 11(12), e2023EF003550. https://doi.org/10.1029/2023EF003550

United Nations (1982). United Nations Convention on the Law of the Sea. https://www.un.org/Depts/los/convention_agreements/convention_overview_convention.htm

United Nations (2021a). The Second World Ocean Assessment. https://www.un.org/regularprocess/woa2launch

United Nations (2021b). The Role of Aquatic Foods in Sustainable Healthy Diets. https://www.unnutrition.org/wp-content/uploads/FINAL-UN-Nutrition-Aquatic-foods-Paper_EN_.pdf

United Nations (2021c). The Sustainable Development Goals Report 2021 - Extended Report. New York, NY. https://unstats.un.org/sdgs/report/2021/extended-report/

United Nations (2022a). Report of the 2022 United Nations Conference to Support the Implementation of Sustainable Development Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development. Lisbon. https://digitallibrary.un.org/record/3993162#record-files-collapse-header

United Nations (2022b). Interactive dialogue 2: Managing, protecting, conserving and restoring marine and coastal ecosystems. Lisbon: United Nations. https://sdgs.un.org/sites/default/files/2022-05/ID_2_Marine_and_coastal_ecosystems.pdf

United Nations (2022c). Sustainable Development Goals Progress Chart 2022. https://unstats.un.org/sdgs/report/2022/Progress-Chart-2022.pdf

United Nations (2023). Agreement on Marine Biodiversity of Areas Beyond National Jurisdiction: BBNJ Agreement. https://www.un.org/bbnjagreement/en

United Nations (2024a). Overview: Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (Factsheet 1). United Nations Division for Ocean Affairs and the Law of the Sea of the Office of Legal Affairs of the United Nations. https://www.un.org/depts/los/reference_files/BBNJ/bbnjagreementoverviewfactsheet.pdf

United Nations (2024b). World Investment Report 2024. New York, USA. https://unctad.org/publication/world-investment-report-2024

United Nations Economic Commission for Europe (1998) Protocol to the 1979 Convention on Long-Range Transboundary Air Pollution on Heavy Metals https://unece.org/environmental-policy/air/protocol-heavy-metals

United Nations Environment Programme (2019). Global Environmental Outlook - GEO-6: Healthy Planet, Healthy People. https://www.unep.org/resources/global-environment-outlook-6

United Nations Environment Programme (2020). Impacts of Sand and Dust Storms on Oceans: A Scientific Environmental Assessment for Policy Makers. Nairobi. https://www.unep.org/resources/report/impacts-sand-and-dust-storms-oceans

United Nations Environment Programme (2021a). From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution. Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/36963/POLSOL.pdf

United Nations Environment Programme (2021b). Making Peace with Nature: A Scientific Blueprint to Tackle the Climate, Biodiversity, and Pollution Emergencies. https://www.unep.org/resources/making-peace-nature

United Nations Environment Programme (2024). First part of the fifth session (INC-5.1). https://www.unep.org/inc-plastic-pollution/session-5

United Nations Environment Programme - World Conservation Monitoring Centre (2021). Protected Planet Report 2020: Tracking Progress Towards Global Targets for Protected and Conserved Areas. Bingham, H.C., Lewis, E., Tayleur, J., Cunningham, C., Kingston, N., Burgess, N.D., Ash, N., Sandwith, T., & MacKinnon, K. (ed.). https://livereport.protectedplanet.net/

United Nations Environment Programme - World Conservation Monitoring Centre and International Union for Conservation of Nature (2024). Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM) and Global Database on Protected Area Management Effectiveness (GD-PAME). Cambridge, United Kingdom. www.protectedplanet.net

United Nations Treaty Collection (2025). Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction. https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXI-10&chapter=21&clang=_en

United States Environmental Protection Agency (2024). Climate Change and the Health of Indigenous Populations. https://www.epa.gov/climateimpacts/climate-change-and-health-indigenous-populations

Van Westen, R.M., Kliphuis, M. and Dijkstra, H.A. (2024). Physics-based early warning signal shows that AMOC is on tipping course. Science advances 10(6), eadk1189. https://doi.org/10.1126/sciadv.adk1189

Vandenbruwaene, W., Maris, T., Cox, T.J.S., Cahoon, D.R., Meire, P. and Temmerman, S. (2011). Sedimentation and response to sea-level rise of a restored marsh with reduced tidal exchange: Comparison with a natural tidal marsh. Geomorphology 130(3), 115-126. https://doi.org/10.1016/j.geomorph.2011.03.004

Varela, R., de Castro, M., Dias, J.M. and Gómez-Gesteira, M. (2023). Coastal warming under climate change: Global, faster and heterogeneous. Science of The Total Environment 886, 164029. https://doi.org/10.1016/j.scitotenv.2023.164029

Vedor, M., Queiroz, N., Mucientes, G., Couto, A., Costa, I.d., Santos, A.d. et al. (2021). Climate-driven deoxygenation elevates fishing vulnerability for the ocean's widest ranging shark. eLife 10, e62508. https://doi.org/10.7554/eLife.62508

Veettil, B.K., Tran, X.-L. and Lopes, M.S. (2024). Mangrove vegetation changes and shoreline erosion along the central coastline of Vietnam: A study from Quang Ngai province. Environmental Development 52, 101065. https://doi.org/10.1016/j.envdev.2024.101065

Vered, G., Nordland, O., Gozlan, I. and Shenkar, N. (2024). Occurrence of plastic additives in coral-reef invertebrates on natural and plastic substrates. Marine Pollution Bulletin 208, 116935. https://doi.org/10.1016/j.marpolbul.2024.116935

Virgen-Urcelay, A. and Donner, S.D. (2023). Increase in the extent of mass coral bleaching over the past half-century, based on an updated global database. Plos one 18(2), e0281719. https://doi.org/10.1371/journal.pone.0281719

von Schuckmann, K., Minière, A., Gues, F., Cuesta-Valero, F.J., Kirchengast, G., Adusumilli, S. et al. (2023). Heat stored in the Earth system 1960–2020: where does the energy go? Earth Syst. Sci. Data 15(4), 1675-1709. https://doi.org/10.5194/essd-15-1675-2023

Waller, M.J., Humphries, N.E., Womersley, F.C., Loveridge, A., Jeffries, A.L., Watanabe, Y. et al. (2024). The vulnerability of sharks, skates, and rays to ocean deoxygenation: Physiological mechanisms, behavioral responses, and ecological impacts. Journal of Fish Biology, 105(2), 482-511. https://doi.org/10.1111/jfb.15830

Walther, B.A. and Bergmann, M. (2022). Plastic pollution of four understudied marine ecosystems: a review of mangroves, seagrass meadows, the Arctic Ocean and the deep seafloor. Emerg Top Life Sci 6(4), 371-387. https://doi.org/10.1042/etls20220017

Wang, H., Wang, G. and Gu, W. (2020). Macroalgal blooms caused by marine nutrient changes resulting from human activities. Journal of Applied Ecology 57(4), 766-776. https://doi.org/10.1111/1365-2664.13587

Wang, J., Church, J.A., Zhang, X., Gregory, J.M., Zanna, L. and Chen, X. (2021a). Evaluation of the local sea-level budget at tide gauges since 1958. Geophysical Research Letters 48(20), e2021GL094502. https://doi.org/10.1029/2021GL094502

Wang, M., Hu, C., Barnes, B.B., Mitchum, G., Lapointe, B. and Montoya, J.P. (2019). The great Atlantic sargassum belt. Science 365(6448), 83-87. https://doi.org/10.1126/science.aaw7912

Wang, Y., Feng, Z., Lin, P., Song, H., Zhang, J., Wu, H. et al. (2024). Enhanced wind mixing and deepened mixed layer in the Pacific Arctic shelf seas with low summer sea ice. Nature Communications 15(1), 10389. 10.1038/s41467-024-54733-w

Wang, Y., Liu, D., Xiao, W., Zhou, P., Tian, C., Zhang, C. et al. (2021b). Coastal eutrophication in China: Trend, sources, and ecological effects. Harmful Algae 107, 102058. https://doi.org/10.1016/j.hal.2021.102058

Wang, Z., Xiao, M., Nicolsky, D., Romanovsky, V., McComb, C. and Farquharson, L. (2023). Arctic coastal hazard assessment considering permafrost thaw subsidence, coastal erosion, and flooding. Environmental Research Letters 18(10), 104003. https://doi.org/10.1088/1748-9326/acf4ac

Ward, R.D., Friess, D.A., Day, R.H. and MacKenzie, R.A. (2016). Impacts of climate change on mangrove ecosystems: A region-by-region overview. Ecosystem Health and Sustainability 2(4), e01211. https://doi.org/10.1002/ehs2.1211

Weilgart, L. (2018). The impact of ocean noise pollution on fish and invertebrates. Report for OceanCare, Switzerland. https://tethys.pnnl.gov/sites/default/files/publications/Weilgart_2018.pdf

Wenning, R.J. and Martello, L. (2014). POPs in marine and freshwater environments. In Environmental Forensics for Persistent Prganic pollutants. Elsevier. 357-390. https://doi.org/10.1016/B978-0-444-59424-2.00008-6

Whitehead, H. and Shin, M. (2022). Current global population size, post-whaling trend and historical trajectory of sperm whales. Scientific Reports 12(1), 19468. https://doi.org/10.1038/s41598-022-24107-7

Wickramage, C., Köhl, A., Jungclaus, J. and Stammer, D. (2023). Sensitivity of MPI-ESM Sea Level Projections to Its Ocean Spatial Resolution. Journal of Climate 36(6), 1957-1980. https://doi.org/10.1175/JCLI-D-22-0418.1

Wilcox, C., Hardesty, B.D. and Law, K.L. (2020). Abundance of Floating Plastic Particles Is Increasing in the Western North Atlantic Ocean. Environmental Science & Technology 54(2), 790-796. https://doi.org/10.1021/acs.est.9b04812

Wild, B., Shakhova, N., Dudarev, O., Ruban, A., Kosmach, D., Tumskoy, V. et al. (2022). Organic matter composition and greenhouse gas production of thawing subsea permafrost in the Laptev Sea. Nature Communications 13(1), 5057. https://doi.org/10.1038/s41467-022-32696-0

Wilkenskjeld, S., Miesner, F., Overduin, P.P., Puglini, M. and Brovkin, V. (2022). Strong increase in thawing of subsea permafrost in the 22nd century caused by anthropogenic climate change. The Cryosphere 16(3), 1057-1069. https://doi.org/10.5194/tc-16-1057-2022

Wong, J., Münnich, M. and Gruber, N. (2024). Column-compound extremes in the global ocean. Agu Advances, 5(3), 2023AV001059. https://doi.org/10.1029/2023AV001059

Woodworth, P.L. (2022). Advances in the observation and understanding of changes in sea level and tides. Annals of the New York Academy of Sciences 1516(1), 48-75. https://doi.org/10.1111/nyas.14851

World Health Organization (1984). The work of WHO in the European Region 1984: Annual report of the Regional Director. https://iris.who.int/handle/10665/351981

Worm, B., Barbier, E.B., Beaumont, N., Duffy, J.E., Folke, C., Halpern, B.S. et al. (2006). Impacts of Biodiversity Loss on Ocean Ecosystem Services. Science 314(5800), 787-790. https://doi.org/10.1126/science.1132294

WoRMS (2023). World Register of Marine Species. https://www.marinespecies.org. Accessed 12 December 2023

Yap, M.L.-M. and Watene, K. (2019). The sustainable development goals (SDGs) and indigenous peoples: Another missed opportunity? Journal of Human Development and Capabilities 20(4), 451-467. https://doi.org/10.1080/19452829.2019.1574725

Zanna, L., Khatiwala, S., Gregory, J.M., Ison, J. and Heimbach, P. (2019). Global reconstruction of historical ocean heat storage and transport. Proceedings of the National Academy of Sciences 116(4), 1126-1131. https://doi.org/10.1073/pnas.1808838115

Zarco-Perello, S., NE, B., S, B., MA, V. and T., W. (2021). Persistence of Tropical Herbivores in Temperate Reefs Constrains Kelp Resilience to Cryptic Habitats. Journal of Ecology 109, 2081-2094. https://doi.org/10.1111/1365-2745.13621

Zerebecki, R.A., Heck Jr., K.L. and Valentine, J.F. (2022). Biodiversity influences the effects of oil disturbance on coastal ecosystems. Ecology and Evolution 12(1), e8532. https://doi.org/10.1002/ece3.8532

Zhang, Z., Bao, Y., Fang, X., Ruan, Y., Rong, Y. and Yang, G. (2024). A circumpolar study of surface zooplankton biodiversity of the Southern Ocean based on eDNA metabarcoding. Environmental Research 255, 119183. https://doi.org/10.1016/j.envres.2024.119183

Zhong, H., Wu, M., Sonne, C., Lam, S.S., Kwong, R.W., Jiang, Y. et al. (2023). The hidden risk of microplastic-associated pathogens in aquatic environments. Eco-Environment & Health. https://doi.org/10.1016/j.eehl.2023.07.004

Zhou, W., Leung, L.R. and Lu, J. (2024). Steady threefold Arctic amplification of externally forced warming masked by natural variability. Nature Geoscience 17(6), 508-515. https://doi.org/10.1038/s41561-024-01441-1

ZoBell, V.M., Hildebrand, J. and Frasier, K. (2024). Moving cargo, keeping whales: Investigating solutions for ocean noise pollution. The Journal of the Acoustical Society of America 155(3_Supplement), a133-a133. https://doi.org/10.1121/10.0027065

06 Freshwater

Coordinating Lead Authors: Tamiru A. Abiye (University of the Witwatersrand, Johannesburg) and Erica Brown Gaddis (SWCA Environmental Consultants)

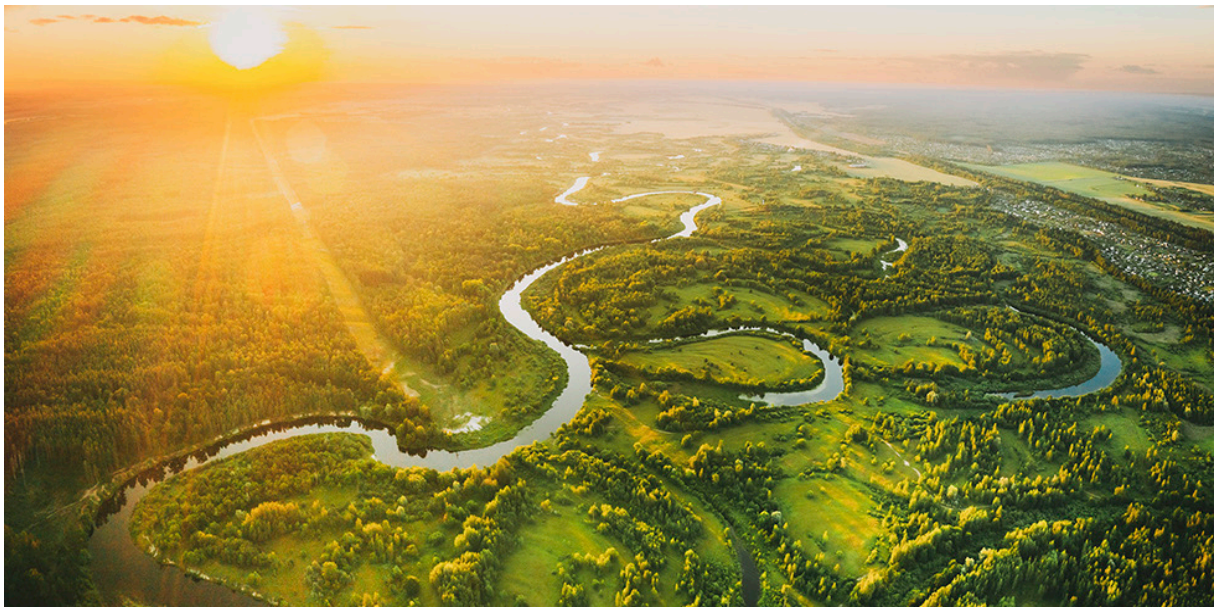
Lead Authors: Shaneel Chandra (Central Queensland University), Vinicius F. Farjalla (Federal University of Rio de Janeiro), and Yolanda López-Maldonado (Indigenous Science)

Contributing Author: Lindsay Beevers (University of Edinburgh)

GEO Fellows: Maryam Eqan (CY Major Group) and Slobodan Gnjato (University of Banja Luka)

Credit: Shaiith/Envato

Chapter summary



Credit: Great_bru/Envato

Water pollution continues to degrade freshwater quality and exacerbate water insecurity (*well established*). It stems both from resource extraction, agricultural intensification, industrial effluents, and urban development. Due to their hydraulic connection, pollution of surface water systems also affects groundwater quality, and vice versa {6.2.1; 6.4.1}.

Approximately 42 per cent of global municipal wastewater sewage is still discharged into the environment untreated (*established but incomplete*). In 2021, the combined global annual volume of domestic and industrial wastewater production was at 359x109 m^3, approximately twice the flow of the Danube River {6.2.1}.

Emerging contaminants, now found in fresh water worldwide, have been linked to serious human health and environmental impacts (*established but incomplete*). They contribute to cancer, cardiovascular disease, respiratory and reproductive health problems, neurodegeneration and a weakened immune system. The list of emerging contaminants continues to grow and includes micro and nano plastics, pharmaceuticals, personal care products, hormones, per- and polyfluorinated substances, flame retardants, plasticizers and corrosion inhibitors {6.4.1}.

Unregulated artisanal and illegal mining are causing freshwater pollution in 173 large river basins across 49 countries (*established but incomplete*). The water quality impacts are degrading ecosystems, contributing to freshwater biodiversity loss, and threatening human health especially in many low- and middle-income countries and vulnerable communities {6.2.1}.

Global freshwater withdrawals, currently estimated at 4,300 km^3 per year, have nearly doubled since 1980 (*well established*) and have reached unsustainable rates in many regions, including North Africa, parts of Southern and Western Asia, Central America, and the Southwestern United States of America (*established but incomplete*). This trend is mostly driven by irrigation for rising food production, population growth, and industry and mining expansion. However, total withdrawals have started to stabilize due to declining per capita water extraction. As of 2020, agricultural production accounted for the majority of freshwater withdrawals at 67 per cent, followed by industrial at 14 per cent, municipal at 12 per cent, and energy at 7 per cent {6.2.2}.

Unsustainable groundwater withdrawals for agriculture, municipal and industrial water supply needs

contribute to severe groundwater depletion in several regions (*well established*). Globally, groundwater supplies around 25 per cent of the water used in irrigated agriculture. Since 2000, groundwater levels have declined in more than 30 per cent of the world's regional aquifers. However, groundwater depletion has slowed in 20 per cent and reversed in 16 per cent of aquifers worldwide {6.2.2; 6.3.1}.

Dam construction, driven by needs for clean energy and water supply, presents a major threat to freshwater biodiversity worldwide (*well established*). The world's 35,000 dams with mapped reservoir areas fragment habitats, disrupting natural water flow patterns, and altering nutrient and suspended sediment circulation. Since the 1990s, these developments have added 49,715 km^2 of new surface water coverage, with the most significant increases in Asia, Africa and South America {6.2.3; 6.5.3}.

Climate change is intensifying the global hydrological cycle, leading to more extreme floods, glacier and permafrost melt, declining snow cover, prolonged droughts, and freshwater biodiversity loss (*well established*). Extreme flood events often damage ecosystems especially in South America, Africa, Asia and Europe. The loss of glaciers, land ice, and snow cover is widespread, especially in mid- and high latitudes and at higher elevations {6.3.1; 6.3.2}.

Global drought trends are primarily driven by climate-related changes in precipitation, temperature, and evapotranspiration and vary by region (*well established*). The frequency, duration and intensity of droughts are increasing in parts of the Americas, Africa, Asia, and Europe. Drought has also been linked to the drying of inland water bodies, including wetlands {6.3.2}.

Harmful algal blooms and freshwater eutrophication are increasing in magnitude and frequency, threatening drinking water supplies and aquatic ecosystems (*well established*). These phenomena are mainly driven by nutrient pollution from fertilizers and untreated wastewater, combined with climate-induced changes in seasonal water temperatures. Between 1982 and 2019, 9 per cent of monitored lakes globally showed increases in harmful algal blooms, damaging economies and the health of billions of people {6.4.1}.

Approximately 40 per cent of the world's largest rivers are experiencing increased sediment pollution from land degradation, damaging freshwater ecosystems and reducing reservoir capacity (*established but incomplete*). Sediment deposition impairs reservoir performance for hydropower and water supply. Suspended sediments lower water quality and aquatic habitat across entire catchments. Globally, about 396 major rivers, spanning 35,000 river kilometres or approximately 6 per cent of large tropical river reaches are affected by suspended sediments, primarily in the regions with intensified land degradation {6.2.1; 6.4.1; 6.4.2}.

Freshwater ecosystems are experiencing the highest rates of biodiversity loss, with an estimated 89 species confirmed extinct, and 178 more suspected extinct (*well established*). Currently, about 24 per cent of freshwater species are threatened with extinction, driven by habitat fragmentation, invasive species, overexploitation, pollution, and climate change. Among the various types of freshwater ecosystems, wetlands face the greatest threats, vanishing three times faster than forests {6.5.1}.

Overexploitation of aquatic species poses a significant threat to the health and stability of freshwater ecosystems (*well established*). This trend is largely driven by the fisheries and aquaculture industries, contributing to biodiversity loss and decline in catch of some important subsistence fisheries {6.5.6}.

Invasive, or non-native, species in freshwater ecosystems are also a major cause of biodiversity decline (*well established*). These species compromise the freshwater ecosystems, alter local hydrological processes, and damage water supply infrastructure {6.5.5}.

Water stress from physical scarcity and pollution is increasing globally due to climate change and persistent drought (*well established*). Limited fresh water availability for human use in some regions, particularly in densely populated cities and in arid or semi-arid regions, hinders sustainable development efforts, especially in Central and Southern Asia and Northern and Southern Africa {6.6.1}.

In 2022, around 22 per cent of the world's population was using a drinking water source that had been contaminated with sewage (*well established*). The resulting microbial contamination poses the greatest health risk to safe drinking water globally, particularly in highly populated areas of Africa, Asia, and Latin America {6.4.1}.

Provision of clean water remains a significant challenge amid growing water demand, leading to widespread water insecurity, especially for Indigenous Peoples, women, and girls (*established but incomplete*). Contributing factors include water quality degradation, inadequate infrastructure, inequitable access to water supplies, poor water governance, and climate-driven physical scarcity {6.6.1; 6.6.5}.

Irrigated agriculture and aquaculture, both highly dependent on fresh water, play a crucial role in securing the global food supply in the face of a growing population (*well established*). However, current irrigation practices on over half of irrigated lands are unsustainable due to high freshwater use and loss. As irrigated land expands, so does the demand on freshwater sources. The expansion of irrigation has also been associated with increased use of pesticides and fertilizers, further contributing to freshwater pollution {6.6.3}.

Global water use efficiency has improved by approximately 19.3 per cent across all sectors, rising from US$17.4 of added value per m^3 in 2015 to US$20.8 per m^3 in 2021 (*well established*). The most significant gains were in the irrigated agriculture sector, which saw a 35.6 per cent improvement over six years {6.2.2}.

Trade of water-intensive products, known as virtual water trade, is offsetting water stress in some countries while contributing to unsustainable irrigation practices in others (*established but incomplete*). Approximately 20 per cent of water used for agriculture is embedded in traded goods, rather than consumed domestically. The most water-intensive exports include livestock products and high-demand cash crops. Between 1986 and 2022, the volume of international virtually traded water tripled, representing 16 per cent of unsustainable water use and 11 per cent of global groundwater depletion. This trade can limit local freshwater availability, which affects Indigenous Peoples and small-scale producers as well as water and food security {6.6.4}.

Transboundary waters, shared by at least two countries, account for around 60 per cent of the world's freshwater flows, including 313 rivers and lakes and 468 aquifers (*well established*). As of now, only 43 out of the 153 countries sharing transboundary waters have operational cooperative arrangements, though a near doubling since 2017. Most cooperation occurs in Europe, North America, and sub-Saharan Africa. Strengthening transboundary water governance and cooperation is vital to reducing the risk of water conflicts {6.6.1}.

New analytical tools, including remote sensing, enhanced data-collection and analysis, artificial intelligence, and robust modelling, are enhancing the understanding of the state of freshwater systems and the underlying trends, causes and interlinkages (*established but incomplete*). Increasingly, these technologies enable real-time monitoring of water consumption in agriculture, improved water management, large-scale assessment of contaminants and analysis of temporal changes in water systems. However, disparities in access to technology and funding could limit the widespread application of these tools {6.3.1}.

Indigenous Knowledge has significantly contributed to the improvement of water risk management systems (*established but incomplete*). Indigenous Peoples have developed sophisticated water harvesting techniques, such as terraces and canals for water capture and distribution and employed water purification and distribution methods, like the Maya. Their observation-based climate forecasting methods and knowledge of astronomy complement modern scientific weather predictions {6.3.1; 6.6.5}.

Indigenous Peoples across the globe maintain deep cultural and spiritual connections to water and freshwater ecosystems (*well established*). Water is sacred and central in many Indigenous cultures, livelihoods and daily practices. The cultural connections are often rooted in natural sites, like rivers, lakes, lagoons, and springs. Disruptions to these water bodies due to pollution, water scarcity, water withdrawals, climate change and other pressures, can break traditional relationships with the hydrological cycle and may lead to the displacement of Indigenous Peoples, threatening their cultural identity, way of life and even survival {6.2.3; 6.3.1; 6.6.5}.

6.1 Introduction

Healthy freshwater systems are essential for human health, vibrant communities, sustainable economic development, and the protection of ecosystems. However, rivers, lakes, wetlands and aquifers continue to face stress from the global environmental crises (the crisis of climate change, the crisis of biodiversity loss, land degradation and desertification and the crisis of pollution and waste), dam construction, and increasing water demands. These freshwater systems are also vital for Indigenous Peoples, as they provide critical resources for traditional food systems, supporting cultural practices and nutritional health through diverse aquatic species and plant life.

Building on the work of other recent global assessments, such as the Intergovernmental Panel on Climate Change (IPCC) report, Climate Change 2022: Impacts, Adaptation and Vulnerability (Caretta et al. 2022), and World Water Assessment Programme series from United Nations Water (UN-Water) and United Nations Educational Scientific and Cultural Organization (UNESCO) (UN Water and UNESCO 2021; UN-Water and UNESCO 2022; UN-Water and UNESCO 2023; UN Water and UNESCO 2024), this chapter examines the unique pressures on freshwater systems, alongside the current state and trends in water resources, water quality and freshwater biodiversity. Additionally, the chapter summarizes some of the most consequential effects of freshwater changes on human well-being, including those affecting Indigenous Peoples, and provides a brief update on internationally agreed water environmental goals.

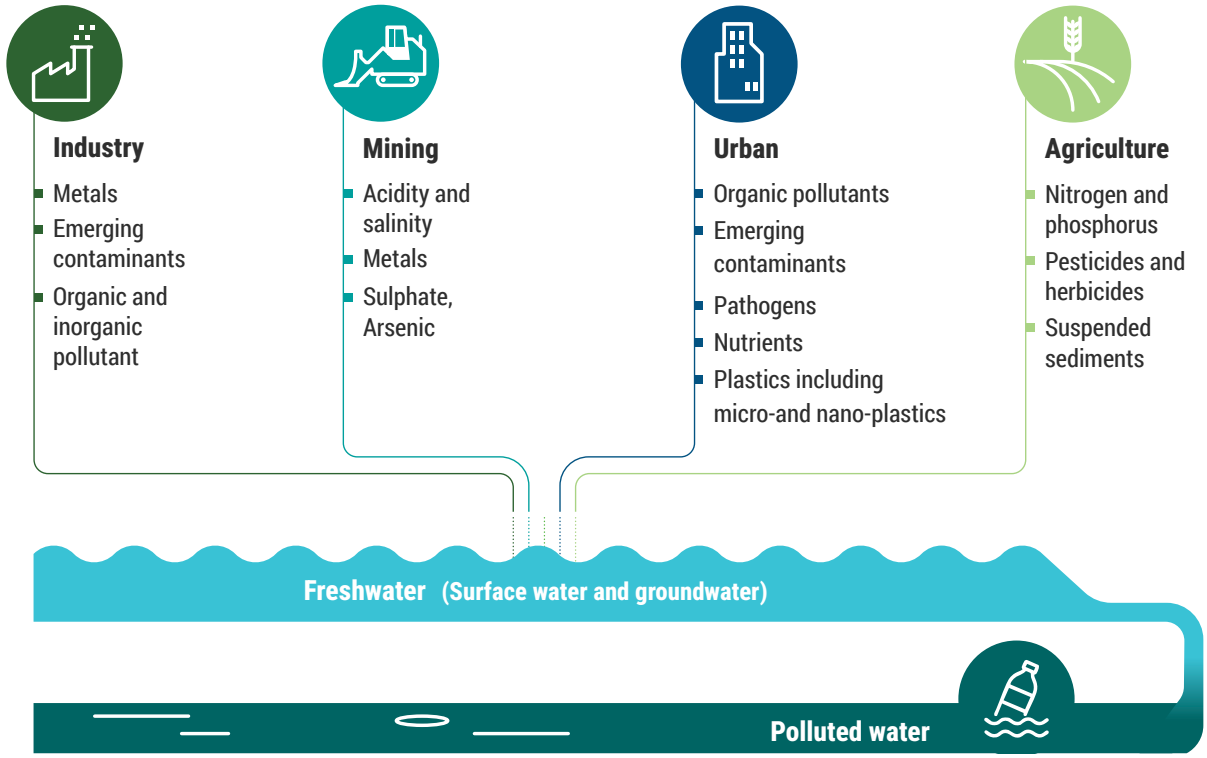
6.2 Pressures on freshwater systems

Alongside the global environmental crises and pressures outlined in Chapter 2, freshwater systems face water-specific pressures, such as freshwater pollution, water use and withdrawals, and dams for hydropower and water supply.

6.2.1 Freshwater pollution

Freshwater pollution has widespread effects on ecosystems, human health, and economic productivity. Freshwater quality continues to deteriorate globally due to increases in water pollution from agricultural intensification, urbanization, expansion of mining, industry, land-use changes, and inadequate waste

Figure 6.1: Primary sources of global pollution



management from these activities (**Figure 6.1**). Water pollution of surface water and groundwater systems often extends across these resources due to their hydrologic connection.

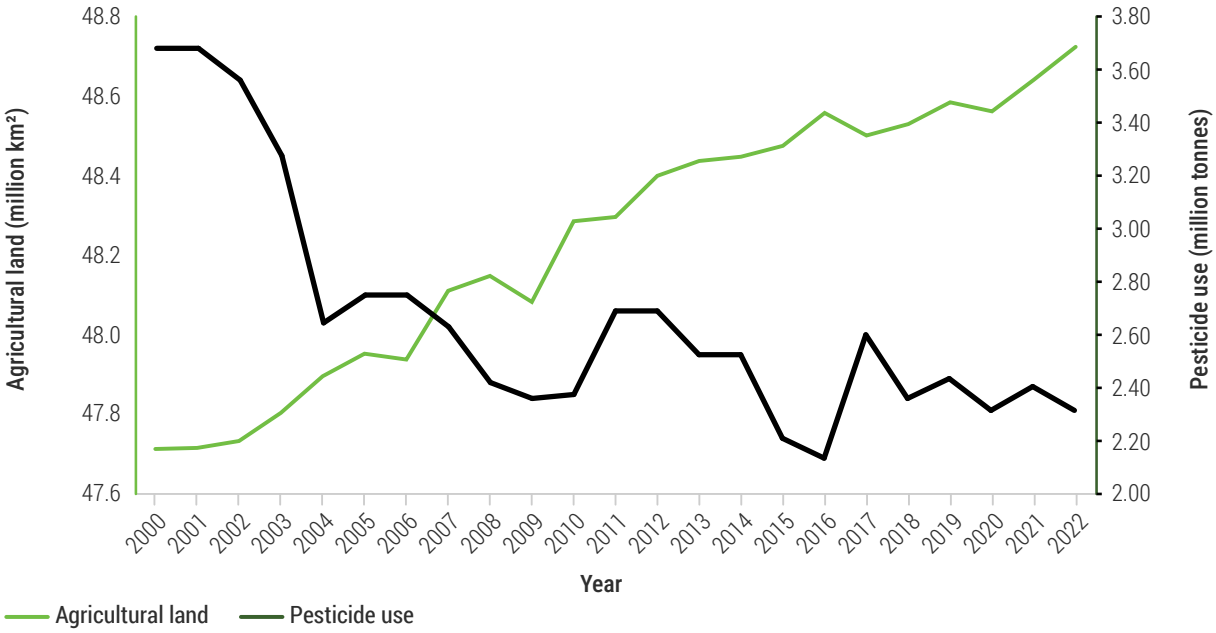
Globally, the human population, including Indigenous Peoples and other marginalized groups, is highly exposed to numerous polluting activities. The impacts of pollution affect freshwater supply, often resulting in serious health problems (Fernández-Llamazares et al. 2019; Basta et al. 2021). Achieving improvements requires the involvement of all stakeholders to participate in the economic activities of a region without affecting freshwater quantity, quality, and biodiversity for all who depend on it.

6.2.1.1 Agriculture

Agricultural practices that pollute fresh water include the application of synthetic fertilizers, the use of pesticides and herbicides, soil disturbance, livestock grazing, concentrated livestock operations, flood irrigation, and the clearing of land for agricultural expansion, which causes soil erosion (Zou et al. 2020; FAO 2022a; Tan et al. 2022; FAO 2023; Ma et al. 2023). Agricultural run-off is driven by heavy rainfall and snowmelt events, combined with poor vegetation cover and over-irrigation due to the use of inefficient irrigation methods. Run-off results in the discharge of synthetic fertilizers, pesticides, and other contaminants, such as degraded plastic mulch, into freshwater systems (Jansen et al. 2024). The run-off from intensive livestock farming also contains harmful residues of veterinary antibiotics and other pharmaceuticals, agrochemicals, growth hormones and nutrients that negatively affect water quality (FAO and IWMI 2018; Ray and Shaju 2023; Liu et al. 2024). The spread of antibiotic-resistant microorganisms represents a serious problem for aquatic ecosystems and human health. In many countries, the use of broad-spectrum pesticides remains common; however, there is a recent trend towards using newer pesticides with greater selectivity and reduced toxicity to humans and the environment (FAO 2022a).

On a global scale, the area of agricultural land under production has shown a decreasing trend, falling from 48.7 million km² in 2000 to 47.8 million km² in 2022. This could suggest a shift from rain-fed agriculture to technology-supported practices. Conversely, pesticide usage increased during the same period, rising from 2.2 million tons to 3.7 million tons, reflecting the heightened intensity of agricultural systems and irrigation, which leads to higher agricultural inputs (**Figure 6.2**).

Figure 6.2: The decreasing trend of global agricultural land and increased use of pesticides from 2000 to 2022



Note: For clearer contrast of the trend lines, the vertical axes do not start at 0.

Source: FAOSTAT (2025)

6.2.1.2 Urban

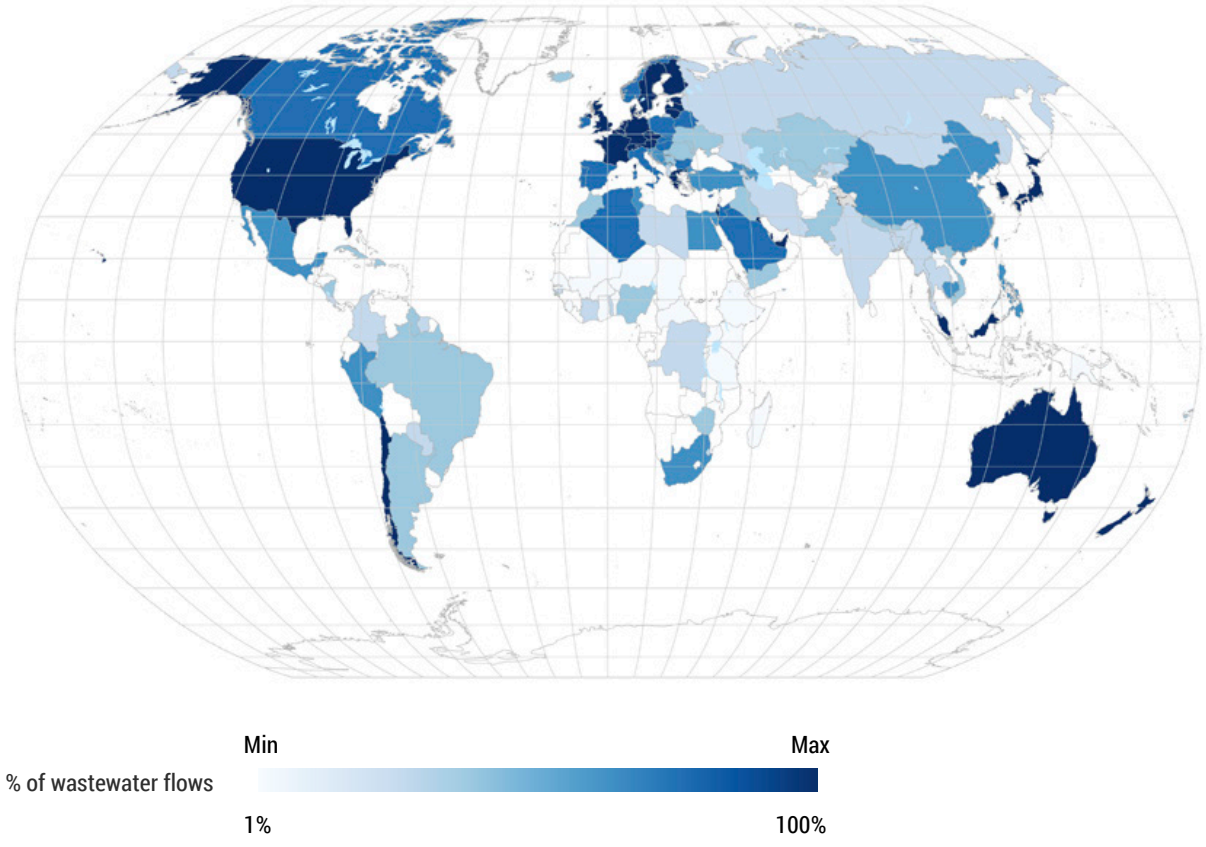
About 56 per cent of the world's population, 4.4 billion, lives in cities. The urban population is projected to double by 2050, at which point nearly seven out of ten people will reside in urban areas (World Bank 2023; Chapter 2.2.4). This population growth leads to increased urban pollution due to wastewater (sewage) generation, stormwater, and leachate from solid waste disposal.

Globally, approximately 42 per cent of the world's municipal wastewater is not safely treated before its release into the environment (UN Water and UNESCO 2023), and only 11 per cent of sewage is treated and reused (UNEP 2023). The global combined volume of annual domestic and industrial wastewater production was estimated at 359×10^9 m^3 in 2021, roughly double the flow of the Danube River. The proportion of safely treated domestic wastewater improved by 2 per cent, rising from 56 per cent in 2020 to 58 per cent in 2022 (WHO 2022; UNEP2024a) (**Figure 6.3**). Although progress is being made, many regions still lack adequate infrastructure for wastewater treatment.

Consequently, many urban rivers experience high levels of pathogens and organic pollution (Wen et al. 2017), disproportionately affecting women and girls, as they are often the primary collectors of water (Chapter 7.3.6). Municipal wastewater also contributes approximately 1.57 per cent of global greenhouse gas emissions (UNEP 2023) through the breakdown of organic waste and the energy used during treatment processes (Dickin et al. 2020). Addressing the discharge of untreated sewage requires the implementation of effective waste management systems, the promotion of wastewater treatment, and the enforcement of environmental regulations to protect ecosystems and human health.

Stormwater runoff from roads and other impervious surfaces mobilizes pollutants, including heavy metals (Maeaba et al. 2019), hydrocarbons, suspended sediments, debris, litter (Werbowski et al. 2021; Awonaike et al. 2022), nutrients (Brudler et al. 2019) and microplastics from degraded tyres (Johannessen et al. 2021; Goehler et al. 2022; Cao et al. 2022). Increases in

Figure 6.3: Percentage of domestic wastewater flows that are safely treated



Source: WHO 2022

Image 6.1 Aerial view of copper mining waste that flooded the village of Geamăna, Romania. Credit: erika8213/Envato

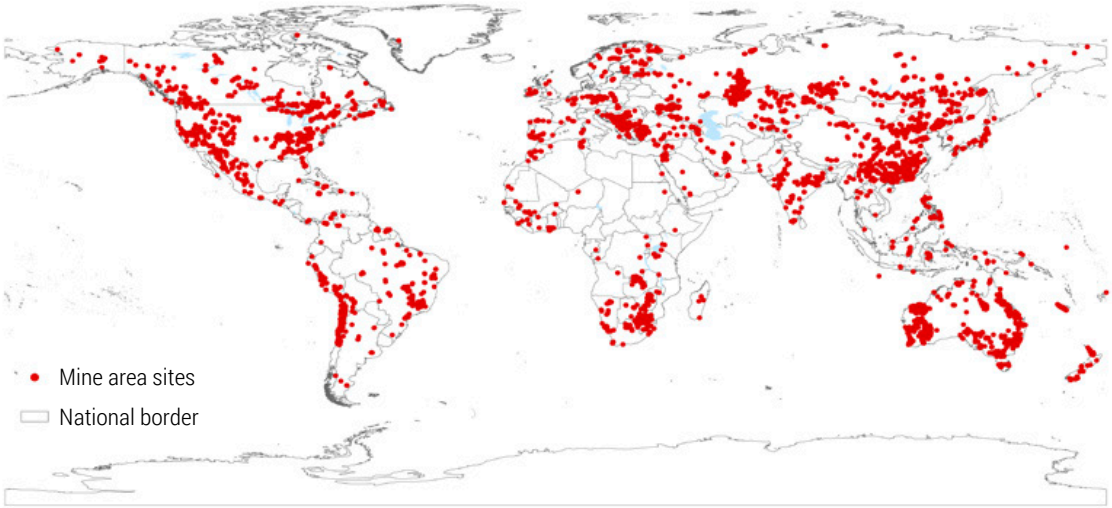
flooding and intense rainfall may contribute to regional increases in the discharge of untreated sewage into rivers (Petrie 2021).

Appropriate solid waste management in urban areas remains a challenge, particularly the disposal of waste in environmentally sensitive areas such as coastal zones and wetlands (Nicholls et al. 2021; Khan et al. 2022; Aslam et al. 2022). Even properly designed landfills, while significantly better than open dump sites, can still be sources of water pollution through leachates (Igboama et al. 2022) that contain heavy metals, organic pollutants, and nutrients (Przydatek and Kanownik 2019). In some areas, tourism exacerbates waste production, further contributing to freshwater pollution.

6.2.1.3 Mining

Mining and mineral processing pollute surface water and groundwater through the discharge of chemicals, the leaching of metals from tailings and disposed low-grade rocks, as well as through the disturbance of land and water. Mining activities on every continent have the potential to contaminate freshwater resources (Liang et al. 2021) (**Figure 6.4**). Mining areas for critical minerals such as copper, lithium, nickel, cobalt, and rare earth metals that are essential components of new energy technologies are rapidly expanding across the world (Sonter et al. 2020), and, in some cases, they present an elevated risk of toxic metal pollution from mercury, lead, cadmium, uranium and others (Zhou et al. 2020; **Image 6.1**). Moreover,

Figure 6.4: Global distribution of mine areas



Source: Liang et al. (2021)

Image 6.2 Sand mining from a lake. Credit: YouraPechkin/Envato

mining operations are known to generate suspended sediments in many river systems (Dethier et al. 2023).

Globally, sand mining has accelerated primarily due to infrastructure demands linked to population growth and rapid urbanization (**Image 6.2**). Sand mining occurs in small river channels, large rivers, deltas, and coastal areas with consequences for natural sediment transport. For example, in the Vietnamese Mekong Delta, sand extraction ranges from 8.5 Mm^3/yr to 45.7 Mm^3/yr (Park 2024). Reduced upstream sediment supply from dam construction and sand mining in the delta has led to 2 cm/yr increases in tidal amplification (Eslami et al. 2019).

Sand and mineral extraction activities are also affecting areas with sparse population densities in the Northern Hemisphere. For example, erosion caused by the melting of the Greenland Ice Sheet has resulted in the deposition of sediments along the coasts of Kalaallit Nunaat, Greenland, which has driven sand extraction activities and caused environmental damage to the coastal areas (Bendixen et al. 2022). Yet, the impacts of mineral extraction are unevenly distributed, with Indigenous Peoples facing greater consequences globally (Fernandez-Llamazares et al. 2020).

Unregulated artisanal and illegal gold panning along rivers has surged over the past 20 years, affecting water quality in 173 large river basins across 49 countries. These activities are known to release mercury and cyanide into freshwater systems and can be mitigated through innovative techniques aimed at reducing freshwater pollution. Globally, approximately 396 major rivers are affected by suspended sediment due to river-based mining, representing 35,000 river kilometres and 7 per cent of all large tropical river reaches, including the Amazon River (Dethier et al. 2023; Voosen 2023).

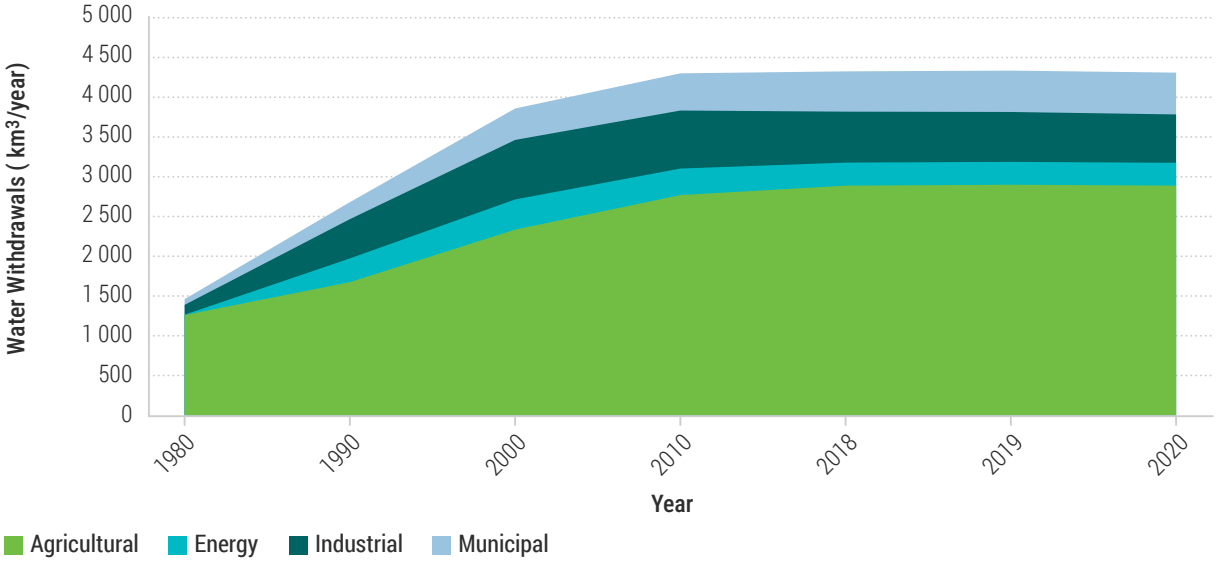
6.2.1.4 Industry

Disposal of untreated industrial effluents, which include chemicals, radioactive substances, hydrocarbons, and organic and inorganic wastes, continues to be a major source of global pollution with direct repercussions on freshwater ecosystems (Iloms et al. 2020; Afrad et al. 2020). Industrial effluent contributes an estimated 300–400 million tons per year of waste discharged into freshwaters (du Plessis 2022). The growth of manufacturing in low and middle-income countries over the past decades has increased the disposal of industrial waste into freshwater systems. For example, approximately 2.55 million m^3/day of wastewater was discharged into the Ganga River without any treatment (Kumar et al. 2021; Muduli et al. 2021; Brunner, Das, and Starkl 2023). The Buriganga River and its tributaries in Bangladesh receive about 60,000 m^3/day of toxic wastes containing organic matter from industrial discharges (Uddin and Jeong 2021; Nargis et al. 2021).

6.2.2 Water use and withdrawals

Fresh water is essential for households, agriculture, irrigation, industry and power generation. Total freshwater withdrawals were estimated to be approximately 4,300 km^3/year in 2020, nearly doubling

Figure 6.5: Summary of global freshwater withdrawals between 1980 and 2020 calculated as the sum of all country data reporting sectoral water withdrawals



Source: AQUASTAT Database 2023

the amount of water withdrawn in 1980 (AQUASTAT 2023) (**Figure 6.5**). This increase is driven by global demand for fresh water which has been increasing by just under 1 per cent annually between the 1980s and 2024 (UNESCO 2024).

Most freshwater withdrawals for human use come from surface waters. However, groundwater accounts for half of the volume withdrawn for domestic purposes worldwide and about 25 per cent of all water withdrawn for irrigation (UN Water and UNESCO 2024). Total withdrawals have levelled off in recent years, indicating a reduction in per capita water withdrawals globally. Due to gender-based roles and responsibilities, women and girls bear a disproportionate burden of water use and collection at the community level (UNICEF 2023).

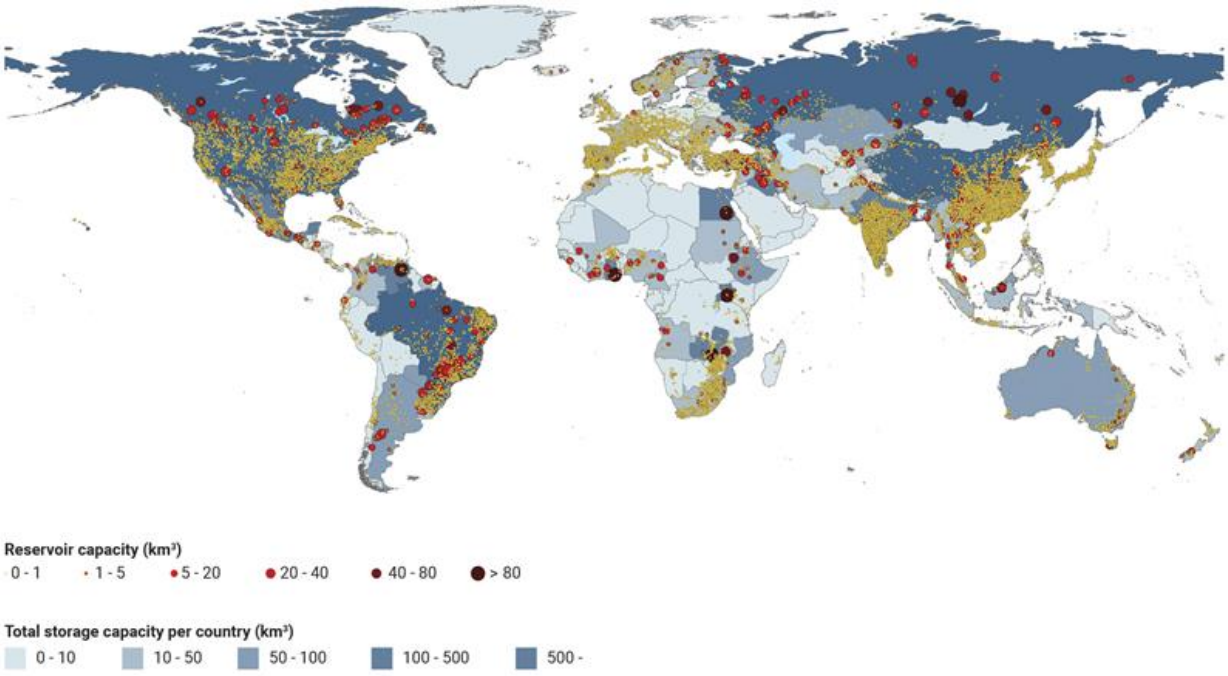
In 2020, most freshwater withdrawals were for agricultural production at 67–70 per cent (Aquastat 2023; UN Water and UNESCO 2024), followed by industry at 14 per cent,domestic or municipal uses at 12 per cent, and energy at 7 per cent (UN Water and UNESCO 2024). However, water-use efficiency has improved globally by approximately 19.3 per cent across all sectors, rising from 17.4 US$/$m^3$ in 2015 to 20.8 US$/$m^3$ in 2021. The largest improvements have occurred in the irrigated agriculture sector, which has seen a 35.6 per cent improvement over those six years (FAO and UN Water 2024). Nevertheless, Rosa et al. (2019) estimated that 52 per cent of global irrigation practices are unsustainable with consumption rates exceeding natural renewable recharge rates, and that unsustainable water consumption increased by 18 per cent between 2000 and 2015. Increasing global irrigation and municipal water demand is resulting in hotspots of groundwater depletion around the world (UN Water and UNESCO 2022; 2023). Approximately 47 per cent of the global land area exceeds the locally estimated Earth system boundary for sustainable groundwater withdrawals (Rockstrom et al. 2023).

Water withdrawal by the mining industry is increasing, particularly in arid and semi-arid regions where the extensive use of fresh water for mining activities competes with other economic sectors (Meißner 2021; Statista 2023). Moreover, one of the most critical issues in water extraction for consumption is the high rate of loss from inefficient distribution systems – up to 40 per cent in developing countries and 15 per cent in developed countries – threatening both the availability and sustainability of water resources (UN Water and UNESCO 2021). Unsustainable water withdrawals contribute to seawater intrusion, impacting coastal aquifers that are critical potable water sources (Tschaikowski et al. 2024).

6.2.3 Dams for hydropower and water supply

The construction of dams for hydropower and water supply has been critical in addressing water security

Figure 6.6: Global distribution of dams and river barriers



Source: Lehner et al. (2024)

in many parts of the world and provides the largest source of renewable energy globally (IEA 2021). There are currently an estimated 35,000 dams worldwide with mapped reservoir areas (Zhang and Gu 2023; Lehner et al. 2024). Irrigation and hydroelectricity are the primary purposes of dam construction, representing 25 per cent and 20 per cent of dams, respectively (Zhang and Gu 2023). Water supply, flood control, recreation, livestock and navigation follow as additional primary purposes for dams (Zhang and Gu 2023). Furthermore, changes in precipitation and temperature patterns are driving climate adaptation needs for greater water storage, often in the form of reservoirs, to compensate for losses in snow, permafrost, and glaciers (Caretta et al. 2022; Fox-Kemper et al. 2021).

However, dams also fragment aquatic habitats, disrupt natural flow patterns, alter nutrient cycling and sediment transport, and interfere with fish migration, thereby threatening freshwater ecosystems (Fearnside 2016; Latrubesse et al. 2017; Belletti et al. 2020; Su et al. 2021; Haase et al. 2023, Zhang and Gu 2023). New dams also frequently displace upstream human communities, and the risk of dam failure jeopardizes the security and livelihoods of downstream communities, often with disproportionate repercussions on Indigenous Peoples (Fearnside 2016; Latrubesse et al. 2017; IHA 2021a; IHA 2022b).

Globally, dam construction has been declining in most developed countries while increasing in many developing countries. There have been notable increases in dam decommissioning in North America and Europe (Zhang and Gu 2023). Nonetheless, over the past three decades, new dam construction has added 49,715 km² of surface water in upstream catchments, a 30 per cent increase over the pre-dam levels, with the most significant increases occurring in Asia, Africa, and South America (Zhang and Gu 2023) (**Figure 6.6**). As this trend continues, new dams for hydropower and water storage are projected to disproportionately affect important areas for freshwater biodiversity in South America, South and East Asia, and the Balkan region (Zarfl et al. 2019).

6.3 Water resources

6.3.1 State and trends of global water resources

6.3.1.1 Global freshwater storage

Globally, of the estimated 42 million km³ of freshwater storage, only about 2 per cent, or 850,000 km³, is available for direct human use (McCartney et al. 2022). Most of the fresh water available for human use is found in groundwater, mountain glaciers, and lakes,

while less than 1.5 per cent is stored in human-made reservoirs (McCartney et al. 2022). Changes to the water cycle linked to climate change, water withdrawals, and land-use changes are driving changes in water storage worldwide (**Figure 6.7**). Between 1971 and 2020, natural storage declined by 33,944 km³, which was partially offset by an increase of 6,865 km³ in reservoir storage and paddy fields (McCartney et al. 2022). The most significant reductions in natural storage are occurring in ice sheets, mountain glaciers, groundwater, wetlands and lakes (**Figure 6.7**). These trends are manifesting differently across the globe. While fresh water is accumulating in certain regions of North America, Europe, Asia, and the wet tropics, the most significant losses of non-frozen fresh water due to drying are occurring in the mid-latitudes (Rodell et al. 2018; Immerzeel et al. 2020; Huggins et al. 2022; McCartney et al. 2022). Climate change is also affecting the timing and reliability of freshwater storage in ice and snow, leading to accelerated melting of mountain glaciers and snowpacks worldwide (Rodell et al. 2018; McCartney et al. 2022).

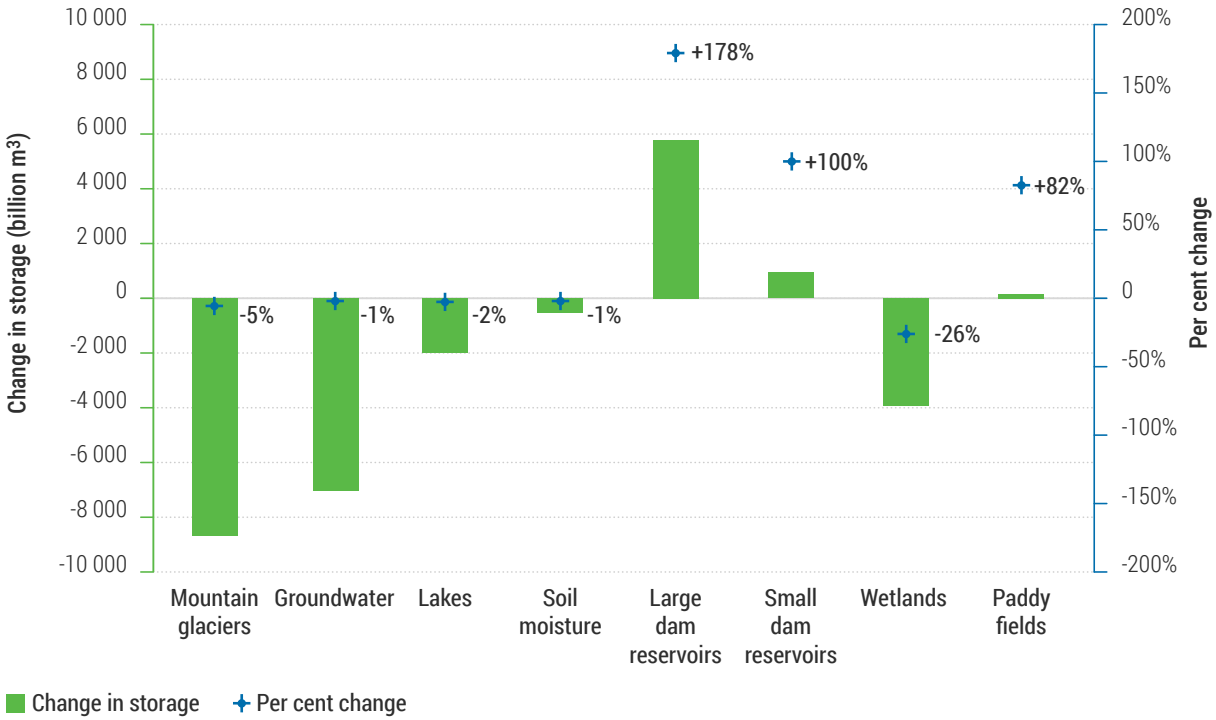
Groundwater level declines (>0.5 m/year) have accelerated in more than 30 per cent of the world's regional aquifers since 2000, when compared to trends from 1980-2000 (Jasechko et al. 2024). However, groundwater level declines have slowed in 20 per cent and reversed in 16 per cent of the world's regional aquifers (Jasechko et al. 2024), reflecting changes associated with natural variation, climate change, drought, human withdrawals, and relevant policy interventions (Jasechko et al. 2024).

6.3.1.2 Environmental flows

Environmental flows are essential for sustaining freshwater ecosystems and encompass measures of quantity, timing, and quality. However, these flows vary by region and catchment, making it challenging to assess global trends. Overall, stream flows are estimated to deviate from pre-industrial ranges across 18.2 per cent of the global land area (Porkka et al. 2024; GCEW 2024).

Groundwater is a critical contributor to sustaining environmental flows, especially during low-flow periods when the risk of losing minimum flows is highest. It has recently been estimated that groundwater sustains 59 per cent of global river flows (Xie et al. 2024). Environmental flow thresholds caused by groundwater extraction have already been exceeded in an estimated 15 to 21 per cent of catchments, particularly in dry climates where the irrigation use of groundwater resources is significant

Figure 6.7: Estimated change in water storage for the period 1971–2020



Source: McCartney et al. (2022)

and natural stream flows are generally lower (de Graaf et al. 2019). These areas include catchments in the High Plains and Central Valley regions of Northern America; arid parts of Mexico; the Upper Ganga basin; the Indus basin; Northeastern America; the Arabian Peninsula including Saudi Arabia, the United Arab Emirates, Oman, Yemen and parts of Argentina (de Graaf et al. 2019).

6.3.1.3 Hydrologic monitoring

Indigenous Peoples across various climate zones have reported observations regarding changes in the hydrological cycle (López-Maldonado et al. 2024; Reyes-Garcia et al. 2024). In the Himalayas, for instance, Indigenous communities have noted alterations in water availability, including drying springs, shifts in freshwater biodiversity (Mukherji et al. 2015), and altered seasonal patterns of local wildlife (Hernandez et al. 2025). In Arctic regions, Indigenous communities have also documented changes in snow types, layers, and permafrost conditions (Krupnik and Jolly 2002; Laptander 2023).

The application of satellite-based Earth observation, along with Indigenous Peoples' observations of components of the water cycle, is helpful in monitoring water quantity and usage by various economic sectors, both in surface water and groundwater. These sources include results from the GRACE gravity method, the Global Precipitation Measurement, and the Tropical Rainfall Measuring Mission (Jasechko et al. 2024; López-Maldonado et al. 2024).

6.3.2 Climate change and the water cycle

The influence of climate change on the water cycle, combined with a growing population and increasing per capita demand for water, profoundly impacts freshwater systems and the communities that depend on them. A warming climate leads to warmer air that holds more water vapour, thereby accelerating aspects of the global water cycle (Held and Soden 2006). However, global models indicate that these climate-driven changes will be unequally distributed in the future, with wet areas becoming wetter and dry areas drier (Konapala et al. 2020). In addition, increases in evapotranspiration may overwhelm precipitation changes over much of the world's land areas in the future (Zaitchik et al. 2023). As climate change intensifies precipitation extremes, accelerating the melting of glaciers, snow, and ice-rich permafrost, and alters the extent of water bodies, future water projections remain highly uncertain, posing challenges for water managers, policymakers, and society.

6.3.2.1 Drought

Trends in drought and their attribution to climate change are related to regional changes in precipitation, temperature, and evapotranspiration patterns (Otkin et al. 2018; Spinoni et al. 2020). Since the 1950s, drought frequency, duration, and maximum intensity have increased in many areas of the world, particularly in parts of the Americas, Africa, Asia (Chiang et al. 2021), and Europe (Böhnisch et al. 2021). Soil moisture has been estimated to deviate from pre-industrial ranges in 15.8 per cent of the global land area (Porkka et al. 2024; GCEW 2024). The IPCC attributes the increase in drought in Southern Australia, Southern Africa, and Southwestern South America to climate change (Caretta et al. 2022). Other regions of Africa, Asia, South America, Australia, and Europe are also experiencing more drought, though with lower confidence in direct attribution to climate change. Conversely, several areas have experienced decreased drought, but with little evidence of anthropogenic influence. These areas include Northern and central Australia, Southeastern South America, central North America, and Northern Europe, Western and Eastern Siberia (Caretta et al. 2022).

Flash droughts refer to those droughts that develop and intensify rapidly compared to typical drought patterns (Otkin et al. 2018). From 1980 to 2015, there was an increase in the occurrences and coverage of flash droughts in central Northern America, central Mexico, the Iberian Peninsula, Asia Minor, Brazil, the Sahel, and Southeastern Australia (Christian et al. 2021). Several other regions experienced a decreasing trend in flash droughts, including India, the Great East African Rift Valley, and Northern Australia (Christian et al. 2021). With high confidence, IPCC (Caretta et al. 2022) reported that the increasing extent and duration of drought are linked to the drying of continental water bodies, including wetlands, thus affecting freshwater ecosystem services. Drought also affects ecological, agricultural, and land-based ecosystems (Chapter 4.3.2.1), as well as human water security (Section 6.6.1).

6.3.2.2 Extreme floods

Floods are one of the most common natural hazards, causing significant repercussions on society (CRED 2023). They can be extremely destructive, disproportionately affecting vulnerable populations (Nearing et al. 2024).

Since the mid-20th century, the frequency of heavy precipitation events, a key driver of extreme floods, has increased in more regions than it has decreased, with high confidence in well-observed areas, such as Western Europe and North America (IPCC 2022).

Land-use change and management also contribute to flooding by increasing impervious cover and reducing the water-absorbing capacity of soils and wetlands (Rogger et al. 2017; McGrane et al. 2016). In temperate climate zones, the magnitude of extreme flood events has increased, whereas in arid, tropical, polar and cold climates, flood magnitudes have generally decreased (Slater et al. 2021). Flood events have been documented to affect human communities across many countries (WMO 2022).

In terms of flood occurrence rates, recent large events across Europe, Asia, Latin America, and Africa suggest an increasing trend. However, millennial-scale records of flood magnitude show that extreme floods have occurred throughout the record when human influence was minimal (Benito et al. 2003; Ngo et al. 2023; Yu et al. 2023).

More consistent and accessible data sets, spanning both time and space and not limited to regional records or post-event compilations, would enable a more accurate assessment for a global picture of the occurrence of extreme floods and droughts (Schlef et al. 2019; He et al. 2020). The application of new tools, such as artificial intelligence, enhanced data-collection and analysis, and remote sensing technologies, also presents tremendous potential for monitoring floods and developing sustainable solutions (Das and Chowdhury 2024).

6.3.2.3 Snow cover and glaciers

Climate change is driving substantial changes to glaciers, permafrost, land ice, and snow cover worldwide, particularly in middle and high latitudes and high-mountain areas (Caretta et al. 2022). The melting and thawing of glaciers and land ice, along with decreased snow cover and shifting seasonal melting patterns, are driven by rising temperatures and changes in precipitation (Caretta et al. 2022). The combination of long-term monitoring by Indigenous Peoples (Deemer et al. 2018; Hauser et al. 2023) and innovative remote sensing techniques has enabled better tracking of these declines in recent years (Roessler and Dietz 2022).

The extent, mass, and duration of snow cover are changing in many areas of the world. Changes in snow cover extent are most pronounced in the Northern Hemisphere, where snow cover peaked in the mid-20th century and has followed a steady decline since 2000 (Mudryk et al. 2020). Globally, snow cover duration has decreased on average by 0.44 days per year between 2000 and 2022 (Roessler and Dietz 2023). These declines are most significant in the Northern Hemisphere, where the length of snow-dominated seasons has declined at a rate of 2 to 6.5 weeks every decade, primarily due to earlier season snowmelt (Fox-Kemper et al. 2021). These changes further impacted the seasonality and magnitude of flow in snow-fed streams, particularly in the Southwest of the Russian Federation, Western United States of America, and Central Asia (Huss et al. 2017; Caretta et al. 2022).

Rising temperatures continue to drive substantial rates of loss in global glaciers (Fox-Kemper et al. 2021; Caretta et al. 2022; Rodell et al. 2018; McCartney et al. 2022; Immerzeel et al. 2020). At the regional level, most glaciers are declining in mass, with some exceptions in Central Asia and South America (Fox-Kemper et al. 2021; Caretta et al. 2022), where changes in debris cover on glacier surfaces are reducing rates of melt (Compagno et al. 2022). Increasing glacial melt is driving a notable 50 per cent increase in the volume and area of glacial lakes (Shugar et al. 2020). The expansion of glacial lakes and the collapse of unstable natural dams are also increasing glacial lake outburst flood events, further threatening downstream populations in high-risk regions such as India, Pakistan, Peru, and China (Taylor et al. 2023). Glaciers in the Canadian Rocky Mountains, European Alps, tropical Andes, and Northern Caucasus have reached or exceeded their peak water stage (Caretta et al. 2022).

Snowmelt is often harnessed into agriculture as irrigation water. It is estimated that 16 per cent of this snowmelt is used for agricultural products, with over 70 per cent of these products originating from Pakistan, India, China, the United States of America and countries of the former Soviet Union (Qin et al. 2022). Irrigation systems in regions dependent on glacial and snowmelt run-off are threatened by the accelerated melting of glaciers, earlier snowmelt, and a transition in some areas from precipitation falling as snow to rain (Caretta et al. 2022). Changes in snowmelt run-off require climate change adaptation strategies that address reduced water storage in snowpacks and reflect landscape changes such as sediment transport and erosion (Li et al. 2022a).

6.3.2.4 Evaporation from lakes and reservoirs

Each year, nearly 340 km³ of fresh water evaporates from the world's largest 7,242 reservoirs (Tian et al. 2022). These losses, recorded between 1985 and 2016, are rising by about 2 km³ per year due to climate change and the construction of new dams in middle-income countries (Tian et al. 2022). Additionally, the evaporation volume from 1.42 million natural lakes globally was estimated at 1,500 km³ per year from 1985 to 2018 (Zhao et al. 2022), increasing at a rate of 3.12 km³ per year. Since evaporation from an open water body is inevitable, particularly in the case of reservoirs, planning for additional storage upstream to compensate for this water loss will be necessary in the future.

6.3.3 Land degradation and the water cycle

Land degradation affects the hydrological system by altering run-off, rainfall infiltration, erosion, and evapotranspiration, which decreases the water availability for both humans and the environment (UNESCO 2019; Hrachowitz et al. 2021; IPCC 2022). Land degradation also releases stored soil organic carbon, contributing to climate change and associated consequences for the water cycle (Amelung et al. 2020; Prăvălie et al. 2021).

6.4 Water quality

6.4.1 State and trends of freshwater quality

Freshwater quality has declined globally since the 1990s and is expected to worsen further, leading to increased threats to human health and ecosystems (du Plessis 2022). Numerous sources of pollution drive the deterioration.

6.4.1.1 Nutrients, eutrophication, and harmful algal blooms

Eutrophication of freshwater occurs when excess nutrients, primarily nitrogen and phosphorus, accumulate in the water column and bottom sediments (Rathore et al. 2016; Zhang et al. 2023). Nutrient pollution typically comes from agricultural run-off containing fertilizers and animal waste, as well as municipal wastewater and urban stormwater. This process often leads to harmful algal blooms and toxin production, along with low dissolved oxygen levels (Pilla and Williamson 2023), which have known impacts on aquatic ecosystems and human health (Namsaraev et al. 2020). The concentration of dissolved oxygen levels in freshwater is critical for healthy fisheries, since few fish species can grow or reproduce in oxygen-poor water (Luo et al. 2024). Often, the most affected freshwater systems are those located downstream of sewage discharges and agricultural areas that generate nutrient run-off from fertilized fields.

Satellite imagery analysis of freshwater lakes, covering 57 per cent of the global lake area, shows that nearly 9 per cent experienced an increase in the severity of harmful algal blooms between 1982 and 2019. The frequency of harmful algal blooms also rose globally, with the most significant increases observed in Asia, South America, and Africa. These regions also show the highest dependence on agricultural fertilizers (Hou et al. 2022). Notable examples of freshwater lakes severely affected by harmful algal blooms include Lake Erie (United States of America/Canada) (Schaefer et al. 2024), Lake Okeechobee (United States of America) (Dang et al. 2023), Lake Winnipeg (Canada), Lake Victoria (Uganda/Kenya/the United Republic of Tanzania), and Lake Taihu (China) (Sha et al. 2021).

6.4.1.2 Pathogens

In 2022, around 22 per cent of the world's population was using a drinking water source that had been contaminated with sewage. The resulting microbial contamination poses the greatest health risk to safe drinking water globally, particularly in highly populated areas of Africa, Asia, and Latin America (WHO 2023). Fecal coliforms and pathogens primarily originate from untreated sewage, wild animals, livestock waste, stormwater discharge, and agricultural run-off. Contaminated waters may contain total coliforms, E. coli, Enterococci, Cryptosporidium parvum, and Clostridium perfringens, along with pathogens, such as Salmonella and Vibrio cholerae O1 or O139, which cause cholera (Kanungo et al. 2022). The health repercussions from waterborne pathogens are discussed in section 6.6.2.1.

6.4.1.3 Suspended sediment

Suspended sediments in freshwater systems result in increased water turbidity and degradation of freshwater quality. Sediment pollution in water bodies is related to increased erosion associated with deforestation, intensification of agriculture, and urbanization. Erosion is known to facilitate the transport of other pollutants, including nutrients, hydrocarbons, humic

Image 6.3 Plastic waste in a remote mountain lake. Credit: bilanol/Envato

substances, and metals, which are typically mobilized during high discharge events (Rügner et al. 2019; Sandström et al. 2020). Suspended sediments also reduce water clarity and obstruct the exchange of gases and nutrients between aquatic habitats and the water (Chen et al. 2022).

At a global scale, approximately 40 per cent of the world's largest rivers have undergone significant changes in suspended sediment flux. Notably, there are increasing trends in water and sediment fluxes in large rivers – the Yellow River in Asia, the Mississippi River in North America, and the Amazon River in South America, for example– over the past 5 to 10 years (Li et al. 2020a; Li et al. 2020b).

Satellite-based estimates of suspended sediment concentration in 414 major rivers reveal strong links to human activity. In the Northern Hemisphere dam construction has reduced sediment flux in downstream rivers compared to pre-dam conditions. For example, an analysis of sediment flux in six rivers in China showed that, from the mid-1950s to 2020, dam construction, water consumption, and land-use changes have reduced sediment delivery to the sea by 49 per cent, 25 per cent, and 19 per cent, respectively (Wang et al. 2022a; Yin et al. 2023). In contrast, in the Southern Hemisphere, land degradation driven by urbanization, forest clearing, and agricultural intensification has increased soil erosion, with suspended sediment concentration averaging 41 per cent higher than levels observed in the 1980s (Dethier, Renshaw and Magilligan 2022; Gardner et al. 2023).

6.4.1.4 Emerging contaminants

Emerging contaminants represent a category of pollutants that are not yet widely monitored or regulated despite their presence (Li et al. 2024). This category includes per- and poly-fluoroalkyl substances (PFAS), hormones, cyanotoxins, detergents, pharmaceuticals, industrial chemicals, personal care products, flame retardants, veterinary medicines, nanomaterials, and microplastics (Anagnostopoulpou et al. 2022; Chakrborty et al. 2023; El-Kalliny et al. 2023; Lim 2023; Mariano et al. 2023; Naeem et al. 2023; Osuoha et al. 2023).

Emerging contaminants are noted for their low biodegradability and recalcitrance characteristics (Olatunde et al. 2020) and are found in nearly all water supplies globally (Pastorino and Ginebreda 2021; Wilkinson et al. 2022; Chandra and Walsh 2024). For instance, up to 74,500 microplastic particles/L have been identified in the Brazilian Amazon and its tributaries (dos Santos Silva et al. 2024), in urban streams (Rico et al. 2023) (**Image 6.3**), and in drinking water sources in the United States of America and Europe (Kosuth et al. 2017), as well as in remote mountain lakes (Machate et al. 2023). In low-income countries, the direct disposal of medical waste into rivers is a common practice, often containing pharmaceuticals alongside harmful microorganisms.

Many pharmaceuticals and other personal care products remain in wastewater after treatment

Image 6.4. Credit: wirestock/Envato

(Ferrando-Climent et al. 2014; Archer et al. 2023; Malnes et al. 2023; Su et al. 2023) and can persist and be biologically active, as endocrine disruptors for instance, in the environment (Feng et al. 2023). A recent study involving 1,052 sampling sites in 258 rivers across 104 countries and all continents reported the presence of pharmaceutical compounds in all samples (Wilkinson et al. 2022).

Derived from many consumer products, PFAS have also been reported in rivers, streams, lakes, water supply wells, and treated wastewater (Sims et al. 2014; Haddaoui and Mateo-Sagasta 2021; Shehu et al. 2022; Maggi et al. 2023), rainwater (Evich et al. 2022), stormwater run-off (Kali et al. 2025), and aquifers (Xu et al. 2021). Most PFAS withstand degradation from normal chemical, physical, or biological processes, while some degrade into other PFAS (Gaines 2022). The use of PFAS-contaminated water affects growth, learning, and behaviour in infants, lowers fertility in women, increases cholesterol levels, compromise and weaken the immune system and potentially reduce the effectiveness of vaccines (Anderko and Pennea 2020).

Nanomaterials may have cellular-level human toxicity suggesting potential health risks for non-human species as well (El-Kalliny et al. 2023; Kumah et al. 2023; Singh et al. 2024). A new category of micropollutants that threatens natural environments is microfibres. Their rapid degradation could release toxic compounds and result in long-term accumulation in groundwater and sediments (Balestra et al. 2024).

6.4.2 Land degradation and water quality

Soil erosion and sediment transport to low-lying areas are natural geological processes. However, human activity intensifies this phenomenon through deforestation, agriculture, mining, and changes in land use, including urban expansion. Erosion generates a complex mixture of fine sediments, minerals, chemicals, and organic matter that is transported to freshwater systems (FAO 2019) (**Image 6.4**). Land degradation is estimated to affect 34 per cent of cropland and pasture through erosion (FAO 2022b). Globally, the mean annual soil loss ranges from 8 to 50 t/ha per year (FAO 2019). This sediment build-up disrupts ecosystems by choking bottom-dwelling organisms. As sediments are deposited in streams and reservoirs, storage capacity gradually declines, and reservoirs eventually become unusable. At the catchment level, revegetation and soil conservation can reduce system vulnerability (Adeloye and Dau 2019).

There are also accounts of land degradation resulting from poor water quality. For example, soil salinization through hypersaline water intrusion or irrigation with saline water can render land unsuitable for agriculture over time. Similarly, soil hypersalinity has been reported to coincide with drought and waterlogging (Issanova et al. 2022), effectively resulting in land degradation.

6.4.3 Climate change and water quality

Climate change is driving increases in the temperature of freshwaters with effects on water quality, chemical

reactions, and aquatic ecosystem health (Souaissi et al. 2021). Furthermore, warmer water temperatures have been linked to the growing frequency and severity of harmful algal blooms worldwide (Gobler 2020; IPCC 2021; Sha et al. 2021; IPCC 2022; Nijhawan and Howard 2022; Elhabashy, Li and Sokolova 2023), especially in semi-arid regions (Ali, Abiye and Adam 2022; Johnson et al. 2024). An increase in ambient temperature is also linked to higher concentrations and persistence of E. coli in surface water used for human consumption and recreation (Nijhawan and Howard 2022). Higher temperatures further accelerate the evaporation of surface water, resulting in more saline water with diminished quality. Likewise, drought caused by increased temperatures also concentrates contaminants in smaller areas due to water loss from evaporation.

Increased rainfall intensity, linked to climate change, leads to high run-off and stormwater overflows, accelerating the transport of pollutants to freshwaters. Furthermore, extreme flooding events in urban areas damage wastewater treatment and drinking water infrastructure, causing the release of untreated wastewater and contamination of drinking water supplies (Nijhawan and Howard 2022). Additionally, flooding of dry soils promotes nutrient leaching, raising nutrient levels in water bodies (Kelly et al. 2020; Jansen et al. 2024; Khan et al. 2024).

Rising sea levels, driven by climate change, combined with excessive withdrawals of groundwater, are resulting in the seawater intrusion and subsequent salinization of important coastal aquifers around the world, compromising drinking water sources for many coastal populations (Ketabchi et al. 2016; Hussain et al. 2019; Basack et al. 2022), particularly affecting the most vulnerable communities in small island developing states (UNESCO 2015).

Large wildfires have become common around the world, partly due to climate change, with examples in Greece, Australia, Canada, Chile, Brazil, Argentina, South Africa, and California in the United States of America (Girona-García et al. 2021). The loss of vegetation due to large fires contributes to soil erosion, which reduces water quality in rivers and reservoirs. For example, following the 2021 fires in Greece, erosion accelerated on 3,600 km² of land (Evelpidou et al. 2022).

The environmental fate of persistent organic pollutants in Arctic ecosystems depends on a multitude of complex, interrelated factors, including environmental conditions, the persistent nature of these pollutants, and biological conditions. Climate change is concurrently altering many of these processes, particularly in polar regions (AMAP 2021).

Despite the wealth of literature on the role of climate change in water quality, the influence of water quality on climate is poorly understood. Similarly, climate change adaptation strategies seldom focus on the water quality challenges intensified by climate change, which increases vulnerability for freshwater systems and human communities in the short term (Bartlett and Dedekorkut-Howes 2023).

6.5 Freshwater biodiversity

Climate change, invasive species, pollution, overexploitation, and land-use change have all been reported to drive biodiversity loss in freshwater ecosystems (Taniwaki et al. 2017; Petsch et al. 2022; Geng et al. 2022; Liu et al. 2023). The combined occurrence of these pressures impacts global freshwater biodiversity change, especially in large basins (Jaureguiberry et al. 2022; Haase et al. 2023). Dams alter water and sediment fluxes, affecting habitat availability and limiting migratory patterns, which in turn modify local population dynamics and freshwater community composition. Pollution and land-use changes in the terrestrial landscape pressure freshwater biodiversity by selecting against non-resistant and slow-growing species. Climate change impacts water temperature and hydrologic patterns, further compounding these effects on freshwater ecosystems.

6.5.1 State and trends of freshwater biodiversity

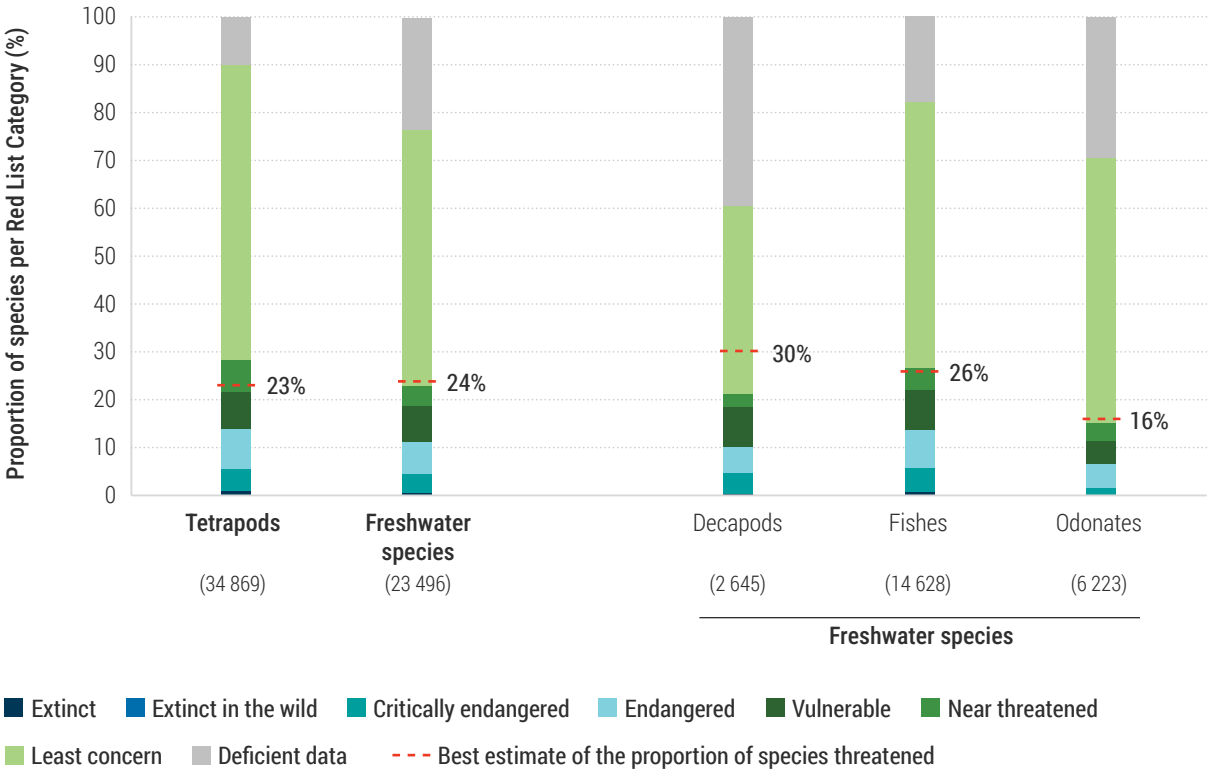
Freshwater ecosystems show the steepest rates of decline when compared to most terrestrial and marine ecosystems. Among the various types of freshwater ecosystems, wetlands face the greatest threats, vanishing three times faster than forests (Fluet-Chouinard et al. 2023). Globally, less than 13 per cent of the wetland area that existed in 1700 remains today (Ramsar Convention on Wetlands 2018). Freshwater species are declining at an alarming rate, with recent estimates suggesting that 24 per cent of all freshwater species are threatened

with extinction (Sayer et al. 2025). Recent surveys estimate that 89 freshwater species are extinct, and an additional 178 are suspected of being extinct (Sayer et al. 2025). Aquatic tetrapods are the most threatened group (**Figure 6.8**) and, among them, amphibians represent the most endangered class, with 40.7 per cent of species threatened worldwide (Luedtke et al. 2023).

The probability of extinction is not evenly distributed among different regions. Tropical areas of South America, Africa, Southeast Asia, and the central parts of the United States of America display the highest probabilities of new extinctions of freshwater vertebrates (He et al. 2021; Verones et al. 2022). The richness, distribution, and abundance of certain aquatic invertebrates – aquatic insects, mollusks, and plankton species – are generally much less understood than those of freshwater vertebrates and large invertebrates. However, there is a documented decline across all major insect orders. Among aquatic invertebrates, decapods, such as shrimps and crabs, exhibit the highest percentage of threatened species at 30 per cent, followed by odonates, including dragonflies and damselflies, at 16 per cent (Sayer et al. 2025).

Other aspects of biological diversity – including genetic diversity, functional diversity, community composition, and ecosystem diversity – have been less assessed on large geographical scales. For example, genetic diversity of freshwater fish species shows only weak correlation with species diversity and is declining faster than species richness (**Image 6.5**) (Van Leeuwen et al. 2018; Manel et al. 2020). Future losses of 10 to 20 per cent in the functional diversity of freshwater fish may occur if currently near threatened (NT) and threatened species, including critically endangered (CR), endangered (ER), and vulnerable (VU), on the International Union for the Conservation of Nature (IUCN) Red List, become extinct (Toussaint et al. 2021), with the Palearctic, Neoarctic, and Australia being the most threatened realms. If data deficient (DD) species are included, these figures could reach 30 per cent, and the data-poor Neotropical and Indo-Malay realms would likely be similar (Toussaint et al. 2021).

Figure 6.8: Extinction risk of tetrapods and freshwater species



Note: The numbers in brackets are the total numbers of species assessed.

Source: Sayer et al. (2025)

Image 6.5. Credit: GreensandBlues/Envato

Changes in community composition typically occur at much lower levels of environmental threat than the established thresholds of altering species richness. In many parts of the world, the composition of fish communities displays remarkable changes even with low levels of urbanization and agricultural land use (Chen and Olden 2020; Cantera et al. 2022). Early changes in community composition are associated with the loss of native specialist species and the range expansion of more tolerant non-native species under degraded conditions (Chen and Olden 2020). Community composition can also shift gradually in response to long-term environmental changes. For instance, rising surface water temperature over the past century has led to the homogenization of cyanobacterial community composition in European alpine lakes (Monchamp et al. 2018).

The loss of freshwater biodiversity results in significant ecological impacts, including decreased ecosystem productivity and resilience. It can also affect cultural diversity, Indigenous Knowledge systems, food security, health, and livelihoods (IPBES 2019). Additionally, it contributes to economic, social, and cultural consequences, such as lost opportunities for recreation and tourism.

6.5.2 Pollution and freshwater biodiversity

Pollution remains one of the main threats to freshwater biodiversity (Le Moal et al. 2019), with various pollutants threatening natural freshwater systems in ways that are hard to measure because of their cumulative effects (Taniwaki et al. 2017). Among these pollutants, inorganic and organic nutrients are of particular concern, along with emerging contaminants. The effects of pollution on freshwater biota include behavioural disruptions, physiological damages, morphological abnormalities, and embryonic and developmental changes (Malik et al. 2020). Pollution also leads to diversity loss and ecological simplification of freshwater communities, as seen in the lakes of the Yangtze River Delta, the most industrialized region in China (Mei et al. 2020; Chen et al. 2020; Wang et al. 2021; Zhang et al. 2021).

Elevated levels of nutrients from urban, industrial, and agricultural catchments contribute to the accelerated growth of primary producers, especially nutrient-demanding species like cyanobacteria, through eutrophication. This excessive growth reduces the diversity of the primary producer community, leading to biotic homogenization (Li et al. 2022b). Additionally, these primary producers, sometimes toxic, are often less palatable to their consumers, causing disruptions in food webs and a decline in diversity across trophic levels (Karpowicz et al. 2020). The unconsumed surplus biomass produced by these primary producers accumulates in sediment, where its decomposition depletes oxygen resulting in a condition called anoxia, intensifying the release of greenhouse gases, like methane and nitrous oxide, and can trigger mass die-offs. For example, seven fish mass mortality events in Moroccan freshwater ecosystems were directly linked to elevated nutrient levels, algal blooms, and anoxia (Baladia et al. 2025).

Assessing the impact of other anthropogenic pollutants in natural settings at broader scales, such as heavy metals, pesticides, hormone and microplastics, remains challenging. However, their potential harm to biota, mainly through processes like

bioaccumulation, is significant (Reid et al. 2019; Bhatt and Chauhan 2023). Overall, pollution has caused widespread deterioration in the quality of freshwater ecosystems. This decline threatens the sustainability of aquatic life and the essential services these ecosystems provide.

Microplastics interact with fish tissues; however, the extent of bioaccumulation in organisms and biomagnification in food webs remains unclear (Azevedos-Santos et al. 2021). Emerging contaminants in water such as microplastics and agrochemicals can persist in invertebrates, fish, and reptiles, causing toxic effects, disrupting reproductive and developmental functions (Marlatt et al. 2022), and altering their feeding and migration behaviours, for example (Saha & Dutta 2024).

Due to their small size and resistance to degradation, microplastics can be consumed by fish and accumulate in aquatic organisms. Furthermore, they have the potential to enter the food chain, posing risks to both ecosystems and human health. Evidence of microplastic ingestion has been reported in more than 150 fish species from both freshwater and marine systems (Khan et al. 2024). The ability of microplastics to translocate to other tissues depends on fish size (McIlwraith et al. 2021), and retention time and bioaccumulation dynamics may vary across fish species (Sulaiman et al. 2023). Similarly, in plants, the effects of microplastics vary depending on polymer type, particle size, dosage, time, and plant species (Wang et al. 2022b). Thus, across plant and animal species, the movement of pollutants may be influenced by the level of biodiversity.

6.5.3 Land degradation, dams, and freshwater biodiversity

Dam construction, wetland drainage, fragmentation, and modification of river channels alter the structure and functioning of freshwater ecosystems, thereby threatening freshwater biodiversity. Since the 1970s, over a third of the world's wetlands and floodplains have been lost due to drainage, agricultural conversion, excessive irrigation, and river modification (Ramsar Convention on Wetlands 2018; Convention on Wetlands 2021).

Habitat fragmentation caused by dam construction has led to a decline in global freshwater biodiversity (Wu et al. 2019; Su et al. 2021). Overall, the most vulnerable species are those adapted to habitats with fast currents, structural complexity and flood pulsing, or those dependent on inter-basin connectivity for their life cycle (Arantes et al. 2019). For example, habitat alteration, division, and loss significantly contribute to the decline of migratory freshwater fish (Deinet et al. 2024), despite some successes using fish ladders and other methods to mitigate these consequences. Comparing the historical and current distribution of migratory freshwater fish in Europe and China, a significant decline in the number and abundance of species was observed (van Puijenbroek et al. 2019; Huang and Li 2024). The remaining viable populations are limited to very few rivers that are unaffected by dams (van Puijenbroek et al. 2019).

6.5.4 Climate change and freshwater biodiversity

Climate change poses a substantial threat to global biodiversity, with freshwater species and ecosystems being disproportionately vulnerable (Urban 2024). Freshwater ecosystems are warming and losing oxygen due to climate change. However, the main risks to global freshwater biodiversity arise from changes in flow patterns and water temperatures. Reduced water flow causes freshwater ecosystems to shrink and disrupts connectivity among them. This results in declines in the population sizes of low-dispersal freshwater species (Troia et al. 2019) and changes in the interactions among species, such as competition and predation (Costa et al. 2022).

Simultaneously, increases in water temperature have profound effects on the physiology of aquatic species, pushing them towards their thermal maximum during extreme heat conditions (Li et al. 2022b; de Visser et al. 2023). These threats are worsening, posing the greatest risk to species with limited dispersal capabilities, smaller body size, and restricted geographical ranges, particularly in tropical and subarid regions worldwide (Barbarossa et al. 2021; Manjárres-Hernández et al. 2021; Li et al. 2022b). In severe cases, drought can cause freshwater systems to dry out (**Image 6.6**), leading to mass die-offs of all freshwater organisms, as seen in the 2023 Amazon drought (Braz-Mota and Luis Val 2024).

Climate change has received greater attention regarding its impact on freshwater fish compared to other groups of freshwater organisms. In a warming world, 36 per cent of freshwater species have more than half of their

Image 6.6 Dried up reservoir. Credit: freedomnaruk/Envato

current geographic range exposed to climate extremes (Barbarossa et al. 2021). Alarmingly, nearly half of all freshwater fish species face the potential complete loss of their spatial ecological niches (Manjárres-Hernández et al. 2021). Amazonian and African fishes are especially threatened. Nearly one-sixth of African freshwater fishes have already been classified as endangered or vulnerable to extinction by the IUCN Red List assessment (IUCN 2025) with accelerating trends of species decline (WWF 2025). Climate change further threatens their survival, with almost 40 per cent of African freshwater fishes considered vulnerable to climate change (Nyboer et al. 2019).

Certain African regions, such as the African Rift Valley lakes, the Congo River basin, and the coastal rivers of West Africa, face increased risks. In the Andean Amazon, a significant share—ranging from 60 to 68 per cent—of freshwater fishes are expected to see a reduction in their distribution range, with 7 to 17 per cent at risk of losing all suitable habitats (Herrera-R et al. 2020). Compounding the issue, over 60 per cent of freshwater fish species are not covered by protected areas that meet the minimum required range for species survival under future climate scenarios for (Frederico et al. 2021). This limitation diminishes the potential effectiveness of these protected areas in the future conservation. Finally, while less extensively studied, other groups of aquatic organisms will also face significant consequences from climate change, including aquatic insects, amphibians, and mammals (GEO BON and FWBON 2022). Notably, nearly three-quarters of native freshwater decapod species are expected to be significantly affected by climate change (Toh et al. 2022).

6.5.5 Biological invasions and freshwater biodiversity

Aquatic invasive species – transported in ballast water, by boating, and through illegal trade – can alter hydrology and diminish water quality, and they are one of the primary threats to freshwater biodiversity. Freshwater aquatic invasive species are increasing globally across all taxonomic groups, including invertebrates, vertebrates, and plants across wetland, lake, and river habitats (Seebens et al. 2023). Globally, riparian habitats are among the most invaded habitats by all groups of animal taxa except insects (Seebens et al. 2023). Mollusks and crustaceans exhibit the highest increasing rates of invasive species among several terrestrial and aquatic groups (Seebens et al. 2023). Other examples of species that have damaged the ecological health of rivers include the Amazonian water hyacinth (Eichhornia crassipes), the feral African common hippo (Hippopotamus amphibius) outside Africa, and the Asian Basa catfish (Pangasianodon hypophthalmus) in the Magdalena River (Salgado et al. 2022).

Aquatic invasive species are often associated with changes in water quality, geomorphology, and flow patterns of aquatic ecosystems. The introduction of bivalve mollusks is a clear example. Without natural predators, their populations can expand rapidly, greatly affecting the ecosystem. For example, high abundances of zebra mussel (Dreissena polymorpha), quagga mussel (Dreissena rostriformis bugensis), and golden mussel (Limnoperna fortunei) enhance water clarity, remove pollutants, and reduce

eutrophication by decreasing turbidity and suspended organic matter in the water column (Burlakova et al. 2023). However, these organisms also colonize drinking water and energy infrastructure in reservoirs, where consolidated substrates are plentiful (Catford 2017).

North American mussel populations are facing alarming declines, including species loss and a significant decrease in abundance (Aldridge et al. 2023). This situation is caused by multiple factors. The widespread proliferation of non-native competitors, such as zebra and quagga mussels, has resulted in declines of native mussel populations due to intense competition. The invasion of zebra mussels in the Great Lakes, North America, has reached densities over 700,000 individuals per square metre, leading to reduced water flow in infrastructure and significant economic impacts (Strayer 2009; Rosaen et al. 2012). Extensive overexploitation of food resources and pearls has significantly depleted native mussel population. Additionally, dam construction has disrupted sediment and nutrient transport, altering the presence of quality habitats in major river basins, directly affecting the occurrence of native species and their feeding behaviour. Droughts induced by climate change have further worsened the crisis, causing mass mortalities. Although these primary drivers are well understood, less-recognized chronic stressors also play a substantial role in the ongoing decline of mussels (Haag et al. 2019). As a result, nearly 50 per cent of North American mussels are now classified as extinct, possibly extinct, critically endangered, endangered, or vulnerable according to the latest IUCN assessment (IUCN 2022).

Introduced fish species, used for recreational fishing, pest control, and aquaculture, can also affect water quality in freshwater ecosystems. Introduced fish, including tilapia native to Africa (Yongo et al. 2023), non-native trout (Fausch 2007; Tiberti et al. 2014; Miró and Ventura 2020), Nile Perch (Syanya et al. 2024), and invasive carp (Camargo and Amorim 2020), are linked to the destruction of native aquatic communities, increased eutrophication and higher nutrient pollution, the spread of pathogens, and higher concentration of suspended materials in the water column (Tiberti et al. 2014; Yongo et al. 2023). The presence of tilapia is linked to high levels of eutrophication in some ecosystems, similar to invasive carp and crayfish in other regions (Camargo and Amorim 2020). The introduction of Nile perch (Lates niloticus) to Lake Victoria in 1954 has led to the extinction of over 200 endemic fish species through predation and competition for food (Syanya et al. 2024).

6.5.6 Overexploitation and freshwater biodiversity

Overexploitation of aquatic species endangers the health and stability of aquatic ecosystems. This problem is especially severe among large-bodied top-predator species due to indiscriminate harvesting and incidental by-catch (Reid et al. 2019). The spectrum of overexploitation spans various taxa, especially fishes, reptiles, and amphibians, driven by diverse factors, such as food demand, recreation, and cultural activities (Stuart et al. 2004; Tregidgo et al. 2020). Historical records of overexploitation of freshwater species date back to the colonial era, exemplified by extensive turtle captures and the destruction of millions of their eggs by Portuguese settlers in Amazonia for meat and oil. The lasting effects of such actions are apparent in the ongoing recovery efforts for affected populations (dos Santos and Fiori 2020). Notably, populations of exploited species are drastically reduced in prominent freshwater bodies. For example, native freshwater mussels in Northern American ecosystems have seen a significant decline in catch per unit effort over the past century, leading to the collapse of the fish industry (Cooke et al. 2023), which affects the food security of key subsistence fisheries. Recent trends in large river basins in China show consistent declines in fish populations and catches (Cao et al. 2024), including Chinese sturgeon in the mainstem Yangtze River, which decreased from about 2,176 individuals in 1980 to fewer than 1,000 in 1989, and around 20 in 2017 (Chen et al. 2020). These trends highlight the current challenges faced by aquatic ecosystems (Chen et al. 2020; Mei et al. 2020). Such high exploitation rates mainly continue in poorer regions where freshwater fishing remains a vital source of sustenance for local communities (Aguirre et al. 2021; Bahtiar et al. 2022).

6.6 Impacts of freshwater system changes on human well-being and human systems

6.6.1 Water security

Global water security refers to the reliable availability of clean freshwater resources to meet social and

economic demands. In this context, security depends on availability, access to services, safety, quality, and effective management of water resources (Gain et al. 2016). Its definitions and measurements continue to evolve. Water security is of particular concern in some regions of Africa and West Asia (Gain et al. 2016).

Regional and national statistics do not reveal water security disparities within individual countries. For instance, Indigenous Peoples in some high-income nations face higher levels of water insecurity compared to the rest of the population (Harper et al. 2020). Water security also disproportionately affects women and girls. Compared to men, women play a larger role in water sanitation and hygiene activities such as washing, bathing, and cooking, making women the most challenged by water scarcity (Kayser et al. 2019). Consequently, women and girls may experience health, psychosocial, political, educational, economic effects, and threats to their well-being due to water insecurity (de Guzman et al. 2023). The gendered dimensions of water security highlight how women's access to water is vital for their health, economic empowerment, and overall well-being.

For small island developing states, water security is particularly concerning due to infrastructure vulnerability to cyclones and storms, saltwater intrusion into freshwater aquifers caused by sea level rise (Filho et al. 2020; Sharan, Lal and Datta 2023), disruptions to the hydrological cycle (Gheuns, Nagabhatla and Perera 2019; Martyr-Koller et al. 2021), and coastal aquifer over-pumping (Hussein et al. 2019; Basack et al. 2022).

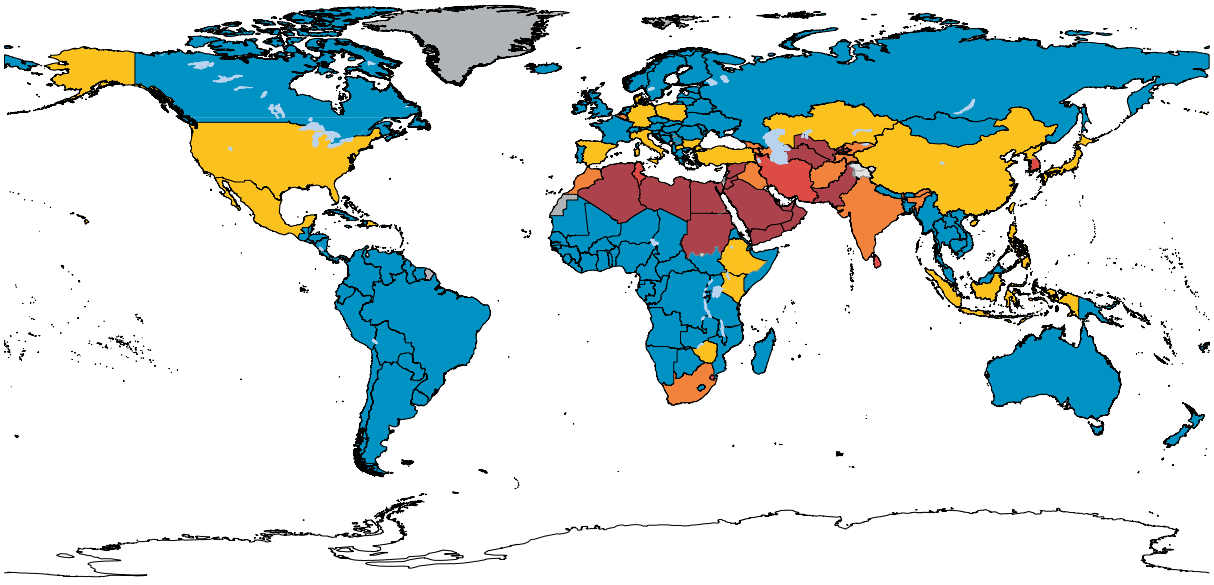
Disasters further reduce water security by causing immediate water shortages. For example, if a community already faces water insecurity, sudden or slow-onset disasters will intensify vulnerabilities, preparedness, response, and recovery efforts (Ho et al. 2019).

6.6.1.1 Water stress

Water stress happens when water demand surpasses the supply of available and safe water resources. Physical water availability per person varies greatly across regions but has been decreasing worldwide due to population growth, drought, climate change, socioeconomic shifts in water needs, and overextraction of vital aquifers. This leads to increased water scarcity and threatens food and energy security (Boretti and Rosa 2019; UN Water and UNESCO 2023).

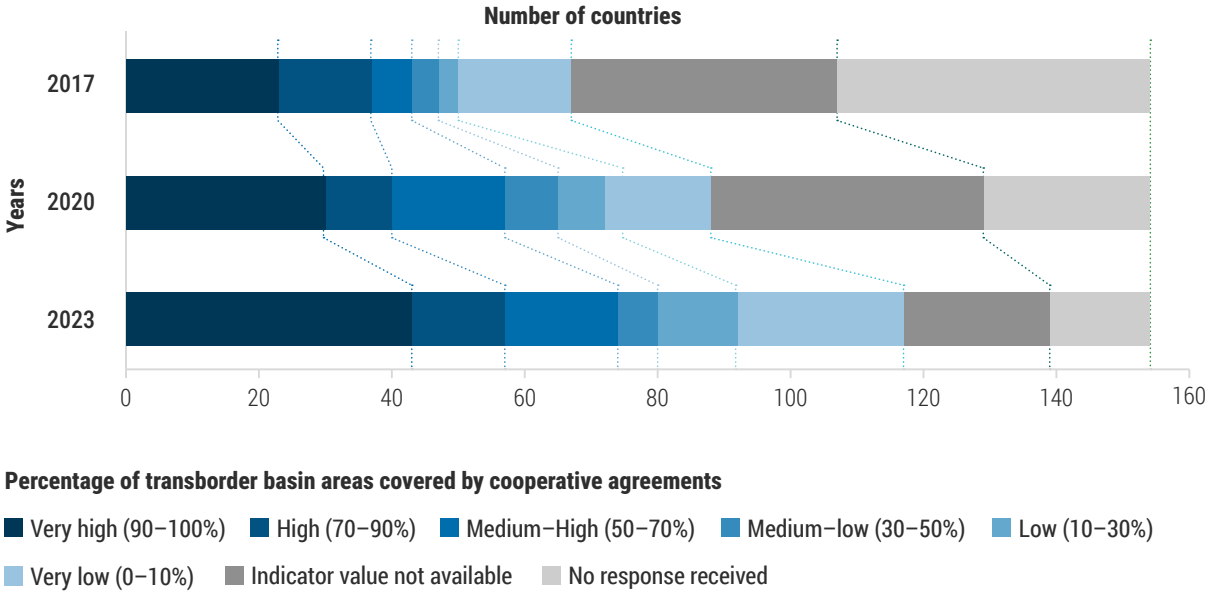
From 2015 to 2020, global water stress measured as freshwater withdrawals as a proportion of total renewable freshwater increased from 18.03% in 2015 to 18.24% in 2020 (FAO and UN Water 2021). These effects are distributed unevenly across the world with

Figure 6.9: Level of water stress by country



Source: FAO and UN-Water 2021

Figure 6.10: Number of countries with 90% or more of their transboundary basin covered by operational arrangements



Source: UNECE et al. 2024

the most water stressed areas found in Northern Africa, and West Asia and the least water stressed areas in the tropics and at high latitudes (**Figure 6.9**).

6.6.1.2 Transboundary waters: Conflict and cooperation

In most parts of the world, water security relies on cooperation in transboundary water management. About 60 per cent of the world's freshwater flows are found in transboundary basins, which include roughly 313 rivers and lakes, as well as 468 aquifers shared by at least two countries. Although only 43 out of the 153 countries sharing transboundary waters have operational cooperative arrangements covering at least 90 per cent of these waters, this reflects nearly double the number reported in 2017 (**Figure 6.10**). The highest levels of cooperation are found in Europe, North America, and sub-Saharan Africa (UNECE et al. 2024). In 2023, the Water Conflict Chronology database recorded 379 armed conflicts related to water resources, showing a sharp upward trend over the past several years (Pacific Institute 2024). Most of these conflicts occurred within a single country, although 38 per cent involved at least two countries. Generally, knowledge-based management and cooperative use of transboundary surface and groundwater are essential to diminish the risk of water conflict.

6.6.2 Human health

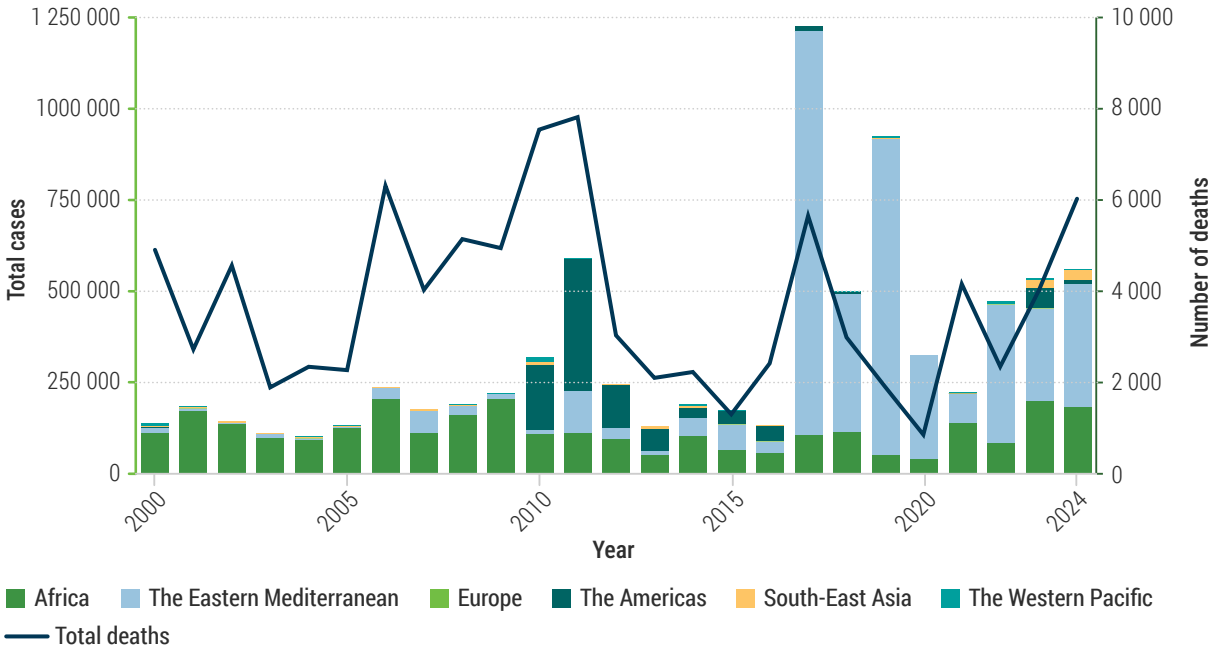
6.6.2.1 Waterborne disease

Waterborne diseases caused by viral or bacterial contamination of drinking water, such as cholera, typhoid fever, giardiasis, gastroenteritis, diarrhoea, hepatitis A, and salmonellosis, are a major cause of death and disability globally. These water-related illnesses lead to 4 billion cases and 3.4 million deaths in children under five years old each year (Osiemo et al. 2019), being especially prevalent among children in developing countries due to poor sanitation (Bhagwat 2019; Rather et al. 2023). The World Health Organization (WHO) reports that in 2019 more than 1 million deaths were caused by diarrhoea, linked to unsafe water, sanitation, and hygiene (WHO 2023). Since 2017, the world has experienced a sharp increase in the seventh cholera pandemic that began in Indonesia in 1961 (Luo et al. 2024), with alarming mortality rates, especially in Asia (**Figure 6.11**). According to the WHO (2023) factsheet on typhoid fever, as of 2019, an estimated 9 million people fall ill from typhoid fever and 110,000 die from it annually worldwide.

6.6.2.2 Health effects of toxic pollutants in water

Many freshwater pollutants are toxic to humans, with effects depending on the type of the pollutant,

Figure 6.11: Cholera cases reported by WHO regions from 2000 to 2024



Source: WHO 2025

the duration and intensity of exposure (Shetty et al. 2023), and the presence of co-pollutants (Chandra and Walsh 2024). Toxicities in humans from heavy metals and metalloids includes neurotoxicity, nephrotoxicity, carcinogenicity, hepatotoxicity, immunological toxicity, cardiovascular toxicity, skin toxicity, genotoxicity, and reproductive and developmental toxicity (Mitra et al. 2022; Saravanan et al. 2022). Pesticides are linked to immunosuppression, hormonal and reproductive system disruptions, and decreased intelligence (Syafrudin et al. 2021). Water pollutants known to affect the heart include lead, mercury, cadmium, arsenic, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons, dioxins, brominated flame retardants, plastic-related chemicals, such as bisphenol A and phthalates, organochlorine pesticides, perfluorinated compounds, hydrocarbons, and pathogens (Rajagopalan and Landrigan 2021; Kshirsagar et al. 2022). Disinfection by-products, heavy metals, dioxins, and PCBs have been shown to affect liver function (Zheng et al. 2021). Human and animal fertility and development are influenced by endocrine disruptors, pesticides, molecules in packaging, plastics, metals, solvents, flame retardants, preservatives, and fracking chemicals (Shulhai et al. 2023), as well as pharmaceuticals associated with industrial and livestock waste (Gonsioroski et al. 2020).

An increasing concern stemming from the use of personal care products and pharmaceuticals contaminated water is the elevated risks by gender. Women are particularly vulnerable, with reported links to higher rates of breast and ovarian cancers, miscarriages, and infertility (Shabaan and Alhajri 2020). Among men, prostate cancer rates are linked to certain chemicals found in hair dyes (Llanos et al. 2023). The long-term impacts of water contaminated by chemicals on young children have also been identified as a critical issue (Shittu et al. 2023).

Metals such as cadmium, chromium, and platinum are known to bioaccumulate in fish due to contaminated water and can pose carcinogenic risks for humans when consumed (Erasmus et al. 2022). Additionally, eating fish contaminated with methylmercury, PCBs, dioxins, pesticides, and plastic waste can cause cancer, kidney failure, adverse neurological effects, and cardiovascular diseases (Abera and Admas 2024).

There are approximately 14 cytotoxin classes identified from various cyanobacteria taxa (Igwaran et al. 2024), including liver toxins, neurotoxins, and others linked to protein disruption, kidney and respiratory failure, and weakened muscles (You and Hua 2019; Silveira and Odebrecht 2019; Filatova et al. 2021; Mohammed and Arockiaraj 2024). Human exposure to cytotoxins can range from mild infections to severe illness or to death (Igwaran et al. 2024). Biosynthetic toxic compounds from plants and cyanobacteria form a chemically diverse

family of at least 20,000 compounds, with phytotoxin monitoring showing that one or more natural toxins are always present in surface water (Hansen et al. 2021).

6.6.2.3 Health effects of elevated fluoride and arsenic in drinking water

Fluoride and arsenic are released from host rocks through water-rock interactions and contaminate groundwater supplies, adversely impacting human health (WHO 2022). High fluoride-containing aquifers are found in the East African Rift Valley with concentrations exceeding 200 mg/L (Mengistu et al. 2019; Mwiathi et al. 2022) and in Asia (Podgorski and Berg 2022). High concentrations of fluoride in drinking water (>1.5 mg/L) are known to cause dental and skeletal fluorosis, while consuming water with arsenic levels above 10 µg/L is associated with cancer and skin lesions. The high toxicity of arsenic has been reported globally, with particularly high incidence in India and Bangladesh (Medunić et al. 2020; Shaji et al. 2021; Stuyfzand and Bonte 2023).

6.6.3 Food security

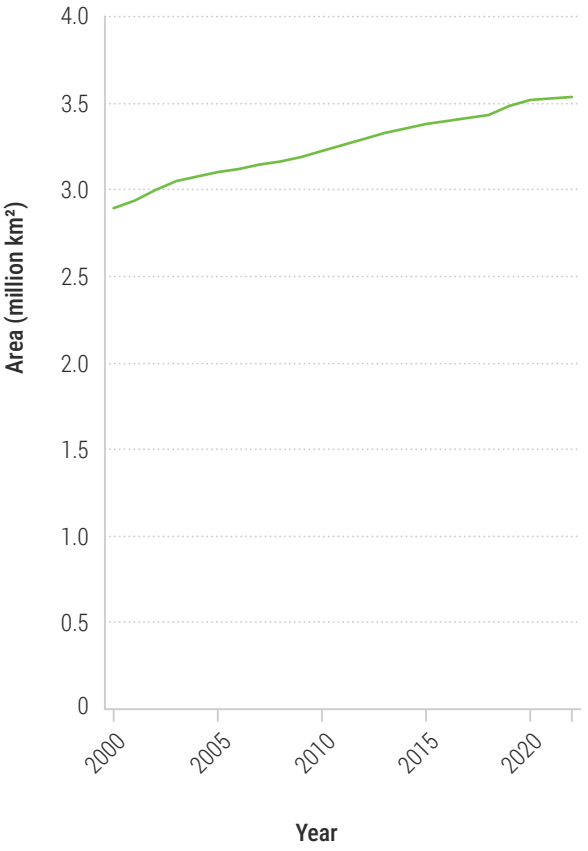
6.6.3.1 Irrigated agriculture

Irrigated agriculture is crucial in securing food supplies for a growing global population, drawing heavily on freshwater from groundwater, rivers, lakes, and reservoirs. About 70 per cent of worldwide groundwater withdrawals are used for food production, supplying water to an estimated 38 per cent of irrigated land (FAO 2022b). However, the overexploitation of groundwater for irrigated agriculture is increasing at a rate of 2.2 per cent per year, leading to a global loss of aquifer storage of approximately 250 km³ annually (FAO 2022b).

Based on FAOSTAT (2025), from 2000 to 2022, irrigated agriculture shows an increasing trend globally (**Figure 6.12**), from 2.9 million km² to 3.5 million km². These increases have been critical to attaining food security for the global population and must be managed as populations grow (FAO 2022b).

The quality of water used in food production and processing affects food quality and safety (Bhagwat 2019). In densely populated areas that generate high volumes of wastewater, using untreated sewage in agriculture presents health risks due to contamination from bacteria, heavy metals, pharmaceuticals, and microplastics (Jaramillo and Restrepo 2017; Pérez-Reverón et al. 2022; Abusah 2023; Mishra et al. 2023). For example, a salmonella outbreak was caused in the United States of America by peppers contaminated with untreated or partially treated wastewater used for irrigation (Uyttendaele et al. 2015). Untreated or partially treated wastewater reuse in agriculture has also been associated with spreading parasitic diseases, such as trichuriasis, ascariaris, and giardiasis, through vegetables in many parts of the world (Amahmid et al. 2023). At the same time, using safely treated wastewater for agricultural activities can help meet the growing water demand globally (Mishra et al. 2023).

Figure 6.12: The trend in the areas equipped for irrigated agriculture from 2000 to 2022

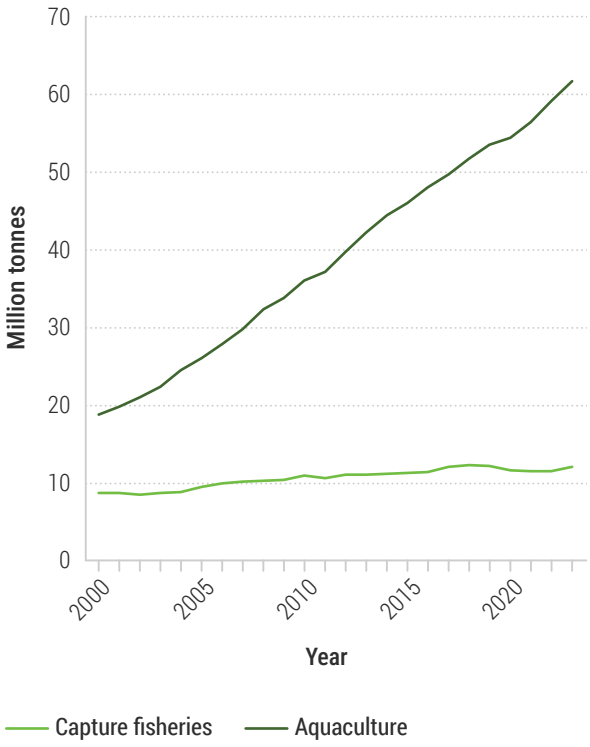


Source: FAOSTAT, 2025

6.6.3.2 Freshwater fisheries and aquaculture

Fisheries and aquaculture production mainly rely on the availability and good quality of freshwater. Inland fisheries are limited to natural freshwater systems such

Figure 6.13: Decadal trend in the capture fisheries and aquaculture production in inland waters



Source: FAO 2024

as lakes, dams, and rivers. Globally, the fisheries and aquaculture sector has become increasingly important for providing food and nutrition, with production steadily rising from 2000 to 2022 (FAO 2024) (**Figure 6.13**). Aquaculture contributes to the economy, reduces poverty, and improves food security. However, researchers highlight that overstocking and excessive feeding of fish can lead to degradation of water bodies, manifesting as eutrophication, toxic algal blooms, loss of biodiversity, anoxia and, in extreme cases, the collapse of fisheries (Legaspi et al. 2015).

6.6.4 Economics and freshwater

6.6.4.1 Value of water-related ecosystem services

Water-related ecosystem services include regulating water flows such as floods, controlling erosion and sediment transport, providing water supply and water purification. On a per-area basis, freshwater wetlands have the highest estimated ecosystem service value of all types at US$1,000,000 per hectare annually (De Groot et al. 2012; UN Water 2021).

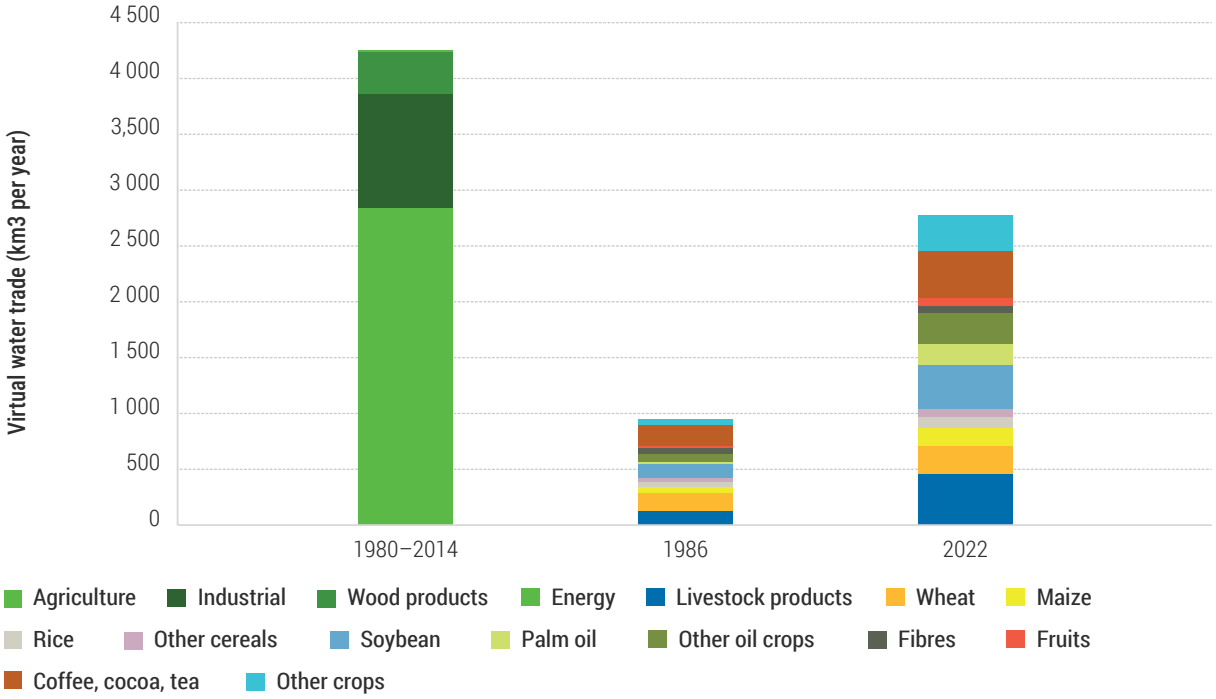
Changes to freshwater systems driven by climate change, water quality decline, and aquatic invasive species have affected various sectors of the economy, including agriculture, industry, navigation and tourism. Examples of these economic impacts include:

- Of the world's total food production, 55 per cent is located in areas experiencing drying or unstable trends in total water storage (Mazzucato et al. 2024).
- Drought and flood-related disasters are estimated to have cost US$34.2 billion and US$44.9 billion in 2022, respectively (CRED 2023).
- The annual costs of eutrophication in freshwater ecosystems are estimated to be US$2.4 billion in the United States of America (Wurtsbaugh et al. 2019).
- Tourism and recreation activities have suffered due to declining snow cover, glaciers, and permafrost in high mountains (Fox-Kemper et al. 2021; Caretta et al. 2022).
- Globally, aquatic invasive species have cost the economy US$345 billion since 1971, with the most significant costs related to invasive invertebrates in North America that have damaged water infrastructure and resources. Generally, costs increased exponentially between 1971 and 2020, with annual costs estimated at US$23 billion in 2020 (Cuthbert et al. 2021).

6.6.4.2 International trade

Virtual water trade refers to the amount of water "embedded" in goods traded internationally (Graham et al. 2020; Mekonnen et al. 2024). It accounts for water stress offset through imports, rather than local production, of water-intensive products (D'Odorico et al. 2019; Rosa et al. 2019; Graham et al. 2020; Mekonnen et al. 2024). Between 1986 and 2022, the volume of virtually traded water across borders increased by 2.9 times, representing 16 per cent of unsustainable water use and 11 per cent of groundwater depletions globally (Rosa et al. 2019; Mekonnen et al. 2024). Around 20 per cent of water used in agriculture is embedded in traded goods rather than domestically consumed. The most

Figure 6.14: Changes in contribution of different products to global virtual water trade (VWT)



Note: Only consumptive water use (green water and blue water) is considered. Between 1980 and 2014, agricultural products accounted for 66% of total virtual water trade, with wood products at 9% and industrial, energy and mining products at 24%. Agricultural virtual water trade is driven largely by livestock, wheat, maize, soybean, oil palm, coffee and cocoa

Source: Mekonnen et al. (2024)

water-intensive exports include livestock products and cash crops such as wheat, maize, soybean, palm oil, coffee and cocoa (D'Odorico et al. 2019; Rosa et al. 2019; Mekonnen et al. 2024) (**Figure 6.14**). Resiliency is threatened by the ongoing dependence on rain-fed agricultural products in international markets, especially in areas where cropland is expanding (Rosa et al. 2019; Aldaya et al. 2010; D'Odorico et al. 2019).

6.6.5 Indigenous Peoples' water monitoring and governance

Through generational experience and careful observations, Indigenous Peoples have developed sophisticated, accurate, and extensive knowledge about Earth processes (Huntington 2011; Nakashima et al. 2012). They were among the first to observe and understand changes in natural phenomena and acquire critical knowledge to adapt to these changes (Reyes-Garcia et al. 2024), especially regarding water systems (López-Maldonado et al. 2014). Research and experience also indicate that nature tends to degrade more slowly on lands owned, managed, and occupied by Indigenous Peoples (Garnett et al. 2018) as their traditional knowledge helps conserve vital ecosystems and biodiversity worldwide (Hill et al. 2020; McElwee et al. 2020).

Indigenous practices can improve water management systems, as shown by the revitalization of traditional techniques in Nepal, where communities restore stone spouts and build biodykes to adapt to climate change (Shrestha et al. 2022). These methods not only supply essential water but also reduce natural hazards. Similarly, the Mayas in Mexico created advanced water management systems, including reservoirs and canals, which enabled them to manage water resources efficiently, demonstrating a remarkable understanding of hydrological systems (López-Maldonado 2021).

The concept of cultural connection to nature is mediated through sacred natural sites, including areas of water or land with special spiritual significance, such as rivers, lakes, lagoons, and springs (UNESCO 2021). Although not all Indigenous Peoples worldwide may consider water sacred, most do appreciate it as a fundamental sacred element for their existence and cultural practices since water plays a crucial role in their livelihoods and rituals (Samakov and Berkes 2016; López-Maldonado et al. 2017).

Image 6.7 The Deni People of the Amazon during their managed fishing of pirarucu (*Arapaima gigas*). With illegal and overfishing driving the species to near extinction, Brazil adopted a total ban for pirarucu fishing in 1996. The Paumari and Deni Peoples have played a crucial role in bringing back the pirarucu population through sustainable, community-based fishery management. Credit: © FAO/Adriano Gambarini/OPAN

Water has long been central to many Indigenous Peoples, who see it connected to their ancestors and identity. Indigenous communities also lead efforts to grant legal personhood to rivers, showing a deep understanding of nature as sentient and interconnected with human well-being (Kramm 2020; Cribb et al. 2024) (**Image 6.7**). They have a profound knowledge of the water cycle, actively monitor water and atmospheric processes, including climate change, and have developed effective systems to manage and use their water resources. Examples are widespread in the scientific literature and encompass various aspects of the hydrological cycle, including cryosphere processes involving snow, ice and permafrost (Breanna et al. 2025), groundwater systems (López-Maldonado 2021), lakes (Knopp et al. 2022) and the atmosphere (Reyes-Garcia et al. 2024).

Women play a vital role in sustainable water practices, as they are often the primary managers and users of water resources in their communities, leading to better water management outcomes. The success of Indigenous strategies in maintaining healthy freshwater habitats and biodiversity is well documented (Turnhout et al. 2012; Ford et al. 2016), as are Indigenous Peoples' methodologies for monitoring and observing changes in some components of the hydrological cycle (López-Maldonado et al. 2024). There is abundant evidence of sophisticated Earth observations by Indigenous Peoples across the globe, developed over millenniums. Examples include the navigation techniques of groups in the Pacific islands and Indigenous Knowledge of cryosphere and snow processes in the Arctic, among others. Other cases include the Māori guardianship principles to monitor freshwater (Forster 2022; McAllister 2023) and the Navajo Nation in the United States of America to observe and manage their natural environment (NASA 2020). However, the relationship between Indigenous Peoples and water has been disrupted by several factors, including colonization, globalization, settlement and industrial expansion (Fernandez-Llamarez et al. 2020; McGregor et al. 2020).

The Kakerdaja Bog in Estonia. Credit: Molenira/Envato

6.7 Progress towards meeting internationally agreed-upon freshwater goals

6.7.1 Environmental aspects of Sustainable Development Goal 6

A recent review of progress on primary environmental aspects of Sustainable Development Goal Targets 6.3 and 6.6 is summarized below. See Chapter 7.3.6 for discussion of the social and economic aspects of Sustainable Development Goal 6, including 6.1, 6.2, and 6.4.

- Water quality and wastewater in Sustainable Development Goal Target 6.3: In 2022, UNEP (2024a) reported that an estimated 42 per cent of all domestic wastewater worldwide was not safely treated before being released into the environment. This figure was derived from data from 128 countries, accounting for 80 per cent of the global population. However, a more detailed global quantification by Jones et al. (2021) indicated that 48 per cent of wastewater was disposed of directly without treatment. Based on this limited data, approximately 56 per cent of the world's water bodies were classified as having 'good' ambient water quality (UN-Habitat and WHO 2024).

- Water-related ecosystems in Sustainable Development Goal Target 6.6: The wetlands extent index indicates an approximately 80 per cent loss since the pre-industrial period. Currently, half of the countries are observed to have one or more water-related ecosystem types in a state of degradation (UNEP 2024b).

6.7.2 Aichi targets and the Global Biodiversity Framework

Almost all the Aichi Biodiversity Targets (2011-2020) include some implicit connection to freshwater biodiversity by addressing the underlying causes of freshwater biodiversity loss, promoting the sustainable use of freshwater resources, and improving freshwater biodiversity conditions. None of the 20 Aichi Biodiversity targets were fully achieved

(SCBD 2020). Target 11 was the most advanced, and it related to conserving at least 17 per cent of terrestrial and inland water areas.

However, freshwater species were seldom included in broad-scale conservation strategies and spatial planning. For example, conservation plans focused on terrestrial species only overlapped with those based on freshwater species by 22 per cent (Leal et al. 2020). In summary, the limited progress made by 2020 has little connection to aquatic biodiversity.

In 2022, the Aichi targets were replaced by 23 new global goals under the Kunming-Montreal Global Biodiversity Framework (CBD/COP/DEC/15/5). Unlike the Aichi targets, the Global Biodiversity Framework includes more specific and measurable objectives, emphasizing national implementation and the inclusion of local communities as well as Indigenous Peoples. It builds on some unachieved Aichi targets, such as the new 30 x 30 commitment, Targets 2 and 3, to conserve and restore 30 per cent of land, freshwater, coastal, and marine areas by 2030. However, its implementation remains uncertain due to the lack of secure funding.

Freshwater ecosystems and biodiversity are directly addressed in several Global Biodiversity Framework targets:

- Target 1: Plan and Manage All Areas to Reduce Biodiversity Loss
- Target 2: Restore 30 per cent of All Degraded Ecosystems
- Target 3: Conserve 30 per cent of Land, Waters, and Seas
- Target 7: Reduce Pollution to Levels That Are Not Harmful to Biodiversity

Currently, the data to evaluate progress on these targets in freshwater ecosystems is still lacking.

6.7.3 Ramsar Convention on Wetlands

The Ramsar Convention on Wetlands is an intergovernmental treaty that provides "…a framework for the conservation and wise use of wetlands and their resources…" (Convention on Wetlands 2021). The world continues to make limited progress towards meeting wetland conservation and restoration targets, with advances confined to a few regions. The 2018 Global Wetland Outlook estimates that the total global wetland area ranges from 1.5 to 1.6 billion hectares, with declining trends observed worldwide (Ramsar Convention on Wetlands 2018). An estimated 35 per cent of wetland areas have been lost since 1970 (Convention on Wetlands 2021). Wetland losses are primarily driven by land-use change, pollution and climate change.

References

Abera, D. B. and Adimas, M. A. (2024). Health benefits and health risks of contaminated fish consumption: Current research outputs, research approaches, and perspectives. Heliyon 10(13). https://doi.org/10.1016/j.heliyon.2024.e33905

Abusah, P. (2023). Wastewater reuse for irrigation: Investigation of heavy metals and pharmaceuticals impact on crop irrigation. School of Business, Society and Engineering, Master 59. https://mdh.diva-portal.org/smash/get/diva2:1777767/FULLTEXT01.pdf

Adeloye, A. J. and Dau, Q. V. (2019). Hedging as an adaptive measure for climate change induced water shortage at the Pong reservoir in the Indus Basin Beas River, India. Science of The Total Environment, 687, 554-566. https://doi.org/10.1016/j.scitotenv.2019.06.021

Afrad, M. S. I., Monir, M. B., Haque, M. E., Barau, A. A. and Haque, M. M. (2020). Impact of industrial effluent on water, soil and Rice production in Bangladesh: a case of Turag River Bank. Journal of Environmental Health Science and Engineering 18, 825-834. https://doi.org/10.1007/s40201-020-00506-8

Aguirre, W. E., Alvarez-Mieles, G., Anaguano-Yancha, F., Morán, R. B., Cucalón, R. V., Escobar-Camacho, D. et al. (2021). Conservation threats and future prospects for the freshwater fishes of Ecuador: A hotspot of Neotropical fish diversity. Journal of Fish Biology 99(4), 1158-1189. https://doi.org/10.1111/jfb.14844

Aldaya, M. M., Allan, J. A. and Hoekstra, A. Y. (2010). Strategic importance of green water in international crop trade. Ecological Economics, 69(4), 887-894. https://doi.org/10.1016/j.ecolecon.2009.11.001

Aldridge, D. C., Ollard, I. S., Bespalaya, Y. V., Bolotov, I. N., Douda, K., Geist, J. et al. (2023). Freshwater mussel conservation: A global horizon scan of emerging threats and opportunities. Global Change Biology 29(3), 575-589. https://doi.org/10.1111/gcb.16510

Ali, K., Abiye, T. and Adam, E. (2022). Integrating In Situ and Current Generation Satellite Data for Temporal and Spatial Analysis of Harmful Algal Blooms in the Hartbeespoort Dam, Crocodile River Basin, South Africa. Remote Sensing 14(17). https://doi.org/10.3390/rs14174277

Amahmid, O., El Guamri, Y., Rakibi, Y., Yazidi, M., Razoki, B., Kaid Rassou, K. et al. (2023). Wastewater reuse in agriculture: A review of soil and crops parasitic contamination, associated health risks and mitigation approach. Environmental Health Engineering and Management Journal 10(1), 107-119. https://doi.org/10.34172/EHEM.2023.12

Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R. et al. (2020). Towards a global-scale soil climate mitigation strategy. Nature Communications 11(1), 5427. https://doi.org/10.1038/s41467-020-18887-7

Anagnostopoulpou, K., Nannou, C., Aschonitis, V. G. and Lambropoulou, D. A. (2022). Screening of pesticides and emerging contaminants in eighteen Greek lakes by using target and non-target HRMS approaches: Occurrence and ecological risk assessment. Science of The Total Environment 849, 157887. https://doi.org/10.1016/j.scitotenv.2022.157887

Anderko, L. and Pennea, E. (2020). Exposures to per-and polyfluoroalkyl substances (PFAS): Potential risks to reproductive and children's health. Current Problems in Pediatric and Adolescent Health Care 50(2). https://doi.org/10.1016/j.cppeds.2020.100760

AQUASTAT (2023). FAO's Global Information System on Water and Agriculture. https://www.fao.org/aquastat/en/databases/maindatabase.

Arantes, C. C., Fitzgerald, D. B., Hoeinghaus, D. J. and Winemiller, K. O. (2019). Impacts of hydroelectric dams on fishes and fisheries in tropical rivers through the lens of functional traits. Current Opinion in Environmental Sustainability 37, 28-40. https://doi.org/10.1016/j.cosust.2019.04.009

Archer, E., Holton, E., Fidal, J., Kasprzyk-Hordern, B., Carstens, A., Brocker, L. et al. (2023). Occurrence of contaminants of emerging concern in the Eerste River, South Africa: Towards the optimisation of an urban water profiling approach for public- and ecological health risk characterisation. Science of The Total Environment 859. https://doi.org/10.1016/j.scitotenv.2022.160254

Arctic Monitoring and Assessment Programme (2021). AMAP Assessment 2020: POPs and Chemicals of Emerging Arctic Concern: Influence of Climate Change. https://www.amap.no/documents/download/6891/inline

Aslam, B., Maqsoom, A., Tahir, M. D., Ullah, F., Rehman, M. S. U. and Albattah, M. (2022). Identifying and Ranking Landfill Sites for Municipal Solid Waste Management: An Integrated Remote Sensing and GIS Approach. Buildings 12(5). https://doi.org/10.3390/buildings12050605

Awonaike, B., Parajulee, A., Lei, Y. D. and Wania, F. (2022). Traffic-related sources may dominate urban water contamination for many organic contaminants. Environmental Research Letters 17(4), 044030. https://doi.org/10.1088/1748-9326/ac5c0e

Azevedo-Santos, V. M., Brito, M. F. G., Manoel, P. S., Perroca, J. F., Rodrigues-Filho, J. L., Paschoal, L. R. P. et al. (2021). Plastic pollution: A focus on freshwater biodiversity. Ambio 50(7), 1313-1324. https://doi.org/10.1007/s13280-020-01496-5

Bahtiar, Muhammad Fajar, P., Muis, Ermayanti, I. and Maruf, K. (2022). The Size Structure, Growth, Mortality, and Exploitation Rate of Freshwater Clam (Batissa violacea var. Celebensis) from Southeast Sulawesi, Indonesia. Journal of Shellfish Research 41(1), 145-152. https://doi.org/10.2983/035.041.0112

Baladia, Y., Ben-Haddad, M., Laadel, N., Hermas, J., Agnaou, M, and Oualid, J. A. (2025). Factors associated with fish mass mortality events in North African freshwater ecosystems, Morocco as a case study. Environmental Science and Pollution Research, 36176. https://doi.org/10.1007/s11356-025-36176-y

Balestra, V., Galbiati, M., Lapadula, S., Barzaghi, B., Manenti, R., Ficetola, G. F. and Bellopede, R. (2024). The problem of anthropogenic microfibres in karst systems: Assessment of water and submerged sediments. Chemosphere 363, 142811. https://doi.org/10.1016/j.chemosphere.2024.142811

Barbarossa, V., Bosmans, J., Wanders, N., King, H., Bierkens, M. F. P., Huijbregts, M. A. J. and Schipper, A. M. (2021). Threats of global warming to the world's freshwater fishes. Nature Communications 12. https://doi.org/10.1038/s41467-021-21655-w

Bartlett, J. A. and Dedekorkut-Howes, A. (2023). Adaptation strategies for climate change impacts on water quality: a systematic review of the literature. Journal of Water and Climate Change 14(3), 651-675. https://doi.org/10.2166/wcc.2022.279

Basack, S., Loganathan, M. K., Goswami, G. and Khabbaz, H. (2022). Saltwater Intrusion into Coastal Aquifers and Associated Risk Management: Critical Review and Research Directives. Journal of Coastal Research 38(3), 654-672, 19. https://doi.org/10.2112/JCOASTRES-D-21-00116.1

Basta, P. C., Viana, P. V. d. S., Vasconcellos, A. C. S. d., Périssé, A. R. S., Hofer, C. B., Paiva, N. S. et al. (2021). Mercury Exposure in Munduruku Indigenous Communities from Brazilian Amazon: Methodological Background and an Overview of the Principal Results. International Journal of Environmental Research and Public Health 18(17), 9222. https://doi.org/10.3390/ijerph18179222

Belletti, B., Garcia de Leaniz, C., Jones, J., Bizzi, S., Börger, L., Segura, G. et al. (2020). More than one million barriers fragment Europe's rivers. Nature 588(7838), 436-441. https://doi.org/10.1038/s41586-020-3005-2

Bendixen, M., Nielsen, R. L., Plesner, J. L. and Minor, K. (2022). Opportunistic climate adaptation and public support for sand extraction in Greenland. Nature Sustainability 5(11), 991-999. https://doi.org/10.1038/s41893-022-00922-8

Benito, G., Díez-Herrero, A. and Fernández de Villalta, M. (2003). Magnitude and Frequency of Flooding in the Tagus Basin (Central Spain) over the Last Millennium. Climatic Change 58(1), 171-192. https://doi.org/10.1023/A:1023417102053

Bhagwat, V. R. (2019). Safety of Water Used in Food Production. In: Singh, R. L. & Mondal, S. (eds.) Food Safety and Human Health. Elsevier. https://doi.org/10.1016/B978-0-12-816333-7.00009-6

Bhatt, V. and Chauhan, J. S. (2023). Microplastic in freshwater ecosystem: bioaccumulation, trophic transfer, and biomagnification. Environmental Science and Pollution Research 30(4), 9389-9400. https://doi.org/10.1007/s11356-022-24529-w

Bishop B., Paquette, E., Carter, N., Ljubicic, G., Oliver E.C.J, and Aporta, C. (2025). Inuit uses of weather, water, ice, and climate indicators to assess travel safety in Arctic Canada, Alaska, and Greenland: a scoping review. FACETS 10, 1-25. https://doi.org/10.1139/facets-2024-0107

Böhnisch, A., Mittermeier, M., Leduc, M. and Ludwig, R. (2021). Hot Spots and Climate Trends of Meteorological Droughts in Europe–Assessing the Percent of Normal Index in a Single-Model Initial-Condition Large Ensemble. Frontiers in Water 3. https://doi.org/10.3389/frwa.2021.716621

Boretti, A. and Rosa, L. (2019). Reassessing the projections of the World Water Development Report. npj Clean Water 2(1), 15. https://doi.org/10.1038/s41545-019-0039-9

Braz-Mota, S. and Luis Val, A. (2024). Fish mortality in the Amazonian drought of 2023: the role of experimental biology in our response to climate change. Journal of Experimental Biology 227(17). https://doi.org/10.1242/jeb.247255

Brudler, S., Rygaard, M., Arnbjerg-Nielsen, K., Hauschild, M. Z., Ammitsøe, C. and Vezzaro, L. (2019). Pollution levels of stormwater discharges and resulting environmental impacts. Science of The Total Environment 663, 754-763. https://doi.org/10.1016/j.scitotenv.2019.01.388

Brunner, N., Das, S. and Starkl, M. (2023). Lotka-Volterra analysis of river Ganga pollution in India. Ecological Indicators 150. https://doi.org/10.1016/j.ecolind.2023.110201

Burlakova, L. E., Karatayev, A. Y., Boltovskoy, D. and Correa, N. M. (2023). Ecosystem services provided by the exotic bivalves Dreissena polymorpha, D. rostriformis bugensis, and Limnoperna fortunei. Hydrobiologia 850(12), 2811-2854. https://doi.org/10.1007/s10750-022-04935-4

Camargo, A. F. M. and Amorim, R. V. (2020). Fish farming in cages: a practice to be restricted in Brazil. Acta Limnologica Brasiliensia 32. https://doi.org/10.1590/S2179-975X5519

Cantera, I., Coutant, O., Jézéquel, C., Decotte, J.-P., Dejean, T., Iribar, A. et al. (2022). Low level of anthropization linked to harsh vertebrate biodiversity declines in Amazonia. Nature Communications 13. https://doi.org/10.1038/s41467-022-30842-2

Cao, G., Wang, W., Zhang, J., Wu, P., Zhao, X., Yang, Z. et al. (2022). New Evidence of Rubber-Derived Quinones in Water, Air, and Soil. Environmental Science & Technology 56(7), 4142-4150. https://doi.org/10.1021/acs.est.1c07376

Cao, L., Shao, W.-H., Yi, W.-J., Zhang, E (2024). A review of conservation status of freshwater fish diversity in China. Journal of Fish Biology 104(2), 345-364. https://doi.org/10.1111/jfb.15606

Caretta, M. A., Mukherji, A., Arfanuzzaman, M., Betts, R. A., Gelfan, A., Hirabayashi, Y. et al. (2022). Water. In: Pörtner, H.-O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A. & Rama, B. (eds.) Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009325844.006

Catford, J. A. (2017). Hydrological Impacts of Biological Invasions. In: Vilà, M. & Hulme, P. E. (eds.) Impact of Biological Invasions on Ecosystem Services. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-45121-3_5

Centre for Research on the Epidemiology of Disasters (2023). 2023 Disasters in Numbers - A Significant Year of Disaster Impact. https://files.emdat.be/reports/2023_EMDAT_report.pdf

Chakraborty, A., Adhikary, S., Bhattacharya, S., Dutta, S., Chatterjee, S., Banerjee, D. et al. (2023). Pharmaceuticals and Personal Care Products as Emerging Environmental Contaminants: Prevalence, Toxicity, and Remedial Approaches. ACS Chemical Health & Safety 30(6), 362-388. https://doi.org/10.1021/acs.chas.3c00071

Chandra, S. and Walsh, K. B. (2024). Microplastics in water: Occurrence, fate and removal. Journal of Contaminant Hydrology 104360. https://doi.org/10.1016/j.jconhyd.2024.104360

Chen, H., Zhang, S., Lv, X., Guo, S., Ma, Y., Han, B. and Hu, X. (2022). Interactions between suspended sediments and submerged macrophytes-epiphytic biofilms under water flow in shallow lakes. Water Research 222, 118911. https://doi.org/10.1016/j.watres.2022.118911

Chen, K. and Olden, J. D. (2020). Threshold responses of riverine fish communities to land use conversion across regions of the world. Global Change Biology 26(9), 4952-4965. https://doi.org/10.1111/gcb.15251

Chen, Y., Qu, X., Xiong, F., Lu, Y., Wang, L. and Hughes, R. M. (2020). Challenges to saving China's freshwater biodiversity: Fishery exploitation and landscape pressures. Ambio 49(4), 926-938. https://doi.org/10.1007/s13280-019-01246-2.

Chiang, F., Mazdiyasni, O. and AghaKouchak, A. (2021). Evidence of anthropogenic impacts on global drought frequency, duration, and intensity. Nature Communications 12. https://doi.org/10.1038/s41467-021-22314-w

Christian, J. I., Basara, J. B., Hunt, E. D., Otkin, J. A., Furtado, J. C., Mishra, V. et al. (2021). Global distribution, trends, and drivers of flash drought occurrence. Nature Communications 12. https://doi.org/10.1038/s41467-021-26692-z

Compagno, L., Huss, M., Zekollari, H., Miles, E. S. and Farinotti, D. (2022). Future growth and decline of high mountain Asia's ice-dammed lakes and associated risk. Communications Earth & Environment 3(1). https://doi.org/10.1038/s43247-022-00520-8

Convention on Wetlands (2021). Global Wetland Outlook: Special Edition 2021. https://static1.squarespace.com/static/5b256c78e17ba335ea89fe1f/t/61b8a904f3ceb458e9b5ca44/1639491853578/Ramsar+GWO_Special+Edition+2021%E2%80%93ENGLISH_WEB.pdf

Cooke, S. J., Piczak, M. L., Nyboer, E. A., Michalski, F., Bennett, A., Koning, A. A. et al. (2023). Managing exploitation of freshwater species and aggregates to protect and restore freshwater biodiversity. Environmental Reviews. https://doi.org/10.1139/er-2022-0118.

Costa, R. M. G., Ferro, J. L. S. and Farjalla, V. F. (2022). Disentangling the mechanisms related to the reduction of aquatic habitat size on predator–prey interactions. Hydrobiologia 849(5), 1207-1219. https://doi.org/10.1007/s10750-021-04781-w

Centre for Research on the Epidemiology of Disasters CRED (2023). 2022 Disasters in numbers: Climate in action. Disasters in numbers 2022. https://www.cred.be/sites/default/files/2022_EMDAT_report.pdf

Cribb, M., Macpherson, E. and Borchgrevink, A. (2024). Beyond legal personhood for the Whanganui River: collaboration and pluralism in implementing the Te Awa Tupua Act. The International Journal of Human Rights, 1-24. https://doi.org/10.1080/13642987.2024.2314532

Cuthbert, R. N., Pattison, Z., Taylor, N. G., Verbrugge, L., Diagne, C., Ahmed, D. A. et al. (2021). Global economic costs of aquatic invasive alien species. Science of The Total Environment, 775. https://doi.org/10.1016/j.scitotenv.2021.145238

Dang, T. D., Arias, M. E., Tarabih, O., Phlips, E. J., Ergas, S. J., Rains, M. C. and Zhang, Q. (2023). Modeling temporal and spatial variations of biogeochemical processes in a large subtropical lake: Assessing alternative solutions to algal blooms in Lake Okeechobee, Florida. Journal of Hydrology: Regional Studies 47, 101441. https://doi.org/10.1016/j.ejrh.2023.101441

D'Odorico, P., Carr, J., Dalin, C., Dell'Angelo, J., Konar, M., Laio, F. et al. (2019). Global virtual water trade and the hydrological cycle: patterns, drivers, and socio-environmental impacts. Environmental Research Letters 14(5). https://doi.org/10.1088/1748-9326/ab05f4

Das, A. and Chowdhury, A. R. (2024). Chapter 19 - Empowering sustainable water management: the confluence of artificial intelligence and Internet of Things. In: Bandh, S. A. & Malla, F. A. (eds.). Current Directions in Water Scarcity Research. Elsevier. https://www.sciencedirect.com/science/article/pii/B9780443236310000194

de Graaf, I. E. M., Gleeson, T., van Beek, L. P. H., Sutanudjaja, E. H. and Bierkens, M. F. P. (2019). Environmental flow limits to global groundwater pumping. Nature 574, 90-94. https://doi.org/10.1038/s41586-019-1594-4

de Groot, R., Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L. et al. (2012). Global estimates of the value of ecosystems and their services in monetary units. Ecosystem Services 1(1), 50-61. https://doi.org/10.1016/j.ecoser.2012.07.005

de Guzman, K., Stone, G., Yang, A. R., Schaffer, K. E., Lo, S., Kojok, R. et al. (2023). Drinking water and the implications for gender equity and empowerment: A systematic review of qualitative and quantitative evidence. International Journal of Hygiene and Environmental Health 247, 114044. https://doi.org/10.1016/j.ijheh.2022.114044

de Visser, S., Scherer, L., Huijbregts, M. and Barbarossa, V. (2023). Characterization factors for the impact of climate change on freshwater fish species. Ecological Indicators, 150. https://doi.org/10.1016/j.ecolind.2023.110238

Deemer, G. J., Bhatt, U. S., Eicken, H., Posey, P. G., Hutchings, J. K., Nelson, J. et al. (2018). Broadening the sea-ice forecaster toolbox with community observations: a case study from the northern Bering Sea. Arctic Science 4(1), 42-70. https://doi.org/10.1139/as-2016-0054

Deinet, S., Flint, R., Puleston, H., Baratech, A., Royte, J., Thieme, M. L. et al. (2024). The Living Planet Index (LPI) for migratory freshwater fish 2024 update - Technical Report. https://files.worldwildlife.org/wwfcmsprod/files/Publication/file/6f6b5o5dn1_LPI_migratory_freshwater_fishes_2024_Technical_report.pdf

Dethier, E. N., Renshaw, C. E. and Magilligan, F. J. (2022). Rapid changes to global river suspended sediment flux by humans. Science 379(6600), 1447-1452. https://www.science.org/doi/10.1126/science.abn7980

Dethier, E. N., Silman, M., Leiva, J. D., Alqahtani, S., Fernandez, L. E., Pauca, P. et al. (2023). A global rise in alluvial mining increases sediment load in tropical rivers. Nature 620, 787–793. https://doi.org/10.1038/s41586-023-06309-9

Dickin, S., Bayoumi, M., Giné, R., Andersson, K. and Jiménez, A. (2020). Sustainable sanitation and gaps in global climate policy and financing. npj Clean Water 3(1), 24. https://doi.org/10.1038/s41545-020-0072-8

dos Santos, C. H. M. and Fiori, M. M. (2020). Turtles, indians and settlers: Podocnemis expansa exploitation and the Portuguese settlement in eighteenth-century Amazonia. Topoi (Rio J.) 21(44), 350-373. https://doi.org/10.1590/2237-101X02104404

dos Santos Silva, J., Cidade, M. J. A., Panero, F. d. S., Ribeiro, L. B. and Campos da Rocha, F. O. (2024). Microplastic pollution in the Amazon Basin: Current scenario, advances and perspectives. Science of The Total Environment 946, 174150. https://doi.org/10.1016/j.scitotenv.2024.174150

du Plessis, A. (2022). Persistent degradation: Global water quality challenges and required actions. One Earth 5(2), 129-131. https://doi.org/10.1016/j.oneear.2022.01.005

El-Kalliny, A. S., Abdel-Wahed, M. S., El-Zahhar, A. A., Hamza, I. A. and Gad-Allah, T. A. (2023). Nanomaterials: a review of emerging contaminants with potential health or environmental impact. Discover Nano 18(1), 68. https://doi.org/10.1186/s11671-023-03787-8

Elhabashy, A., Li, J. and Ekaterina Sokolova, E. (2023). Water quality modeling of a eutrophic drinking water source: Impact of future climate on Cyanobacterial blooms. Ecological Modelling, 477. https://doi.org/10.1016/j.ecolmodel.2023.110275

Erasmus, J. H., Zimmermann, S., Smit, N. J., Malherbe, W., Nachev, M., Sures, B. and Wepener, V. (2022). Human health risks associated with consumption of fish contaminated with trace elements from intensive mining activities in a peri-urban region. Science of The Total Environment 825, 154011. https://doi.org/10.1016/j.scitotenv.2022.154011

Eslami, S., Hoekstra, P., Nguyen Trung, N., Ahmed Kantoush, S., Van Binh, D., Duc Dung, D. et al. (2019). Tidal amplification and salt intrusion in the Mekong Delta driven by anthropogenic sediment starvation. Scientific Reports 9(1), 18746. https://doi.org/10.1038/s41598-019-55018-9

Evelpidou, N., Tzouxanioti, M., Gavalas, T., Spyrou, E., Saitis, G., Petropoulos, A. and Karkani, A. (2022). Assessment of Fire Effects on Surface Runoff Erosion Susceptibility: The Case of the Summer 2021 Forest Fires in Greece. Land 11(1). https://doi.org/10.3390/land11010021

Evich, M. G., Davis, M. J. B., McCord, J. P., Acrey, B., Awkerman, J. A., Knappe, D. R. U. et al. (2022). Per- and polyfluoroalkyl substances in the environment. Science 375(6580), eabg9065. https://doi.org/10.1126/science.abg9065

FAOSTAT (2025). Land Use. https://www.fao.org/faostat/en/#data/RL/visualize. Accessed 15the February 2025.

Fausch, K.D. (2007). Introduction, establishment and effects of non-native salmonids: considering the risk of rainbow trout invasion in the United Kingdom. Journal of fish biology 71, 1-32. https://doi.org/10.1111/j.1095-8649.2007.01682.x

Fearnside, P.M. (2016). Tropical dams: To build or not to build? Science 351(6272), pp.456-457. https://doi.org/10.1126/science.351.6272.456-b

Feng, W., Deng, Y., Yang, F., Miao, Q. and Ngien, S. K. (2023). Systematic Review of Contaminants of Emerging Concern (CECs): Distribution, Risks, and Implications for Water Quality and Health. Water 15(22) 3922. https://doi.org/10.3390/w15223922

Fernández-Llamazares, Á., Garteizgogeascoa, M., Basu, N., Brondizio, E. S., Cabeza, M., Martínez-Alier, J. et al. (2020). A State-of-the-Art Review of Indigenous Peoples and Environmental Pollution. Integrated Environmental Assessment and Management 16(3), 324-341. https://doi.org/10.1002/ieam.4239

Ferrando-Climent, L.,Rodriguez-Mozaz, S. and Barceló, D. (2014). Incidence of anticancer drugs in an aquatic urban system: From hospital effluents through urban wastewater to natural environment. Environmental Pollution 193, 216-223. https://doi.org/10.1016/j.envpol.2014.07.002

Filatova, D., Jones, M. R., Haley, J. A., Núñez, O., Farré, M. and Janssen, E. M.-L. (2021). Cyanobacteria and their secondary metabolites in three freshwater reservoirs in the United Kingdom. Environmental Sciences Europe, 33. https://doi.org/10.1186/s12302-021-00472-4

Filho, W. L., Ha'apio, M. O., Lütz, J. M. and Li, C. (2020). Climate change adaptation as a development challenge to small Island states: A case study from the Solomon Islands. Environmental Science & Policy 107, 179-187. https://doi.org/10.1016/j.envsci.2020.03.008

Fluet-Chouinard, E., Stocker, B. D., Zhang, Z., Malhotra, A., Melton, J. R., Poulter, B. et al. (2023). Extensive global wetland loss over the past three centuries. Nature 614, 281–286. https://doi.org/10.1038/s41586-022-05572-6

Food and Agriculture Organization and United Nations Water (2021). Progress on the level of water stress: Global status and acceleration needs for SDG indicator 6.4.2. https://openknowledge.fao.org/handle/20.500.14283/cb6241en

Food and Agriculture Organization and United Nations Water (2024). Progress on change in water-use efficiency – Mid-term status of SDG Indicator 6.4.1 and acceleration needs, with special focus on food security and climate change, 2024. https://doi.org/10.4060/cd2023en

Food and Agriculture Organization of the United Nations (2019). Soil erosion: the greatest challenge for sustainable soil management. https://www.fao.org/3/ca4395en/ca4395en.pdf

Food and Agriculture Organization of the United Nations (2022a). World Food and Agriculture – Statistical Yearbook 2022. https://doi.org/10.4060/cc2211en

Food and Agriculture Organization of the United Nations (2022b). The state of the world's land and water resources for food and agriculture – Systems at breaking point. https://www.fao.org/3/cb9910en/cb9910en.pdf.

Food and Agriculture Organization of the United Nations (2023). Agriculture: cause and victim of water pollution, but change is possible. https://www.fao.org/land-water/news-archive/news-detail/en/c/1032702. Accessed 20th October 2024.

Food and Agriculture Organization of the United Nations (2024). The State of World Fisheries and Aquaculture 2024 – Blue Transformation in action. https://openknowledge.fao.org/server/api/core/bitstreams/f985caed-cc7a-457e-8107-7ce16c6ef209/content

Food and Agriculture Organization of the United Nations and International Water Management Institute (2018). More People, More Food, Worse Water? A Global Review of Water Pollution from Agriculture. http://www.fao.org/3/CA0146EN/ca0146en.pdf

Ford, J. D., Cameron, L., Rubis, J., Maillet, M., Nakashima, D., Willox, A. C. and Pearce, T. (2016). Including indigenous knowledge and experience in IPCC assessment reports. Nature Climate Change 6(4), 349-353. https://doi.org/10.1038/nclimate2954

Forster, M. (2022). Amplifying the influence of Māori knowledge in environmental management. Environment and Planning 2(1-2), 229-246. https://doi.org/10.1177/26349825221133095

Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L. et al. (2021). Ocean, Cryosphere and Sea Level Change. In AGU fall meeting abstracts (Vol. 2021, U13B-09). https://doi.org/10.1017/9781009157896.011

Frederico, R. G., Dias, M. S., Jézéquel, C., Tedesco, P. A., Hugueny, B., Zuanon, J. et al. (2021). The representativeness of protected areas for Amazonian fish diversity under climate change. Aquatic Conservation: Marine and Freshwater Ecosystems 31(5), 1158-1166. https://doi.org/10.1002/aqc.3528

Gain, A. K., Giupponi, C. and Wada, Y. (2016). Measuring global water security towards sustainable development goals. Environmental Research Letters 11(12). https://doi.org/10.1088/1748-9326/11/12/124015

Gaines, L. G. T. (2022). Historical and current usage of per- and polyfluoroalkyl substances (PFAS): A literature review. American Journal of Industrial Medicine 66(5), 353-378. https://doi.org/10.1002/ajim.23362

Gardner, J., Pavelsky, T., Topp, S., Yang, X., Ross, M. R. V. and Cohen, S. (2023). Human activities change suspended sediment concentration along rivers. Environmental Research Letters 18. https://doi.org/10.1088/1748-9326/acd8d8

Garnett, S. T., Burgess, N. D., Fa, J. E., Fernández-Llamazares, Á., Molnár, Z., Robinson, C. J. et al. (2018). A spatial overview of the global importance of Indigenous lands for conservation. Nature Sustainability 1(7), 369-374. https://doi.org/10.1038/s41893-018-0100-6

Geng, M., Zhang, W., Hu, T., Wang, R., Cheng, X. and Wang, J. (2022). Eutrophication causes microbial community homogenization via modulating generalist species. Water Research 210. https://doi.org/10.1016/j.watres.2021.118003

Gheuens, J., Nagabhatla, N. and Perera, E. D. P. (2019). Disaster-Risk, Water Security Challenges and Strategies in Small Island Developing States (SIDS). Water 11(4). https://doi.org/10.3390/w11040637

Girona-García, A., Vieira, D. C. S., Silva, J., Fernández, C., Robichaud, P. R. and Keizer, J. J. (2021). Effectiveness of post-fire soil erosion mitigation treatments: A systematic review and meta-analysis. Earth-Science Reviews, 217. https://doi.org/10.1016/j.earscirev.2021.103611

Global Commission on the Economics of Water (2024). The Economics of Water: Valuing the Hydrological Cycle as a Global Common Good. https://economicsofwater.watercommission.org/report/economics-of-water.pdf

Gobler, C. J. (2020). Climate Change and Harmful Algal Blooms: Insights and perspective. Harmful Algae, 91. https://doi.org/10.1016/j.hal.2019.101731

Goehler, L. O., Moruzzi, R. B., Tomazini da Conceição, F., Júnior, A. A. C., Speranza, L. G., Busquets, R. and Campos, L. C. (2022). Relevance of tyre wear particles to the total content of microplastics transported by runoff in a high-imperviousness and intense vehicle traffic urban area. Environmental Pollution 314, 120200. https://doi.org/10.1016/j.envpol.2022.120200

Gonsioroski, A., Mourikes, V. E. and Flaws, J. A. (2020). Endocrine Disruptors in Water and Their Effects on the Reproductive System. International Journal of Molecular Sciences 21(6). https://doi.org/10.3390/ijms21061929

Graham, N. T., Hejazi, M. I., Kim, S. H., Davies, E. G. R., Edmonds, J. A. and Miralles-Wilhelm, F. (2020). Future changes in the trading of virtual water. Nature Communications 11(1). https://doi.org/10.1038/s41467-020-17400-4

Group on Earth Observations Biodiversity Observation Network and Freshwater Biodiversity Observation Network (2022). Inland Waters in the Post-2020 Biodiversity Framework. https://geobon.org/science-briefs/

Haag, W. R., Culp, J. J., McGregor, M. A., Bringolf, R. and Stoeckel, J. A. (2019). Growth and survival of juvenile freshwater mussels in streams: Implications for understanding enigmatic mussel declines. Freshwater Science 38(4). https://doi.org/10.1086/705919

Haase, P., Bowler, D. E., Baker, N. J., Bonada, N., Domisch, S., Garcia Marquez, J. R. et al. (2023). The recovery of European freshwater biodiversity has come to a halt. Nature 620(7974), 582-588. https://doi.org/10.1038/s41586-023-06400-1

Haddaoui, I. and Mateo-Sagasta, J. (2021). A review on occurrence of emerging pollutants in waters of the MENA region. Environmental Science and Pollution Research 28(48), 68090–68110. https://doi.org/10.1007/s11356-021-16558-8

Hansen, H. C. B., Hilscherova, K. and Bucheli, T. D. (2021). Natural toxins: environmental contaminants calling for attention. Environmental Sciences Europe 33(1), 112. https://doi.org/10.1186/s12302-021-00543-6

Harper, S. L., Wright, C., Masina, S. and Coggins, S. (2020). Climate change, water, and human health research in the Arctic. Water Security 10, 100062. https://doi.org/10.1016/j.wasec.2020.100062

Hauser, D. D. W., Glenn, R. T., Lindley, E. D., Pikok, K. K., Heeringa, K., Jones, J. et al. (2023). Nunaaqqit Savaqatigivlugich—working with communities: evolving collaborations around an Alaska Arctic observatory and knowledge hub. Arctic Science 9(3), 635-656. https://doi.org/10.1139/as-2022-0044

He, F., Langhans, S. D., Zarfl, C., Wanke, R., Tockner, K. and Jähnig, S. C. (2021). Combined effects of life-history traits and human impact on extinction risk of freshwater megafauna. Conservation Biology 35(2), 643-653. https://doi.org/10.1111/cobi.13590

He, X., Pan, M., Wei, Z., Wood, E. F. and Sheffield, J. (2020). A Global Drought and Flood Catalogue from 1950 to 2016. Bulletin of the American Meteorological Society 101(5), E508–E535. https://doi.org/10.1175/BAMS-D-18-0269.1

Held, I. M. and Soden, B. J. (2006). Robust Responses of the Hydrological Cycle to Global Warming. Journal of Climate 19(21), 5686-5699. https://doi.org/10.1175/JCLI3990.1

Hernández-Carrasco D., Tylianakis J.M., Lytle D.A., and Tonkin J.D. (2025) Ecological and evolutionary consequences of changing seasonality. Science 388. https://www.science.org/doi/10.1126/science.ads4880

Herrera-R, G. A., Oberdorff, T., Anderson, E. P., Brosse, S., Carvajal-Vallejos, F. M., Frederico, R. G. et al. (2020). The combined effects of climate change and river fragmentation on the distribution of Andean Amazon fishes. Global Change Biology 26(10), 5509-5523. https://doi.org/10.1111/gcb.15285

Hill, R., Adem, Ç., Alangui, W. V., Molnár, Z., Aumeeruddy-Thomas, Y., Bridgewater, P. et al. (2020). Working with Indigenous, local and scientific knowledge in assessments of nature and nature's linkages with people. Current Opinion in Environmental Sustainability 43, 8-20. https://doi.org/10.1016/j.cosust.2019.12.006

Ho, J. Y.-e., Chan, E. Y. Y., Lam, H. C. Y., Yeung, M. P. S., Wong, C. K. P. and Yung, T. K. C. (2019). Is "Perceived Water Insecurity" Associated with Disaster Risk Perception, Preparedness Attitudes, and Coping Ability in Rural China? (A Health-EDRM Pilot Study). International Journal of Environmental Research and Public Health 16(7), 1254. https://doi.org/10.3390/ijerph16071254

Hou, X., Feng, L., Dai, Y., Hu, C., Gibson, L., Tang, J. et al. (2022). Global mapping reveals increase in lacustrine algal blooms over the past decade. Nature Geoscience 15(2), 130-134. https://doi.org/10.1038/s41561-021-00887-x

Hrachowitz, M., Stockinger, M., Coenders-Gerrits, M., van der Ent, R., Bogena, H., Lücke, A. and Stumpp, C. (2021). Deforestation reduces the vegetation-accessible water storage in the unsaturated soil and affects catchment travel time distributions and young water fractions. Hydrology and Earth System Sciences 25(9), 4887–4915. https://doi.org/10.5194/hess-25-4887-2021

Huang, Z. and Li, H. (2024). Dams trigger exponential population declines of migratory fish. Science Advances 10(19), eadi6580. https://doi.org/10.1126/sciadv.adi6580

Huggins, X., Gleeson, T., Kummu, M., Zipper, S. C., Wada, Y., Troy, T. J. and Famiglietti, J. S. (2022). Hotspots for social and ecological impacts from freshwater stress and storage loss. Nature Communications 13(1), 439. https://doi.org/10.1038/s41467-022-28029-w

Huntington, H. P. (2011). The local perspective. Nature 478(7368), 182-183. https://doi.org/10.1038/478182a

Huss, M., Bookhagen, B., Huggel, C., Jacobsen, D., Bradley, R. S., Clague, J. J. et al. (2017). Toward mountains without permanent snow and ice. Earth's Future 5(5). https://doi.org/10.1002/2016EF000514

Hussain, M. S., Abd-Elhamid, H. F., Javadi, A. A., & Sherif, M. M. (2019). Management of seawater intrusion in coastal aquifers: a review. Water 11(12), 2467. https://doi.org/10.3390/w11122467

Igboama, W. N., Hammed, O. S., Fatoba, J. O., Aroyehun, M. T. and Ehiabhili, J. C. (2022). Review article on impact of groundwater contamination due to dumpsites using geophysical and physiochemical methods. Applied Water Science 12. https://doi.org/10.1007/s13201-022-01653-z

Igwaran, A., Kayode, A. J., Moloantoa, K. M., Khetsha, Z. P. and Unuofin, J. O. (2024). Cyanobacteria Harmful Algae Blooms: Causes, Impacts, and Risk Management. Water, Air, & Soil Pollution 235(1), 71. https://doi.org/10.1007/s11270-023-06782-y

Iloms, E., Ololade, O. O., Ogola, H. J. O. and Selvarajan, R. (2020). Investigating Industrial Effluent Impact on Municipal Wastewater Treatment Plant in Vaal, South Africa. International Journal of Environmental Research and Public Health 17(3). https://doi.org/10.3390/ijerph17031096

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T. et al. (2020). Importance and vulnerability of the world's water towers. Nature 577(7790), 364-369. https://doi.org/10.1038/s41586-019-1822-y

Intergovernmental Energy Agency (2021). Hydropower Special Market Report: Analysis and forecast to 2030. https://iea.blob.core.windows.net/assets/4d2d4365-08c6-4171-9ea2-8549fabd1c8d/HydropowerSpecialMarketReport_corr.pdf

Intergovernmental Panel on Climate Change (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger. et al. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391. https://doi.org/10.1017/9781009157896.

Intergovernmental Panel on Climate Change (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. et al. (eds.). Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056. https://doi.org/10.1017/9781009325844

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Service. https://www.ipbes.net/global-assessment

International Hydropower Association (2021a). How-to Guide: Hydropower and Indigenous Peoples. https://cdn.prod.website-files.com/64f9d0036cb97160cc26feba/64f9d0036cb97160cc271328_How-to%20Guide%20-%20Hydropower%20and%20Indigenous%20Peoples.pdf

International Hydropower Association (2021b). How-to Guide: Hydropower Environmental and Social Assessment and Management. https://cdn.prod.website-files.com/64f9d0036cb97160cc26feba/64f9d0036cb97160cc27123b_Hydropower%20HtG%20E%26S%20268x190%20030821.pdf

International Union for Conservation of Nature (2022). The IUCN Red List of Threatened Species. Version 2022-2. https://www.iucnredlist.org Accessed 17 November 2023.

International Union for Conservation of Nature (2025). The IUCN Red List of Threatened Species. Version 2025-1. https://www.iucnredlist.org Accessed 01 May 2025.

Issanova, G., Abuduwaili, J., Tynybayeva, K., Kalybayeva, A., Saduakhas, A., Kulymbet, K. et al. (2022). Soil salinisation as a land degradation process in the dried bed of the North-eastern Aral Sea, Kazakhstan. Arabian Journal of Geosciences 15(11), 1055. https://doi.org/10.1007/s12517-022-09627-w

Jansen, M. A. K., Andrady, A. L., Bornman, J. F., Aucamp, P. J., Bais, A. F., Banaszak, A. T. et al. (2024). Plastics in the environment in the context of UV radiation, climate change and the Montreal Protocol: UNEP Environmental Effects Assessment Panel, Update 2023. Photochemical & Photobiological Sciences 23(4), 629-650. https://doi.org/10.1007/s43630-024-00552-3

Jaramillo, M. F. and Restrepo, I. (2017). Wastewater Reuse in Agriculture: A Review about Its Limitations and Benefits. Sustainability 9(10). https://doi.org/10.3390/su9101734

Jasechko, S., Seybold, H., Perrone, D., Fan, Y., Shamsudduha, M., Taylor, R. G. et al. (2024). Rapid groundwater decline and some cases of recovery in aquifers globally. Nature 625(7996), 715-721. https://doi.org/10.1038/s41586-023-06879-8

Jaureguiberry, P., Titeux, N., Wiemers, M., Bowler, D. E., Coscieme, L., Golden, A. S. et al. (2022). The direct drivers of recent global anthropogenic biodiversity loss. Science Advances 8(45). https://doi.org/10.1126/sciadv.abm9982

Johannessen, C., Helm, P. and Metcalfe, C. D. (2021). Detection of selected tire wear compounds in urban receiving waters. Environmental Pollution 287, 117659. https://doi.org/10.1016/j.envpol.2021.117659

Johnson, M. F., Albertson, L. K., Algar, A. C., Dugdale, S. J., Edwards, P., England, J. et al. (2024). Rising water temperature in rivers: Ecological impacts and future resilience. WIREs Water 11(4), e1724. https://doi.org/10.1002/wat2.1724

Jones, E. R., van Vliet, M. T. H., Qadir, M. and Bierkens, M. F. P. (2021). Country-level and gridded estimates of wastewater production, collection, treatment and reuse. Earth System Science Data 13(2), 237-254. https://doi.org/10.5194/essd-13-237-2021

Kali, S. E., Österlund, H., Viklander, M. and Blecken, G.-T. (2025). Stormwater discharges affect PFAS occurrence, concentrations, and spatial distribution in water and bottom sediment of urban streams. Water Research 271, 122973. https://doi.org/10.1016/j.watres.2024.122973

Kanungo, S., Azman, A. S., Ramamurthy, T., Deen, J. and Dutta, S. (2022). Cholera. The Lancet 399(10333), 1429-1440. https://doi.org/10.1016/S0140-6736(22)00330-0.

Karpowicz, M., Zieliński, P., Grabowska, M., Ejsmont-Karabin, J., Kozłowska, J. and Feniova, I. (2020). Effect of eutrophication and humification on nutrient cycles and transfer efficiency of matter in freshwater food webs. Hydrobiologia 847(11), 2521-2540. https://doi.org/10.1007/s10750-020-04271-5

Kayser, G. L., Rao, N., Jose, R. and Raj, A. (2019). Water, sanitation and hygiene: measuring gender equality and empowerment. Bulletin of the World Health Organization 97(6), 438-440. http://dx.doi.org/10.2471/BLT.18.223305

Kelly, T. J., Hamilton, E., Watts, M. J., Ponting, J. and Sizmur, T. (2020). The Effect of Flooding and Drainage Duration on the Release of Trace Elements from Floodplain Soils. Environmental Toxicology and Chemistry 39(11), 2124-2135. https://doi.org/10.1002/etc.4830

Ketabchi, H., Mahmoodzadeh, D., Ataie-Ashtiani, B., & Simmons, C. T. (2016). Sea-level rise impacts on seawater intrusion in coastal aquifers: Review and integration. Journal of Hydrology 535, 235-255. https://doi.org/10.1016/j.jhydrol.2016.01.083

Khan, A. H., Sharholy, M., Alam, P., Al-Mansour, A. I., Ahmad, K., Kamal, M. A. et al. (2022). Evaluation of cost benefit analysis of municipal solid waste management systems. Journal of King Saud University - Science 34(4). https://doi.org/10.1016/j.jksus.2022.101997

Khan, S. U., Hooda, P. S., Blackwell, M. S. A. and Busquets, R. (2024). Influence of soil drying followed by flooding on micronutrient solubilization. Soil Use and Management 40(1), e12946. https://doi.org/10.1111/sum.12946

Knopp, J.A., Levenstein, B., Watson, A., Ivanova, I. and Lento, J. (2022). Systematic review of documented Indigenous Knowledge of freshwater biodiversity in the circumpolar Arctic. Freshwater Biology 67(1),194-209. https://doi.org/10.1111/fwb.13570

Konapala, G., Mishra, A. K., Wada, Y. and Mann, M. E. (2020). Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. Nature Communications 11(1), 3044. https://doi.org/10.1038/s41467-020-16757-w

Kosuth, M., Wattenberg, E., Mason, S. A., Tyree, C. and Morrison, D. (2017). Synthetic Polymer Contamination in Global Drinking Water. https://orbmedia.org/invisibles-final-report

Kramm, M. (2020). When a River Becomes a Person. Journal of Human Development and Capabilities 21(4), 307-319. https://doi.org/10.1080/19452829.2020.1801610

Krupnik, I. and Jolly, D. (eds.). (2002). The Earth is Faster Now: Indigenous Observations of Arctic Environmental Change. Fairbanks, Alaska: Arctic Research Consortium of the United States.

Kshirsagar, A. V., Zeitler, E. M., Weaver, A., Franceschini, N. and Engel, L. S. (2022). Environmental Exposures and Kidney Disease. Kidney360 3(12), 2174-2182. https://doi.org/10.34067/kid.0007962021

Kumah, E. A., Fopa, R. D., Harati, S., Boadu, P., Zohoori, F. V. and Pak, T. (2023). Human and environmental impacts of nanoparticles: a scoping review of the current literature. BMC Public Health 23(1), 1059. https://doi.org/10.1186/s12889-023-15958-4

Kumar, C., Ghosh, A.,Yash, Debnath, M. and Bhadury, P. (2021). Seasonal dynamicity of environmental variables and water quality index in the lower stretch of the River Ganga. Environmental Research Communications 3(7). https://doi.org/10.1088/2515-7620/ac10fd

Laptander, R. (2023). The Yamal Nenets' traditional and contemporary environmental knowledge of snow, ice, and permafrost. Ecology and Society 28(3). https://doi.org/10.5751/ES-14353-280306

Larson, A. M. and Lewis-Mendoza, J. (2012). Decentralisation and devolution in Nicaragua's North Atlantic autonomous region: Natural resources and indigenous peoples' rights. International Journal of the Commons 6(2), 179-199. https://doi.org/10.18352/ijc.315

Latrubesse, E.M., Arima, E.Y., Dunne, T., Park, E., Baker, V.R., d'Horta. et al. 2017. Damming the rivers of the Amazon basin. Nature 546(7658), 363-369. https://doi.org/10.1038/nature22333

Le Moal, M., Gascuel-Odoux, C., Ménesguen, A., Souchon, Y., Étrillard, C., Levain, A. et al. (2019). Eutrophication: A new wine in an old bottle? Science of The Total Environment 651, 1-11. https://doi.org/10.1016/j.scitotenv.2018.09.139

Leal, C. G., Lennox, G. D., Ferraz, S. F. B., Ferreira, J., Gardner, T. A., Thomson, J. R. et al. (2020). Integrated terrestrial-freshwater planning doubles conservation of tropical aquatic species. Science 370(6512), 117-121. https://doi.org/10.1126/science.aba7580

Legaspi, K., Lau, A. Y. A., Jordan, P., Mackay, A., Mcgowan, S., Mcglynn, G. et al. (2015). Establishing the impacts of freshwater aquaculture in tropical Asia: the potential role of palaeolimnology. Geo: Geography and Environment 2(2), 148-163. https://doi.org/10.1002/geo2.13

Lehner, B., Beames, P., Mulligan, M., Zarfl, C., De Felice, L., van Soesbergen, A. et al. (2024). The Global Dam Watch database of river barrier and reservoir information for large-scale applications. Scientific Data 11(1), 1069. https://doi.org/10.1038/s41597-024-03752-9

Li, D., Lu, X., Walling, D. E., Zhang, T., Steiner, J. F., Wasson, R. J. et al. (2022a). High Mountain Asia hydropower systems threatened by climate-driven landscape instability. Nature Geoscience 15(7), 520-530. https://doi.org/10.1038/s41561-022-00953-y

Li, L., Ni, J., Chang, F., Yue, Y., Frolova, N., Magritsky, D. et al. (2020a). Global trends in water and sediment fluxes of the world's large rivers. Science Bulletin 65(1), 62-69. https://doi.org/10.1016/j.scib.2019.09.012

Li, T., Wang, S., Liu, Y., Fu, B. and Gao, D. (2020b). Reversal of the sediment load increase in the Amazon basin influenced by divergent trends of sediment transport from the Solimões and Madeira Rivers. Catena, 195. https://doi.org/10.1016/j.catena.2020.104804

Li, X. ,Shen, X., Jiang, W., Xi, Y. and Li, S. (2024). Comprehensive review of emerging contaminants: Detection technologies, environmental impact, and management strategies. Ecotoxicology and Environmental Safety 278, 116420. https://doi.org/10.1016/j.ecoenv.2024.116420

Li, D., Lu, X., Walling, D. E., Zhang, T., Steiner, J. F., Wasson, R. J. et al. (2022a). High Mountain Asia hydropower systems threatened by climate-driven landscape instability. Nature Geoscience 15(7), 520-530. https://doi.org/10.1038/s41561-022-00953-y

Li, Y., Geng, M., Yu, J., Du, Y., Xu, M., Zhang, W. et al. (2022b). Eutrophication decrease compositional dissimilarity in freshwater plankton communities. Science of The Total Environment, 821. https://doi.org/10.1016/j.scitotenv.2022.153434

Liang, T., Werner, T. T., Heping, X., Jingsong, Y. and Zeming, S. (2021). A global-scale spatial assessment and geodatabase of mine areas. Global and Planetary Change 204, 103578. https://doi.org/10.1016/j.gloplacha.2021.103578

Lim, X. Z. (2023). Could the world go PFAS-free? Proposal to ban 'forever chemicals' fuels debate. Nature 620, 24-27. https://doi.org/10.1038/d41586-023-02444-5

Liu, X., Wang, Y., Liu, H., Zhang, Y., Zhou, Q., Wen, X. et al. (2024). A systematic review on aquaculture wastewater: Pollutants, impacts, and treatment technology. Environmental Research 262, 119793. https://doi.org/10.1016/j.envres.2024.119793

Liu, Y.,Jiang, X.,Li, D.,Shen, J.,An, S. and Leng, X. (2023). Intensive human land uses cause the biotic homogenization of algae and change their assembly process in a major watershed of China. Science of The Total Environment 871. https://doi.org/10.1016/j.scitotenv.2023.162115

Llanos, A. A. M., Rockson, A., Getz, K., Greenberg, P., Portillo, E., McDonald, J. A. et al. (2023). Assessment of personal care product use and perceptions of use in a sample of US adults affiliated with a university in the Northeast. Environmental Research 236, 116719. https://doi.org/10.1016/j.envres.2023.116719

Lopez-Maldonado, Y. and Berkes, F. (2017). Restoring the environment, revitalizing the culture: cenote conservation in Yucatan, Mexico. Ecology and Society 22(4). https://doi.org/10.5751/ES-09648-220407

Lopez-Maldonado, Y. (2021). Understanding groundwater common-pool resources. Commonisation and decommonisation of cenotes in Yucatan, Mexico. In: NAYAK, P. K. (ed.) Making Commons Dynamic: Understanding Change Through Commonisation and Decommonisation. London: Routledge. https://doi.org/10.4324/9780429028632

López-Maldonado, Y., Anstee, J., Neely, M. B., Marty, J., Mastracci, D., Ngonyani, H. et al. (2024). The contributions of Indigenous People's earth observations to water quality monitoring. Frontiers in Water 6. https://doi.org/10.3389/frwa.2024.1363187

Luedtke, J. A., Chanson, J., Neam, K., Hobin, L., Maciel, A. O., Catenazzi, A. et al. (2023). Ongoing declines for the world's amphibians in the face of emerging threats. Nature 622(7982), 308-314. https://doi.org/10.1038/s41586-023-06578-4

Luo, A., Chen, H., Gao, X., Carvalho, L., Zhang, H. and Yang, J. (2024). The impact of rainfall events on dissolved oxygen concentrations in a subtropical urban reservoir. Environmental Research 244. https://doi.org/10.1016/j.envres.2023.117856

Ma, J., Gao, H., Cheng, C., Fang, Z., Zhou, Q. and Zhou, H. (2023). What influences the behavior of farmers' participation in agricultural nonpoint source pollution control?—Evidence from a farmer survey in Huai'an, China. Agricultural Water Management 281. https://doi.org/10.1016/j.agwat.2023.108248

Maeaba, W., Prasad, S. and Chandra, S. (2019). First Assessment of Metals Contamination in Road Dust and Roadside Soil of Suva City, Fiji. Archives of Environmental Contamination and Toxicology 77(249–262). https://doi.org/10.1007/s00244-019-00635-8

Machate, O., Schmeller, D. S., Schulze, T. and Brack, W. (2023). Review: mountain lakes as freshwater resources at risk from chemical pollution. Environmental Sciences Europe 35(1), 3. https://doi.org/10.1186/s12302-022-00710-3

Maggi, F., Tang, F. H. M. and Tubiello, F. N. (2023). Agricultural pesticide land budget and river discharge to oceans. Nature. https://doi.org/10.1038/s41586-023-06296-x

Malik, D., Sharma, A. K., Sharma, A., Thakur, R. and Sharma, M. (2020). A review on impact of water pollution on freshwater fish species and their aquatic environment. Annals of The Entomological Society of America 10-28. https://doi.org/10.26832/aesa-2020-aepm-02

Malnes, D., Waara, S., Figuière, R., Ahrens, L., Wiberg, K., Köhler, S. J. and Golovko, O. (2023). Hazard screening of contaminants of emerging concern (CECs) in Sweden's three largest lakes and their associated rivers. Journal of Hazardous Materials 453. https://doi.org/10.1016/j.jhazmat.2023.131376

Manel, S., Guerin, P.-E., Mouillot, D., Blanchet, S., Velez, L., Albouy, C. and Pellissier, L. (2020). Global determinants of freshwater and marine

fish genetic diversity. Nature Communications 11(1), 692. https://doi.org/10.1038/s41467-020-14409-7

Manjarrés-Hernández, A., Guisande, C., García-Roselló, E., Heine, J., Pelayo-Villamil, P., Pérez-Costas, E. et al. (2021). Predicting the effects of climate change on future freshwater fish diversity at global scale. Nature Conservation 43, 1-24. https://doi.org/10.3897/natureconservation.43.58997

Mariano, S. M. F., Angeles, L. F., Aga, D. S., Villanoy, C. L. and Jaraula, C. M. B. (2023). Emerging pharmaceutical contaminants in key aquatic environments of the Philippines. Frontiers in Earth Science 11. https://doi.org/10.3389/feart.2023.1124313

Marlatt, V. L., Bayen, S., Castaneda-Cortès, D., Delbès, G., Grigorova, P., Langlois, V. S. et al. (2022). Impacts of endocrine disrupting chemicals on reproduction in wildlife and humans. Environmental Research 208, 112584. https://doi.org/10.1016/j.envres.2021.112584

Martyr-Koller, R., Thomas, A., Schleussner, C.-F., Nauels, A. and Lissner, T. (2021). Loss and damage implications of sea-level rise on Small Island Developing States. Current Opinion in Environmental Sustainability 50, 245-259. https://doi.org/10.1016/j.cosust.2021.05.001

Mazzucato, M., N. Okonjo-Iweala, J. Rockström and T. Shanmugaratnam. (2024). The Economics of Water: Valuing the Hydrological Cycle as a Global Common Good. Global Commission on the Economics of Water. https://economicsofwater.watercommission.org

McAllister, T., Hikuroa, D. and Macinnis-Ng, C. (2023). Connecting Science to Indigenous Knowledge: kaitiakitanga, conservation, and resource management. New Zealand Journal of Ecology 47(1). https://doi.org/10.20417/nzjecol.47.3521

McBride, J. 2015. The Gold King Mine spill 2015. https://www.durangoherald.com/articles/the-gold-king-mine-spill-2015. Accessed 17th February 2025.

McCartney, M.,Rex, W.,Yu, W.,Uhlenbrook, S. and von Gnechten, R. (2022). Change in global freshwater storage. International Water Management Institute. https://doi.org/10.5337/2022.204

McElwee, P., Fernández-Llamazares, Á., Aumeeruddy-Thomas, Y., Babai, D., Bates, P., Galvin, K. et al. (2020). Working with Indigenous and local knowledge (ILK) in large-scale ecological assessments: Reviewing the experience of the IPBES Global Assessment. Journal of Applied Ecology 57(9), 1666-1676. https://doi.org/10.1111/1365-2664.13705

McGrane, S. J. (2016). Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. Hydrological Sciences Journal 61(13), 2295–2311. https://doi.org/10.1080/02626667.2015.1128084

McGregor, D., Whitaker, S. and Sritharan, M. (2020). Indigenous environmental justice and sustainability. Current Opinion in Environmental Sustainability 43, 35-40. https://doi.org/10.1016/j.cosust.2020.01.007

McIlwraith, H. K., Kim, J., Helm, P., Bhavsar, S. P., Metzger, J. S. and Rochman, C. M. (2021). Evidence of Microplastic Translocation in Wild-Caught Fish and Implications for Microplastic Accumulation Dynamics in Food Webs. Environmental Science & Technology 55(18), 12372-12382. https://doi.org/10.1021/acs.est.1c02922

Medunić, G., Fiket, Ž. and Ivanić, M. (2020). Arsenic Contamination Status in Europe, Australia, and Other Parts of the World. In: SRIVASTAVA, S. (ed.) Arsenic in Drinking Water and Food Springer Singapore. https://doi.org/10.1007/978-981-13-8587-2_6

Mei, Z., Cheng, P., Wang, K., Wei, Q., Barlow, J. and Wang, D. (2020). A first step for the Yangtze. Science 367(6484), 1314. https://doi.org/10.1126/science.abb5537

Meißner, S. (2021). The Impact of Metal Mining on Global Water Stress and Regional Carrying Capacities—A GIS-Based Water Impact Assessment. Resources 10(12). https://doi.org/10.3390/resources10120120

Mekonnen, M.M., Kebede, M.M., Demeke, B.W., Carr, J.A., Chapagain, A., Dalin, C. et al. (2024). Trends and environmental impacts of virtual water trade. Nature Reviews Earth & Environment, 1-16. https://doi.org/10.1038/s43017-024-00605-2

Mengistu, H. A., Demlie, M. B. and Abiye, T. A. (2019). Review: Groundwater resource potential and status of groundwater resource development in Ethiopia. Hydrogeology Journal 27(3), 1051–1065. https://doi.org/10.1007/s10040-019-01928-x

Miró, A. and Ventura, M. (2020). Introduced fish in Pyrenean high mountain lakes: impact on amphibians and other organisms, and conservation implications. Limnetica 39(1), 283-297. https://doi.org/10.23818/limn.39.19

Mishra, S., Kumar, R. and Kumar, M. (2023). Use of treated sewage or wastewater as an irrigation water for agricultural purposes- Environmental, health, and economic impacts. Total Environment Research Themes 6, 100051. https://doi.org/10.1016/j.totert.2023.100051

Mitra, S., Chakraborty, A. J., Tareq, A. M., Emran, T. B., Nainu, F., Khusro, A. et al. (2022). Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. Journal of King Saud University - Science 34(3). https://doi.org/10.1016/j.jksus.2022.101865

Mohammed, V. and Arockiaraj, J. (2024). Unveiling the trifecta of cyanobacterial quorum sensing: LuxI, LuxR and LuxS as the intricate machinery for harmful algal bloom formation in freshwater ecosystems. Science of The Total Environment 924, 171644. https://doi.org/10.1016/j.scitotenv.2024.171644

Monchamp, M.-E., Spaak, P., Domaizon, I., Dubois, N., Bouffard, D. and Pomati, F. (2018). Homogenization of lake cyanobacterial communities over a century of climate change and eutrophication. Nature Ecology & Evolution 2(2), 317-324. https://doi.org/10.1038/s41559-017-0407-0

Mudryk, L., Santolaria-Otín, M., Krinner, G., Ménégoz, M., Derksen, C., Brutel-Vuilmet, C. et al. (2020). Historical Northern Hemisphere snow cover trends and projected changes in the CMIP6 multi-model ensemble. The Cryosphere 14(7), 2495-2514. https://doi.org/10.5194/tc-14-2495-2020

Muduli, P. R., Kumar, A., Kanuri, V. V., Mishra, D. R., Acharya, P., Saha, R. et al. (2021). Water quality assessment of the Ganges River during COVID-19 lockdown. International Journal of Environmental Science and Technology 18(6), 1645-1652. https://doi.org/10.1007/s13762-021-03245-x

Mukherji, A., Molden, D., Nepal, S., Rasul, G. and Wagnon, P. (2015). Himalayan waters at the crossroads: issues and challenges. International Journal of Water Resources Development 31(2), 151-160. https://doi.org/10.1080/07900627.2015.1040871

Mwiathi, N. F., Gao, X., Li, C. and Rashid, A. (2022). The occurrence of geogenic fluoride in shallow aquifers of Kenya Rift Valley and its implications in groundwater management. Ecotoxicology and Environmental Safety 229. https://doi.org/10.1016/j.ecoenv.2021.113046

Naeem, M., Gill, R., Gill, S. S., Singh, K., Sofo, A. and Tuteja, N. (2023). Editorial: Emerging contaminants and their effect on agricultural crops. Frontiers in Plant Science 14, 1296252. https://doi.org/10.3389/fpls.2023.1296252

Nakashima, D. J., Galloway McLean, K., Thulstrup, H. D., Ramos Castillo, A. and Rubis, J. T. (2012). Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation. https://unesdoc.unesco.org/ark:/48223/pf0000216613

Namsaraev, Z., Melnikova, A., Komova, A., Ivanov, V., Rudenko, A. and Ivanov, E. (2020). Algal Bloom Occurrence and Effects in Russia. Water 12(1), 285. https://doi.org/10.3390/w12010285

Nargis, A., Habib, A., Harun Or, R., Harun, H. B., Islam Sarker, M. S., Jin, R. et al. (2021). Status of multielement in water of the river Buriganga, Bangladesh: Aquatic chemistry of metal ions in polluted river water. Emerging Contaminants 7, 99-115. https://doi.org/10.1016/j.emcon.2021.03.001

NASA (2020). Tracking Water for the Navajo Nation. https://earthobservatory.nasa.gov/images/146565/tracking-water-for-the-navajo-nation. Accessed 8th February 2025.

Nearing, G., Cohen, D., Dube, V., Gauch, M., Gilon, O., Harrigan, S. et al. (2024). Global prediction of extreme floods in ungauged watersheds. Nature 627(8004), 559-563. https://doi.org/10.1038/s41586-024-07145-1

Ngo, H., Bomers, A., Augustijn, D. C. M., Ranasinghe, R., Filatova, T., van der Meulen, B. et al. (2023). Reconstruction of the 1374 Rhine river flood event around Cologne region using 1D-2D coupled hydraulic modelling approach. Journal of Hydrology 617. https://doi.org/10.1016/j.jhydrol.2022.129039

Nicholls, R. J., Beaven, R. P., Stringfellow, A., Monfort, D., Cozannet, G. L., Wahl, T. et al. (2021). Coastal Landfills and Rising Sea Levels: A

Challenge for the 21st Century. Frontiers in Marine Science 8. https://doi.org/10.3389/fmars.2021.710342

Nijhawan, A. and Howard, G. (2022). Associations between climate variables and water quality in low- and middle-income countries: A scoping review. Water Research 210. https://doi.org/10.1016/j.watres.2021.117996

Nyboer, E. A., Liang, C. and Chapman, L. J. (2019). Assessing the vulnerability of Africa's freshwater fishes to climate change: A continent-wide trait-based analysis. Biological Conservation 236, 505-520. https://doi.org/10.1016/j.biocon.2019.05.003

Olatunde, O. C., Kuvarega, A. T. and Onwudiwe, D. C. (2020). Photo enhanced degradation of contaminants of emerging concern in wastewater. Emerging Contaminants 6, 283-302. https://doi.org/10.1016/j.emcon.2020.07.006

Osiemo, M. M., Ogendi, G. M. and M'Erimba, C. (2019). Microbial Quality of Drinking Water and Prevalence of Water-Related Diseases in Marigat Urban Centre, Kenya. Environmental Health Insights 13, 1-7. https://doi.org/10.1177/1178630219836988

Osuoha, J. O., Anyanwu, B. O. and Ejileugha, C. (2023). Pharmaceuticals and personal care products as emerging contaminants: Need for combined treatment strategy. Journal of Hazardous Materials Advances 9, 100206. https://doi.org/10.1016/j.hazadv.2022.100206

Otkin, J. A., Svoboda, M., Hunt, E. D., Ford, T. W., Anderson, M. C., Hain, C. and Basara, J. B. (2018). Flash Droughts: A Review and Assessment of the Challenges Imposed by Rapid-Onset Droughts in the United States. Bulletin of the American Meteorological Society 99(5), 911-919. https://doi.org/10.1175/BAMS-D-17-0149.1

Prăvălie, R. (2021). Exploring the multiple land degradation pathways across the planet. Earth-Science Reviews 220, 103689. https://doi.org/10.1016/j.earscirev.2021.103689

Pacific Institute (2024). Water Conflict Chronology. https://www.worldwater.org/water-conflict. Accessed 12th October 2024.

Park, E. (2024). Sand mining in the Mekong Delta: Extent and compounded impacts. Science of The Total Environment 924, 171620. https://doi.org/10.1016/j.scitotenv.2024.171620

Pastorino, P. and Ginebreda, A. (2021). Contaminants of Emerging Concern (CECs): Occurrence and Fate in Aquatic Ecosystems. International Journal of Environmental Research and Public Health 18(24). https://doi.org/10.3390/ijerph182413401

Pérez-Reverón, R., González-Sálamo, J., Hernández-Sánchez, C., González-Pleiter, M., Hernández-Borges, J. and Díaz-Peña, F. J. (2022). Recycled wastewater as a potential source of microplastics in irrigated soils from an arid-insular territory (Fuerteventura, Spain). Science of The Total Environment 817, 152830. https://doi.org/10.1016/j.scitotenv.2021.152830

Petrie, B. (2021). A review of combined sewer overflows as a source of wastewater-derived emerging contaminants in the environment and their management. Environmental Science and Pollution Research 28(25), 32095-32110. https://doi.org/10.1007/s11356-021-14103-1

Petsch, D. K., dos Santos Bertoncin, A. P., Ortega, J. C. G. and Thomaz, S. M. (2022). Non-native species drive biotic homogenization, but it depends on the realm, beta diversity facet and study design: a meta-analytic systematic review. Oikos 2022(6). https://doi.org/10.1111/oik.08768

Pilla, R. M. and Williamson, C. E. (2023). Multidecadal trends in ultraviolet radiation, temperature, and dissolved oxygen have altered vertical habitat availability for Daphnia in temperate Lake Giles, USA. Freshwater Biology 68(3), 523-533. https://doi.org/10.1111/fwb.14044

Podgorski, J. and Berg, M. (2022). Global analysis and prediction of fluoride in groundwater. Nature Communications 13. https://doi.org/10.1038/s41467-022-31940-x

Porkka, M., Virkki, V., Wang-Erlandsson, L., Gerten, D., Gleeson, T., Mohan, C. et al. (2024). Notable shifts beyond pre-industrial streamflow and soil moisture conditions transgress the planetary boundary for freshwater change. Nature Water 2(3), 262-273. https://doi.org/10.1038/s44221-024-00208-7

Przydatek, G. and Kanownik, W. (2019). Impact of small municipal solid waste landfill on groundwater quality. Environmental Monitoring and Assessment 191. https://doi.org/10.1007/s10661-019-7279-5

Qin, Y., Hong, C., Zhao, H., Siebert, S., Abatzoglou, J. T., Huning, L. S. et al. (2022). Snowmelt risk telecouplings for irrigated agriculture. Nature Climate Change 12(11), 1007-1015. https://doi.org/10.1038/s41558-022-01509-z

Rajagopalan, S. and Landrigan, P. J. (2021). Pollution and the Heart. New England Journal of Medicine 385(20), 1881-1892. https://doi.org/10.1056/NEJMra2030281

Ramsar Convention on Wetlands (2018). Global Wetland Outlook: State of the World's Wetlands and their Services to People. https://www.ramsar.org/sites/default/files/documents/library/gwo_e.pdf

Rather, R. A., Ara, S., Padder, S. A., Sharma, S., Pathak, S. P. and Baba, T. R. (2023). Seasonal fluctuation of water quality and ecogenomic phylogeny of novel potential microbial pollution indicators of Veshaw River Kashmir-Western Himalaya. Environmental Pollution 320. https://doi.org/10.1016/j.envpol.2023.121104

Rathore, S. S., Chandravanshi, P., Chandravanshi, A. and Jaiswal, K. (2016). Eutrophication: Impacts of Excess Nutrient Inputs on Aquatic Ecosystem. IOSR Journal of Agriculture and Veterinary Science 9(10). https://doi.org/10.9790/2380-0910018996

Ray, S. and Shaju, S. T. (2023). Bioaccumulation of pesticides in fish resulting toxicities in humans through food chain and forensic aspects. Environmental Analysis Health and Toxicology 38(3), e2023017-0. https://doi.org/10.5620/eaht.2023017

Reid, A. J., Carlson, A. K., Creed, I. F., Eliason, E. J., Gell, P. A. ,Johnson, P. T. J. et al. (2019). Emerging threats and persistent conservation challenges for freshwater biodiversity. Biological Reviews 94(3), 849-873. https://doi.org/10.1111/brv.12480

Reyes-García, V., García-del-Amo, D., Álvarez-Fernández, S., Benyei, P., Calvet-Mir, L., Junqueira, A. B. et al. (2024). Indigenous Peoples and local communities report ongoing and widespread climate change impacts on local social-ecological systems. Communications Earth & Environment 5(1), 29. https://doi.org/10.1038/s43247-023-01164-y.

Rico, A., Redondo-Hasselerharm, P. E., Vighi, M., Waichman, A. V.,de Souza Nunes, G. S.,de Oliveira, R. et al. (2023). Large-scale monitoring and risk assessment of microplastics in the Amazon River. Water Research 232. https://doi.org/10.1016/j.watres.2023.119707

Riquetti, N. B., Beskow, S., Guo, L. and Mello, C. R. (2023). Soil erosion assessment in the Amazon basin in the last 60 years of deforestation. Environmental Research 236. https://doi.org/10.1016/j.envres.2023.116846

Rockström, J., Gupta, J., Qin, D., Lade, S. J., Abrams, J. F., Andersen, L. S. et al. (2023). Safe and just Earth system boundaries. Nature 619(7968), 102-111. https://doi.org/10.1038/s41586-023-06083-8

Rodell, M., Famiglietti, J. S., Wiese, D. N., Reager, J. T., Beaudoing, H. K., Landerer, F. W. and Lo, M.-H. (2018). Emerging trends in global freshwater availability. Nature 557, 651–659. https://doi.org/10.1038/s41586-018-0123-1

Rogger, M., Agnoletti, M., Alaoui, A., Bathurst, J. C., Bodner, G., Borga, M. et al. (2017). Land use change impacts on floods at the catchment scale: Challenges and opportunities for future research. Water Resources Research 53(7), 5209-5219. https://doi.org/10.1002/2017WR020723

Rosa, L., Chiarelli, D. D., Tu, C., Rulli, M. C. and D'Odorico, P. (2019). Global unsustainable virtual water flows in agricultural trade. Environmental Research Letters 14(11). https://doi.org/10.1088/1748-9326/ab4bfc

Rosaen, A. L., Grover, E. A., Spencer, C. W. and Anderson, P. L. (2012). The costs of aquatic invasive species to Great Lakes states. Aderson Economic Group. https://www.andersoneconomicgroup.com/Portals/0/upload/AEG%20Report%20-%20AIS%20Econ%20Impact-Final.pdf

Rügner, H., Schwientek, M., Milačič, R., Zuliani, T., Vidmar, J., Paunović, M. et al. (2019). Particle bound pollutants in rivers: Results from suspended sediment sampling in Globaqua River Basins. Science of The Total Environment 647, 645-652. https://doi.org/10.1016/j.scitotenv.2018.08.027

Saha, R. and Dutta, S. M. (2024). Pesticides' mode of action on aquatic life. Toxicology Reports 13, 101780. https://doi.org/10.1016/j.toxrep.2024.101780

Salgado, J., Shurin, J. B., Vélez, M. I., Link, A., Lopera-Congote, L., González-Arango, C. et al. (2022). Causes and consequences of recent degradation

of the Magdalena River basin, Colombia. Limnology and Oceanography Letters 7(6), 451-465. https://doi.org/10.1002/lol2.10272

Samakov, A. and Berkes, F. (2016). Ysyk-Köl Lake, the planet's third eye: sacred sites in Ysyk-KölBiosphere Reserve. In: Verschuuren, B. & Furuta, N. (eds.) Asian Sacred Natural Sites, Philosophy and Practice in Protected Areas and Conservation. London and New York: Routledge. https://doi.org/10.4324/9781315676272

Sandström, S., Futter, M. N., Kyllmar, K., Bishop, K., O'Connell, D. W. and Djodjic, F. (2020). Particulate phosphorus and suspended solids losses from small agricultural catchments: Links to stream and catchment characteristics. Science of The Total Environment 711, 134616. https://doi.org/10.1016/j.scitotenv.2019.134616

Saravanan, A., Kumar, P. S., Hemavathy, R. V., Jeevanantham, S., Harikumar, P., Priyanka, G. and Devakirubai, D. R. A. (2022). A comprehensive review on sources, analysis and toxicity of environmental pollutants and its removal methods from water environment. Science of The Total Environment 812, 152456. https://doi.org/10.1016/j.scitotenv.2021.152456

Sayer, C. A., Fernando, E., Jimenez, R. R., Macfarlane, N. B. W, Rapacciuolo, G., Böhmet, M. et al. (2025). One-quarter of freshwater fauna threatened with extinction. Nature 638, 138–145. https://doi.org/10.1038/s41586-024-08375-z

Schaeffer, B. A., Reynolds, N., Ferriby, H., Salls, W., Smith, D., Johnston, J. M., & Myer, M. (2024). Forecasting freshwater cyanobacterial harmful algal blooms for Sentinel-3 satellite resolved US lakes and reservoirs. Journal of Environmental Management, 349, 119518. https://doi.org/10.1016/j.jenvman.2023.119518

Schlef, K. E., Moradkhani, H. and Lall, U. (2019). Atmospheric Circulation Patterns Associated with Extreme United States Floods Identified via Machine Learning. Scientific Reports 9(1), 7171. https://doi.org/10.1038/s41598-019-43496-w

Seebens, H., Meyerson, L. A., Rahlao, S. J., Lenzner, B., Tricarico, E., Aleksanyan, A. et al. (2023). Chapter 2: Trends and status of alien and invasive alien species. In: Roy, H. E., Pauchard, A., Stoett, P. & Renard Truong, T. (eds.) Thematic Assessment Report on Invasive Alien Species and their Control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES secretariat. https://doi.org/10.5281/zenodo.7430725

Sha, J.,Xiong, H.,Li, C.,Lu, Z.,Zhang, J.,Zhong, H. et al. (2021). Harmful algal blooms and their eco-environmental indication. Chemosphere 274. https://doi.org/10.1016/j.chemosphere.2021.129912

Shaaban, H. and Alhajri, W. (2020). Usage Patterns of Cosmetic and Personal Care Products among Female Population in Saudi Arabia: Important Factors for Exposure and Risk Assessment. Journal of Environmental and Public Health 2020 (1), 8434508. https://doi.org/10.1155/2020/8434508

Shaji, E., Santosh, M., Sarath, K. V., Prakash, P., Deepchand, V. and Divya, B. V. (2021). Arsenic contamination of groundwater: A global synopsis with focus on the Indian Peninsula. Geoscience Frontiers 12(3). https://doi.org/10.1016/j.gsf.2020.08.015

Sharan, A., Lal, A. and Datta, B. (2023). Evaluating the impacts of climate change and water over-abstraction on groundwater resources in Pacific island country of Tonga. Groundwater for Sustainable Development 20. https://doi.org/10.1016/j.gsd.2022.100890

Shehu, Z., Nyakairu, G. W. A., Tebandeke, E. and Odume, O. N. (2022). Overview of African water resources contamination by contaminants of emerging concern. Science of The Total Environment 852. https://doi.org/10.1016/j.scitotenv.2022.158303

Shetty, S. S., D, D., S, H., Sonkusare, S., Naik, P. B., Kumari, N. S. and Madhyastha, H. (2023). Environmental pollutants and their effects on human health. Heliyon 9(9), e19496. https://doi.org/10.1016/j.heliyon.2023.e19496

Shittu, E., Lakhanpaul, M., Vigurs, C., Sarkar, K., Koch, M., Parikh, P. and Campos, L. C. (2023). A rapid systematic scoping review of research on the impacts of water contaminated by chemicals on very young children. Science of The Total Environment 891, 164604. https://doi.org/10.1016/j.scitotenv.2023.164604

Shrestha, A., Shah, D. N., Bajracharya, R. M. and Shrestha, S. (2022). Traditional stone water spouts status and its practical significance in urbanizing Kathmandu Valley, Nepal – a review. Environmental Challenges 8, 100573. https://doi.org/10.1016/j.envc.2022.100573

Shugar, D. H., Burr, A., Haritashya, U. K., Kargel, J. S., Watson, C. S., Kennedy, M. C. et al. (2020). Rapid worldwide growth of glacial lakes since 1990. Nature Climate Change 10, 939-945. https://doi.org/10.1038/s41558-020-0855-4

Shulhai, A.-M., Palanza, P. and Street, M. E. (2023). Current Evidence on the Effects of Endocrine-Disrupting Chemicals (EDCs) on Bone Growth and Health. Exposure and Health 16(4), 1001-1025. https://doi.org/10.1007/s12403-023-00607-3

Silva-Junior, C. H. L., Silva, F. B., Arisi, B. M., Mataveli, G., Pessôa, A. C. M., Carvalho, N. S. et al. (2023). Brazilian Amazon indigenous territories under deforestation pressure. Scientific Reports 13(1), 5851. https://doi.org/10.1038/s41598-023-32746-7

Silveira, S. B. and Odebrecht, C. (2019). Effects of Salinity and Temperature on the Growth, Toxin Production, and Akinete Germination of the Cyanobacterium Nodularia spumigena. Frontiers in Marine Science 6. https://doi.org/10.3389/fmars.2019.00339

Sims, D. B., Monk, J. R., Woldetsadik, D., Hudson, A. C., Garner, M. C., Lindley, K. et al. (2024). Per- and polyfluoroalkyl substances (PFAS) in the rivers of the Western United States. International Journal of Environmental Science and Technology, 1-18. https://doi.org/10.1007/s13762-024-06269-1

Singh, G., Thakur, N. and Kumar, R. (2024). Nanoparticles in drinking water: Assessing health risks and regulatory challenges. Science of The Total Environment 949, 174940. https://doi.org/10.1016/j.scitotenv.2024.174940

Slater, L., Villarini, G., Archfield, S., Faulkner, D., Lamb, R., Khouakhi, A. and Yin, J. (2021). Global Changes in 20-Year, 50-Year, and 100-Year River Floods. Geophysical Research Letters 48(6), e2020GL091824. https://doi.org/10.1029/2020GL091824

Soden, B. J. and Held, I. M. (2006). An Assessment of Climate Feedbacks in Coupled Ocean–Atmosphere Models. Journal of Climate 19(14), 3354-3360. https://doi.org/10.1175/JCLI3799.1.

Sonter, L. J., Dade, M. C., Watson, J. E. M. and Valenta, R. K. (2020). Renewable energy production will exacerbate mining threats to biodiversity. Nature Communications 11(1), 4174. https://doi.org/10.1038/s41467-020-17928-5

Souaissi, Z., Ouarda, T. B. M. J. and St-Hilaire, A. (2021). River water temperature quantiles as thermal stress indicators: Case study in Switzerland. Ecological Indicators 131, 108234. https://doi.org/10.1016/j.ecolind.2021.108234

Spinoni, J., Barbosa, P., Bucchignani, E., Cassano, J., Cavazos, T., Christensen, J. H. et al. (2020). Future Global Meteorological Drought Hot Spots: A Study Based on CORDEX Data. Journal of Climate 33(9), 3635-3661. https://doi.org/10.1175/JCLI-D-19-0084.1

Statista (2023). Total consumption of water by the mining industry across Australia from financial year 2018 to 2022. https://www.statista.com/statistics/1033539/australia-mining-water-consumption-volume Accessed 15th August 2023.

Strayer, D. L. (2009). Twenty years of zebra mussels: lessons from the mollusk that made headlines. Frontiers in Ecology and the Environment 7(3), 135-141. https://doi.org/10.1890/080020

Stuart, S.N., Chanson, J.S., Cox, N.A., Young, B.E., Rodrigues, A.S., Fischman, D.L. and Waller, R.W., (2004). Status and trends of amphibian declines and extinctions worldwide. Science 306(5702), 1783-1786. https://doi.org/10.1126/science.1103538

Stuyfzand, P. J. and Bonte, M. (2023). A critical review of arsenic occurrence, fate and transport in natural and modified groundwater systems in The Netherlands. Applied Geochemistry 150. https://doi.org/10.1016/j.apgeochem.2023.105596

Su, G., Logez, M., Xu, J., Tao, S., Villéger, S. and Brosse, S. (2021). Human impacts on global freshwater fish biodiversity. Science 371(6531), 835-838. https://doi.org/10.1126/science.abd3369

Su, Z., Wang, K., Yang, F. and Zhuang, T. (2023). Antibiotic pollution of the Yellow River in China and its relationship with dissolved organic matter: Distribution and Source identification. Water Research 235. https://doi.org/10.1016/j.watres.2023.119867

Sulaiman, B., Woodward, J. C. and Shiels, H. A. (2023). Riverine microplastics and their interaction with freshwater fish. Water Biology and Security 2(4), 100192. https://doi.org/10.1016/j.watbs.2023.100192

Syafrudin, M., Kristanti, R. A., Yuniarto, A., Hadibarata, T., Rhee, J., Al-onazi, W. A. et al. (2021). Pesticides in Drinking Water—A Review. International Journal of Environmental Research and Public Health 18(2). https://doi.org/10.3390/ijerph18020468

Syanya, F.J., Winam, Z.O. and Mathia, W.M. (2024). Vanishing splendor: a comprehensive review of the decline in the original fish fauna of Lake Victoria. Marine & Fishery Sciences 37(1), 209-231. https://doi.org/10.47193/mafis.3712024010107

Tan, J. F., Anastasi, A. and Chandra, S. (2022). Electrochemical detection of nitrate, nitrite and ammonium for on-site water quality monitoring. Current Opinion in Electrochemistry 32. https://doi.org/10.1016/j.coelec.2021.100926

Taniwaki, R.H., Piggott, J.J., Ferraz, S.F. and Matthaei, C.D. (2017). Climate change and multiple stressors in small tropical streams. Hydrobiologia 793, 41-53. https://doi.org/10.1007/s10750-016-2907-3

Taylor, C., Robinson, T. R., Dunning, S., Rachel Carr, J. and Westoby, M. (2023). Glacial lake outburst floods threaten millions globally. Nature Communications 14(1), 487. https://doi.org/10.1038/s41467-023-36033-x

Tian, W., Liu, X., Wang, K., Bai, P., Liu, C. and Liang, X. (2022). Estimation of global reservoir evaporation losses. Journal of Hydrology 607. https://doi.org/10.1016/j.jhydrol.2022.127524

Tiberti, R., von Hardenberg, A. and Bogliani, G. (2014). Ecological impact of introduced fish in high altitude lakes: a case of study from the European Alps. Hydrobiologia 724(1), 1-19. https://doi.org/10.1007/s10750-013-1696-1.

Toh, E. X. P., Gan, L. X. and Yeo, D. C. J. (2022). A global overview of climate change impacts on freshwater decapods: substantial research gaps across taxa and biogeographic regions. Journal of Crustacean Biology 42(1). https://doi.org/10.1093/jcbiol/ruab088

Toussaint, A., Brosse, S., Bueno, C. G., Pärtel, M., Tamme, R. and Carmona, C. P. (2021). Extinction of threatened vertebrates will lead to idiosyncratic changes in functional diversity across the world. Nature Communications 12(1), 5162. https://doi.org/10.1038/s41467-021-25293-0

Tregidgo, D., Barlow, J., Pompeu, P. S. and Parry, L. (2020). Tough fishing and severe seasonal food insecurity in Amazonian flooded forests. People and Nature 2(2), 468-482. https://doi.org/10.1002/pan3.10086

Troia, M. J., Kaz, A. L., Niemeyer, J. C. and Giam, X. (2019). Species traits and reduced habitat suitability limit efficacy of climate change refugia in streams. Nature Ecology & Evolution 3(9), 1321-1330. https://doi.org/10.1038/s41559-019-0970-7

Tschaikowski, J. M. P., Putra, D. P. E., Pracoyo, A. and Moosdorf, N. (2024). Tourism-Related Pressure on the Freshwater Lens of the Small Coral Island Gili Air, Indonesia. Water 16(2). https://doi.org/10.3390/w16020237

Turnhout, E., Bloomfield, B., Hulme, M., Vogel, J. and Wynne, B. (2012). Listen to the voices of experience. Nature 488(7412), 454-455. https://doi.org/10.1038/488454a

Uddin, M. J. and Jeong, Y.-K. (2021). Urban river pollution in Bangladesh during last 40 years: potential public health and ecological risk, present policy, and future prospects toward smart water management. Heliyon 7(2). https://doi.org/10.1016/j.heliyon.2021.e06107

United Nations (2022). The Sustainable Development Goals Report 2022. New York. https://unstats.un.org/sdgs/report/2022/

United Nations International Children's Emergency Fund. (2023). Progress on household drinking water, sanitation and hygiene 2000–2022: special focus on gender. New York. https://www.unicef.org/wca/media/9161/file/jmp-2023-wash-households-launch-version.pdf

United Nations Economic Commission for Europe and The United Nations Educational Scientific and Cultural Organization and United Nations Water (2024). Progress on Transboundary Water Cooperation: Mid-term status of SDG Indicator 6.5.2, with a special focus on Climate Change. https://doi.org/10.54677/QMQX8780

United Nations Educational Scientific and Cultural Organization (2019). Erosion and sediment problems: Global Hotspots. Paris. https://unesdoc.unesco.org/ark:/48223/pf0000369887.locale=en

United Nations Educational Scientific and Cultural Organization and International Hydrological Programme (2015). GRAPHIC – Groundwater and Climate Change; Small Island Developing States (SIDS). https://unesdoc.unesco.org/ark:/48223/pf0000242861

United Nations Educational Scientific and Cultural Organization (2019). Erosion and sediment problems: Global Hotspots. Paris. https://unesdoc.unesco.org/ark:/48223/pf0000369887.locale=en

United Nations Environment Programme (2024a). Progress on Water-related Ecosystems. Mid-term status of SDG Indicator 6.6.1 and acceleration needs, with a special focus on Biodiversity. Nairobi. https://www.unwater.org/sites/default/files/2024-08/SDG6_Indicator_Report_661_Progress-on-Water-related-Ecosystems_2024_EN.pdf

United Nations Environment Programme (2024b). Progress on Ambient Water Quality: Mid-term status of SDG Indicator 6.3.2 and acceleration needs, with a special focus on Health. Nairobi. https://www.unwater.org/sites/default/files/2024-08/SDG6_Indicator_Report_632_Progress-on-Ambient-Water-Quality_2024_EN.pdf

United Nations Human Settlements Programme and the World Health Organization (2024). Progress on the proportion of domestic and industrial wastewater flows safely treated: mid-term status of SDG indicator 6.3.1 and acceleration needs, with a special focus on climate change, wastewater reuse and health. https://www.unwater.org/sites/default/files/2024-08/SDG6_Indicator_Report_631_Progress-on-Wastewater-Treatment_2024_EN_0.pdf

United Nations Water and The United Nations Educational Scientific and Cultural Organization (2021). United Nations World Water Development Report (2021): Valuing Water. https://www.unwater.org/publications/un-world-water-development-report-2021

United Nations Water and The United Nations Educational Scientific and Cultural Organization (2022). The United Nations World Water Development Report 2022: Groundwater: Making the invisible visible. https://www.unwater.org/publications/un-world-water-development-report-2022

United Nations Water and The United Nations Educational Scientific and Cultural Organization (2023). The United Nations World Water Development Report: Partnerships and cooperation for water; facts, figures and action examples. https://www.unwater.org/publications/un-world-water-development-report-2023.

United Nations Water and The United Nations Educational Scientific and Cultural Organization (2024). The United Nations World Water Development Report: Water for Prosperity and Peace; facts, figures and action examples. https://www.unwater.org/publications/un-world-water-development-report-2024

United Nations Water (2021). Summary Progress Update 2021: SDG 6 — water and sanitation for all. Geneva. https://www.unwater.org/publications/summary-progress-update-2021-sdg-6-water-and-sanitation-all

Urban, M. C. (2024). Climate change extinctions. Science 386, 1123-1128. https://doi.org/10.1126/science.adp4461

Uyttendaele, M., Jaykus, L.-A., Amoah, P., Chiodini, A., Cunliffe, D., Jacxsens, L. et al. (2015). Microbial Hazards in Irrigation Water: Standards, Norms, and Testing to Manage Use of Water in Fresh Produce Primary Production. Comprehensive Reviews in Food Science and Food Safety 14(4), 336-356. https://doi.org/10.1111/1541-4337.12133

Van Leeuwen, C. H. A., Dalen, K., Museth, J., Junge, C. and Vøllestad, L. A. (2018). Habitat fragmentation has interactive effects on the population genetic diversity and individual behavior of a freshwater salmonid fish. River Research and Applications 34(1), 60-68. https://doi.org/10.1002/rra.3226

van Puijenbroek, P. J. T. M., Buijse, A. D., Kraak, M. H. S. and Verdonschot, P. F. M. (2019). Species and river specific effects of river fragmentation on European anadromous fish species. River Research and Applications 35(1), 68-77. https://doi.org/10.1002/rra.3386.

Verones, F., Kuipers, K., Núñez, M., Rosa, F., Scherer, L., Marques, A. et al. (2022). Global extinction probabilities of terrestrial, freshwater, and marine species groups for use in Life Cycle Assessment. Ecological Indicators 142. https://doi.org/10.1016/j.ecolind.2022.109204

Voosen, P. (2023). Illegal mining has muddied tropical rivers worldwide. Science 379, 124-1125. https://doi.org/10.1126/science.adg6274

Wang, J., Chen, L., Tang, W., Heino, J. and Jiang, X. (2021). Effects of dam construction and fish invasion on the species, functional and phylogenetic diversity of fish assemblages in the Yellow River Basin. Journal of Environmental Management 293. https://doi.org/10.1016/j.jenvman.2021.112863

Wang, J., Shi, B., Zhao, E., Yuan, Q. and Chen, X. (2022a). The long-term spatial and temporal variations of sediment loads and their causes of the Yellow River Basin. Catena 209. https://doi.org/10.1016/j.catena.2021.105850

Wang, W., Yuan, W., Xu, E. G., Li, L., Zhang, H. and Yang, Y. (2022b). Uptake, translocation, and biological impacts of micro(nano)plastics in terrestrial plants: Progress and prospects. Environmental Research 203, 111867. https://doi.org/10.1016/j.envres.2021.111867

Weiss, S., Apostolou, A., Đug, S., Marčić, Z., Mušović, M., Oikonomou, A. et al. (2018). Endangered Fish Species in Balkan Rivers: their distributions and threats from hydropower development. https://doi.org/10.13140/RG.2.2.22638.10563

Wen, Y., Schoups, G. and van de Giesen, N. (2017). Organic pollution of rivers: Combined threats of urbanization, livestock farming and global climate change. Scientific Reports 7(1), 43289. https://doi.org/10.1038/srep43289

Werbowski, L. M., Gilbreath, A. N., Munno, K., Zhu, X., Grbic, J., Wu, T. et al. (2021). Urban Stormwater Runoff: A Major Pathway for Anthropogenic Particles, Black Rubbery Fragments, and Other Types of Microplastics to Urban Receiving Waters. ACS ES&T Water 1(6), 1420-1428. https://doi.org/10.1021/acsestwater.1c00017

Wilkinson, J. L., Boxall, A. B. A., Kolpin, D. W., Leung, K. M. Y., Lai, R. W. S., Galbán-Malagón, C. et al. (2022). Pharmaceutical pollution of the world's rivers. Proceedings of the National Academy of Sciences 119(8), e2113947119. https://doi.org/10.1073/pnas.2113947119

World Bank (2023). Urban Development. https://www.worldbank.org/en/topic/urbandevelopment/overview. Accessed 4th February 2024.

World Health Organization (2022). Guidelines for drinking water quality: fourth edition incorporating the first and second addenda. Geneva. https://www.who.int/publications/i/item/9789240045064

World Health Organization (2023). Disease Outbreak News; Cholera – Global situation. https://www.who.int/emergencies/disease-outbreak-news/item/2023-DON437. Accessed 11th February 2023.

World Meteorological Organization. (2022). The State of the Climate in 2021. Geneva. https://wmo.int/publication-series/state-of-global-climate-2021

World Wildlife Fund. (2025). Africa's Forgotten Fishes...and the emergency recovery plan to save them. https://files.worldwildlife.org/wwfcmsprod/files/Publication/file/5bgjf8vbiy_WWF_Africas_Forgotten_Fishes.pdf Accessed 01 September 2025.

Wu, H., Chen, J., Xu, J., Zeng, G., Sang, L., Liu, Q. et al. (2019). Effects of dam construction on biodiversity: A review. Journal of Cleaner Production 221, 480-489. https://doi.org/10.1016/j.jclepro.2019.03.001

Wurtsbaugh, W. A., Paerl, H. W., and Dodds, W. K. (2019). Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum. WIREs Water 6, 1373. https://doi.org/10.1002/wat2.1373

Xie, J., Liu, X., Jasechko, S., Berghuijs, W. R., Wang, K., Liu, C. et al. (2024). Majority of global river flow sustained by groundwater. Nature Geoscience 17(8), 770-777. https://doi.org/10.1038/s41561-024-01483-5

Xu, B., Liu, S., Zhou, J. L., Zheng, C., Weifeng, J., Chen, B. et al. (2021). PFAS and their substitutes in groundwater: Occurrence, transformation and remediation. Journal of Hazardous Materials 412, 125159. https://doi.org/10.1016/j.jhazmat.2021.125159

Yin, S., Gao, G., Huang, A., Li, D., Ran, L., Nawaz, M. et al. (2023). Streamflow and sediment load changes from China's large rivers: Quantitative contributions of climate and human activity factors. Science of The Total Environment 876. https://doi.org/10.1016/j.scitotenv.2023.162758

Yongo, E., Zhang, P., Mutethya, E., Zhao, T. and Guo, Z. (2023). The invasion of tilapia in South China freshwater systems: A review. Lakes & Reservoirs: Science, Policy and Management for Sustainable Use 28(1), e12429. https://doi.org/10.1111/lre.12429

You, A. J. and Hua, L. (2019). Optimization and Effect of Inner Water Diversion and Distribution in the West Lake of Hangzhou. IOP Conference Series: Earth and Environmental Science 264(1), 012018. https://dx.doi.org/10.1088/1755-1315/264/1/012018

Yu, S.-Y., Li, W.-J., Zhou, L., Yu, X., Zhang, Q. and Shen, Z. (2023). Human disturbances dominated the unprecedentedly high frequency of Yellow River flood over the last millennium. Science Advances 9(8), eadf8576. https://doi.org/10.1126/sciadv.adf8576

Zaitchik, B. F., Rodell, M., Biasutti, M. and Seneviratne, S. I. (2023). Wetting and drying trends under climate change. Nature Water 1(6), 502-513. https://doi.org/10.1038/s44221-023-00073-w

Zarfl, C., Berlekamp, J., He, F., Jähnig, S. C., Darwall, W. and Tockner, K. (2019). Future large hydropower dams impact global freshwater megafauna. Scientific Reports 9. https://doi.org/10.1038/s41598-019-54980-8

Zhang, A. T. and Gu, V. X. (2023). Global Dam Tracker: A database of more than 35,000 dams with location, catchment, and attribute information. Scientific Data 10. https://doi.org/10.1038/s41597-023-02008-2

Zhang, W., Shen, J. and Wang, J. (2021). Linking pollution to biodiversity and ecosystem multifunctionality across benthic-pelagic habitats of a large eutrophic lake: A whole-ecosystem perspective. Environmental Pollution 285, 117501. https://doi.org/10.1016/j.envpol.2021.117501

Zhao, G., Li, Y., Zhou, L. and Gao, H. (2022). Evaporative water loss of 1.42 million global lakes. Nature Communications 13. https://doi.org/10.1038/s41467-022-31125-6

Zheng, S., Yang, Y., Wen, C., Liu, W., Cao, L., Feng, X. et al. (2021). Effects of environmental contaminants in water resources on nonalcoholic fatty liver disease. Environment International 154, 106555. https://doi.org/10.1016/j.envint.2021.106555

Zhou, Q., Yang, N., Li, Y., Ren, B., Ding, X., Bian, H. and Yao, X. (2020). Total concentrations and sources of heavy metal pollution in global river and lake water bodies from 1972 to 2017. Global Ecology and Conservation 22. https://doi.org/10.1016/j.gecco.2020.e00925

Zou, L., Liu, Y., Wang, Y. and Hu, X. (2020). Assessment and analysis of agricultural non-point source pollution loads in China: 1978–2017. Journal of Environmental Management 263. https://doi.org/10.1016/j.jenvman.2020.110400

07 Implication of Environmental Crises on the Socioeconomic Dimensions of the Sustainable Development Goals

Co-ordinating Lead Authors: Mark Elder (Institute for Global Environmental Strategies), Riya Rahiman (Coalition for Disaster Resilient Infrastructure)

Lead Authors: Aliyu Aliyu (University of Lincoln), Farshad Amiraslani (University of Tehran), Elliot Boateng (Kwame Nkrumah University of Science and Technology), Lindsay Beevers (The University of Edinburgh), Erica Gaddis (SWCA Environmental Consultants), Maryna Henrysson (Royal Institute of Technology), Saleemul Huq (late), Andrei Kirilenko (University of Florida), Mahdi Kolahi (Ferdowsi University of Mashhad), Jyotsna Krishnakumar (Keystone Foundation), Govind Kelkar (GenDev Centre for Research and Innovation), Tao Lin (Institute of Urban Environment, Chinese Academy of Sciences), Simon Høiberg Olsen (Institute for Global Environmental Strategies), Maria Cristina Tirado (University of California | SHE Foundation), Nomanesi Madikizela-Madiya (University of South Africa), Valerie Nelson (University of Greenwich), Jaee Nikam (Stockholm Environment Institute/Carleton University), Kamaljit K Sangha (Charles Darwin University)

Contributing Authors: Sandya Gunasekara (Centre for Policy Futures), Savio Rousseau Rozario (International Centre for Climate Change and Development),

Fellows: Alison Amoussou (United Nations Resident Coordinator Office in UAE), Iryna Ponedelnik (Independent), Ekaterina Terenteva (Russian Federation)

Credit: Panxunbin/Envato

Chapter summary

Credit: crshelare/Envato

The global environmental crises – climate change, biodiversity loss, land degradation and desertification, and pollution and waste – are damaging human well-being and hindering progress of the economic and social dimensions of all the SDGs (*well established*). Addressing these crises is a prerequisite for achieving the SDGs. Therefore, environmental goals and targets must be given higher priority to minimize the scale, speed, and costs of environmental damage.

Global environmental crises are intensifying multidimensional poverty and putting some middle-income populations at risk of falling into poverty (*well established*). These crises are threatening access to essential services and rights, such as safe water, housing, energy, food, health, education, decent work, and sustainable livelihoods for all. The degradation of ecosystem services and goods is worsening this situation, especially for vulnerable and disadvantaged groups, including displaced people, refugees, economically disadvantaged people, particularly women and children, persons with disabilities, and marginalized populations, such as Indigenous People, as well as traditional local communities {7.2.1, 7.2.3, 7.2.10, 7.2.11}.

Environmental crises are undermining energy security (*established but incomplete*). Both fossil fuels and renewable energy are threatened by climate change-related disasters and natural hazards, which damage energy infrastructure and hinder progress towards affordable and clean energy for all {7.2.7}.

Climate change and environmental degradation are undermining global food security (*well established*). Climate change impacts, such as sea level rise, extreme weather events, biodiversity loss and various forms of pollution, undermine agricultural productivity and contribute to food price inflation. Pollution also contaminates food sources. More than three-quarters of global food crops depend, at least partially, on pollination by insects and other animals, a process at risk from environmental degradation {7.2.2}.

Water security is also under threat (*well established*). Pollution is contaminating water supplies and reducing the availability of clean water for households, industry and agriculture. Climate-related droughts, floods and sea level rise are further intensifying water scarcity {7.2.6}.

Environmental crises are affecting housing security. Climate-related extreme weather events, such as severe storms, wildfires, landslides, flooding, and sea level rise are damaging homes and infrastructure {7.2.11}.

Environmental crises are undermining human health and health systems (*well established*). Environmental risks account for a quarter of the global disease burden, and pollution is estimated to cause 9 million premature deaths annually. Climate change is exacerbating heat-related health risks, non-communicable diseases, malnutrition, premature mortality, and mental health issues, as well as communicable diseases, including vector-borne, waterborne, and food-borne illnesses. People who are highly vulnerable to heat stress include, but are not limited to, the chronically ill, older adults, young children, pregnant persons, outdoor workers, persons with disabilities, and displaced and socially marginalized population groups in cities, informal settlements, and refugee camps. Air pollution caused an estimated 8.1 million deaths in 2021 and led to 93 billion days lived with illness in 2019. In addition, widespread emerging contaminants, originating from over 350,000 commonly used chemicals, are present in many water supplies and have been linked to serious environmental and human health deterioration {7.2.3, 7.2.6}.

Environmental crises are reducing basic educational capacity, especially for disadvantaged groups (*well established*). Pollution and extreme heat impair individual learning ability, while extreme weather and disasters damage infrastructure and disrupt educational systems and services, limiting access to instructional time. The effect is particularly severe on young children, especially girls, from rural areas and on Indigenous Peoples as well as local communities {7.2.4, 7.2.5, 7.2.10}.

Critical infrastructure and basic services, especially in cities, are increasingly vulnerable to environmental crises (*well established*). Climate change and associated disasters damage buildings, housing, water supply and sanitation, telecommunication, power supply, and transport networks, including railways and roads. These disruptions will increasingly affect essential urban services {7.2.6, 7.2.9, 7.2.11}.

Environmental crises are also inflicting significant damage on industry and business (*established but incomplete*). Climate-related disasters are damaging industrial facilities and disrupting supply chains, while extreme weather and pollution are endangering worker health, safety, and well-being and reducing productivity. Heat stress alone is projected to cut total working hours worldwide by 2.2 per cent and reduce global GDP by US$2.4 trillion by 2030. Biodiversity loss is diminishing the availability of raw materials and inputs for certain industries. Migration from certain areas may reduce workforce availability {7.2.8, 7.2.9}.

Jobs and decent work are also at risk (*established but incomplete*). About 1.2 billion jobs – about 40 per cent of global employment and primarily in Africa, Asia and the Pacific – depend directly on ecosystem services. Employment is further threatened by damage to infrastructure. To protect livelihoods, environmental solutions should be designed and managed to more directly support economic and social goals and targets, particularly in terms of creating jobs and promoting decent work {7.2.1, 7.2.8}.

Economic growth is increasingly undermined by the escalating costs from environmental damage caused by the cascading consequences of interconnected environmental crises (*well established*). In 2020, about half of the world's GDP, approximately US$44 trillion, was moderately or highly dependent on nature and its services. Between 2000 and 2019, losses from recorded disasters were US$2.97 trillion. The estimated annual loss of ecosystem services from 1997 to 2011 ranged from US$4.3 to US$20.2 trillion. Between 1970 and 2020, small island developing states (SIDS) experienced a cumulative GDP loss of approximately US$153 billion due to extreme weather, water hazards, and climate change. In 2019, health-related air pollution costs were about US$8.1 trillion, about 6.1 per cent of global GDP (PPP adjusted). As a result, the cost of implementing the SDGs is rising, while the available financial resources are being increasingly diverted to managing the damage from environmental crises. Indigenous Peoples' ways of organizing economies, based on the ethics of care, offer alternative models that move away from extractivism and consumerism {7.2.8, 7.2.9, 7.2.11, 7.2.17}.

Environmental crises deepen inequalities and inequities, disproportionately affecting vulnerable and marginalized groups, including Indigenous Peoples as well as local communities, and urban and rural populations with limited resources (*well established*). Many people depend on natural ecosystems and resource-based economies for their livelihoods and well-being, while others face systemic barriers to social and economic security. Structural and political challenges, including gender

discrimination, economic disparities, legal barriers, and social exclusion, shape these inequities. Affected populations include, but are not limited to, economically disadvantaged people, particularly children and women, older adults, displaced persons, persons with disabilities, LGBTQ+ individuals, women and girls in rural developing areas, and other marginalized populations, such as stateless displaced persons and Indigenous Peoples as well as local communities {7.2.5, 7.2.10}.

Environmental crises are driving increased resource use, pollution and waste (*well established*). As climate-related disasters become more frequent and intense, there is an urgent need for greater investment in disaster risk reduction and climate adaptation. Extreme weather events generate a large volume of debris due to damaged landscapes, infrastructure and buildings, while also disrupting the management and disposal of hazardous chemicals and waste {7.2.11, 7.2.12}.

Environmental crises are diminishing the availability of ecosystem services that support human well-being, affecting all ecosystems and people globally (*well established*). The decline is particularly significant for SDG 14 and 15 targets, which aim to increase benefits for SIDS and least developed countries (LDCs) through the sustainable use of forest and marine resources, conservation of mountain ecosystems, and securing access for Indigenous Peoples as well as local communities, including small-scale artisanal fishers {7.2.14, 7.2.15}.

Environmental crises can undermine nature-based solutions aimed at achieving environment-related SDGs. Some interventions targeting one environmental crisis may unintentionally worsen others (*well established*). Global warming above 1.5 degrees increases the risk of ecosystem collapse and intensifies extreme weather events, which in turn damages nature and infrastructure for both renewable and fossil-based energy. Additionally, mining and production of materials for climate mitigation technologies can cause significant environmental harm, which needs to be addressed {7.2.7; 7.2.12}.

Environmental crises are contributing to conflicts, political instability, and large-scale displacement, particularly among rural populations in LDCs, including Indigenous Peoples as well as local communities (*well established*). Resource scarcity, intensified by environmental degradation and unsustainable consumption, contributes to conflicts and violence. Natural resource exploitation has been linked to 40 per cent of intrastate conflicts since the mid-20th century. Climate change, climate-linked disasters and land degradation are directly displacing populations, with projections estimating up to 216 million people by 2050. Crises such as wars, disaster events, and pandemics amplify the social and economic damage of environmental crises, underscoring the urgency of implementing sustainable solutions rather than delaying them {7.2.16}.

Environmental crises have serious, high magnitude, long-term cascading and compounding effects, particularly for vulnerable and marginalized populations, including Indigenous Peoples as well as local communities (*well established*). The food-energy-water nexus is a key example, where the disruption of one resource's production further destabilizes the others. Many studies illustrate the complex interlinkages among the SDGs. Moreover, wars, conflicts, disasters resulting from natural hazards, economic shocks, and pandemics further exacerbate environmental crises {7.2.1, 7.2.2, 7.2.3, 7.2.4, 7.2.5, 7.2.6, 7.2.8, 7.2.10, 7.2.14, 7.2.15, 7.2.16}.

The socioeconomic repercussions of the environmental crises will affect everyone, including middle class working people and those in developed countries. While regional and national disparities will shape the severity of impacts, the adverse effects on SDG achievement will be widespread, extending beyond people in vulnerable situations, to harm people in both developing and developed countries alike.

7.1 Introduction

The Sustainable Development Goals (SDGs) are a global action plan, employing an integrated approach to transform the environment, economy, and society, with the aim of achieving sustainable development worldwide. However, numerous reports have found that the SDGs are not on track (Sachs et al. 2024; United Nations 2024).

This chapter examines the implications of the environmental crises of climate change, biodiversity loss and land degradation, and pollution and waste – explained in this report's Global Environmental Crises Chapeau – that affect human well-being through the lens of the economic and social dimensions of the SDGs, building on UNEP's *Making Peace with Nature* (UNEP 2021b). The chapter complements other state and trend chapters (Chapters 3 to 6), which discuss the repercussions of environmental crises for human systems but are not organized by SDGs.

This chapter highlights how environmental crises significantly impede progress on the economic and social aspects of the SDGs. The environment is a vital life support system, sustaining humanity on Earth (Steffen et al. 2015). Earth system boundaries, such as the climate, biosphere, water, nutrient cycles, and aerosols, define the safe and just limits within which human civilization can operate (Rockström et al. 2023). Unfortunately, unsustainable development has led to breaches of seven out of eight globally recognized boundaries, endangering human society, as detailed in Chapters 3 through 6. Therefore, tackling environmental crises is essential to achieving the SDGs and supporting human society within the Earth system boundaries.

This chapter does not address the progress of the environmental dimensions of the SDGs, the current status of SDG implementation, methods of achieving SDGs or SDG targets, or interlinkages among SDGs. It also does not offer a thorough analysis of the reasons for the slow progress on most SDGs. Instead, it primarily concentrates on the impact of the global environmental crises on socioeconomic dimensions of the SDGs.

Additionally, the chapter differs significantly from GEO-6's discussion of the SDGs, which examined achievement levels of environment-related SDG targets and developed quantitative future scenarios for selected indicators to explore their interconnections across environmental, economic, and social dimensions (United Nations Environment Programme [UNEP] 2019). The 17 SDGs cannot be simply categorized into environmental or socioeconomic goals (Elder and Olsen 2019). Most SDGs have an integrated design, with each including at least one target related to society, the economy, and the environment. Therefore, this chapter examines the economic and social aspects of all SDGs, except SDG 13 on climate, which is itself a part of the environmental crises. It does evaluate how the climate crisis affects the economic and social facets of the other 16 SDGs, treating climate as a cross-cutting issue. Generally, this chapter does not focus on solution-oriented targets, except in a few cases where environmental crises clearly influence them.

The discussion of each SDG covers the broad headline goals as well as their relevant targets, rather than the indicators. This is because the targets are broader and more multidimensional, capturing the essence of each SDG. Most targets are qualitative, while the quantitative indicators tend to focus on narrow, unidimensional, and easily measurable aspects of the targets, which may oversimplify complex issues (Elder and Olsen 2019) and hinder integrated approaches.

This assessment focuses on individual SDGs so that each goal's results are visible to its stakeholder community. Certainly, the SDGs are deeply interconnected in complex ways (Pradhan et al. 2017; Kroll et al. 2019; Independent Group of Scientists 2023). Additionally, there are many ways to group SDGs, but there is no widely accepted clustering method or other practical approach for conducting this particular assessment.

Nevertheless, this chapter synthesizes the common trends and patterns identified in the assessment, including the compounded effects of environmental crises impeding the progress of the SDGs' socioeconomic dimensions. There are various commonalities and overlaps among some SDGs regarding the impacts of environmental crises. Several poverty-related SDGs, such as SDGs 1 to 3, are also connected to SDGs on gender and inequality, SDGs 5 and 10. SDGs 7 to 12 are directly related to the economy and infrastructure, but all other SDGs also contain economic elements. There are many interlinkages among SDGs, but a substantial body of literature already exists on this subject (Pradhan et al. 2017;

Kroll et al. 2019; Independent Group of Scientists 2023). Analysing SDG interlinkages is beyond the scope of this chapter, which focuses on impact assessment.

The chapter's structure begins by assessing the socioeconomic consequences of environmental crises on each SDG. Then, it synthesizes the common trends, including the compounded effects of environmental crises, and concludes with the implications of the assessment.

7.2 Implications of the global environmental crises on the socioeconomic dimensions of individual SDGs

7.2.1 SDG 1. No Poverty

Poverty affects every socioeconomic aspect of human well-being, including access to land, food, safe water and health care. The global goal of ending extreme poverty by 2030 will not be achieved (World Bank 2022), and poverty remains disproportionately high in rural areas (Barbier and Hochard 2016). While poverty has many drivers, this section focuses on the role of environmental crises in contributing to poverty. Climate change alone could push between 35 and 122 million more people into poverty by 2030. Limiting global warming to 1.5°C could reduce the number of people exposed to climate-related risks and vulnerable to poverty by several hundred million by 2050 (UNEP 2021b).

There is a well-established link between poverty and climate change events (World Bank 2015; WHO and the Secretariat of the Convention on Biological Diversity [CBD] 2015; Fujii 2016). These events are becoming more frequent, intense, and long-lasting, and can cause flooding, droughts, wildfires, and damage to farmland infrastructure. The socioeconomic impacts are significant, worsening livelihoods, health, and poverty, as well as driving migration and displacement. Poverty often increases social vulnerability to climate hazards, so the severity and the scale of extreme weather events are not the only factors behind livelihood disruptions.

Many impoverished communities rely on biodiversity for their livelihoods (Roe, Walpole and Elliott 2010; WHO and CBD 2015; IPBES 2019). Biodiversity offers these communities an affordable and accessible form of insurance against various risks, including food insecurity threats, environmental hazards, and health issues (CBD 2010, p.7). When biodiversity resources become degraded, their situation worsens. Some rural poor depend mainly on forests for their income. However, these forests are rapidly degrading due to climate change, land conversion, mining, and the collection of wood fuel. Additionally, conserving biodiversity can serve as a pathway out of poverty (CBD 2010; Allendorf 2022). Effective conservation efforts strengthen livelihoods, especially for Indigenous Peoples as well as local communities. Global environmental crises are intensifying poverty in many forms and pose risks of some middle-income individuals slipping into poverty. The decline of ecosystem services and resources will further impair the livelihoods of both urban and rural populations, particularly affecting women and vulnerable Indigenous Peoples as well as local communities.

Land degradation and pollution are closely linked to poverty, with a well-documented relationship (Barbier and Hochard 2016; UNCCD 2019). Over recent decades, global land quality has deteriorated rapidly (UNCCD 2019). A significant number of people live on degraded lands: 1.7 billion in Asia, 621 million in Africa, and 355 million in Latin America. These lands suffer from poor soil quality, decreased water retention, disaggregated soil particles, reduced microorganism activity, and toxic salt build-up. Each of these deficiencies leads to lower crop yields and lost production (UNCCD 2022). The resulting shortfalls prompt increased expenditure on expensive fertilizers, water, and land reclamation. Access to fertile land is essential for alleviating rural poverty, but these low-yield lands cannot generate enough income for impoverished farmers, often causing them to abandon the land. This cycle results in more debt, unemployment, poverty, land degradation, and migration (Afifi 2011).

Degradation of natural resources like land and soil directly reduces farmers' income, disrupts food markets, and makes crops more vulnerable to climate change. This can hinder income-generating activities and raise the risk of poverty among vulnerable populations, creating a negative cycle that exacerbates both poverty and environmental degradation (Banerjee and Duflo 2011; Amiraslani 2021).

7.2.2 SDG 2. Zero Hunger

Progress on ending hunger has nearly stalled, posing a serious risk of disaster. In 2022, 691 to 783 million

people experienced hunger, an increase of about 122 million since 2019, using the mid-range estimate of around 735 million. Women and those living in rural areas are disproportionately affected (FAO et al. 2023). These trends are deteriorating due to various causes (FAO et al. 2023). The interconnected environmental crises – climate change, biodiversity loss and land degradation, and pollution and waste – are adversely impacting agrifood systems and the global food supply. This worsens food price inflation, food insecurity, and malnutrition (**Table 7.1**).

More frequent extreme weather events disrupt plant hydraulic transport, alter key minerals, and increase pest and pathogen occurrences, threatening crop yields and food security (Ziska and Bunce 2007; McDowell et al. 2008: Kang, Khan and Ma 2009; Goulart et al. 2023; Pickson et al. 2024). Vulnerable groups, especially Indigenous Peoples and subsistence farmers, are particularly affected by climate extremes (Dumenu and Obeng 2016; UNFCCC 2018). Severe drought in many areas reduces pasture and livestock feed, while heat stress diminishes fish productivity and growth (Islam, Kunzmann and Slater 2022). If left unaddressed, these issues will drive up food prices, increasing malnutrition and hunger, especially among marginalized communities worldwide (FAO et al. 2023; Mirzabaev et al. 2023).

Biodiversity provides essential ecosystem services like soil fertility, pollination, and pest control, which underpin agricultural productivity and support households that depend directly on natural resources for their livelihoods (Garrido-Jurado, González-Mas, and Youse-Yousef 2023; Prangel et al. 2023). The loss of biodiversity clearly diminishes the productivity and resilience of both food systems and human communities (Asafu-Adjaye 2003; Robinson, Ryan, and Newman 2012). Communities relying on food crops for nutrition become more vulnerable to crop failures, food shortages, and rising food prices. Consequently, biodiversity loss has

Table 7.1: The impact of environmental crises on food security

	Climate change	Pollution	Biodiversity loss	Land degradation
Availability and stability	Extreme weather events reduce crop yields and threaten food and aquaculture production (Godde et al. 2021; Rezaei et al. 2023)	Crop contamination, and increased parasites and diseases harm livestock and fish, making food unsafe for consumption (Deb 2018; Shaheryar et al. 2025)	Reduced soil fertility, pest control function, and destruction of aquatic habitats, decreased food production (Katumo et al. 2022)	Reduced soil nutrients, crop yields, water availability, livestock grazing land, and threatened aquatic systems all reduce food production (Hossain et al. 2020)
Accessibility	Crop and harvest losses reduce supply and lead to higher food prices (Vargas 2011)	Soil, water and air pollution reduce food access (Mateo-Sagasta et al. 2018)	Loss of income from fisheries and agriculture reduces purchasing power of the affected communities (Scheper et al. 2023)	Lower soil quality reduces crop yields, reducing food access (Hossain 2020)
Utilization and nutrition	Climate change affects nutritional content of food and its quality by decreasing dietary and food diversity (Fanzo et al. 2018)	Higher atmospheric carbon reduces protein and mineral content in most plant species (Taub, Miller and Allen 2008; Gojon et al. 2023) Mining waste contaminates soil, degrading crop quality, affecting plant and human health (Angon et al. 2024)	Limited availability of diverse and nutritious foods leads to deficiencies in essential vitamins and minerals (Heywood 2013)	Soil erosion limits crop production (Pimentel 2006; Naorem et al. 2023)
Food safety	Climate change worsens food safety hazards at various stages of the food chain (Tirado et al. 2010; Mirón et al. 2023)	Water and soil pollution, especially heavy metals, cause various human health risks (Lu et al. 2015)	Reduced biodiversity makes food production more vulnerable to pests and diseases (Lin 2011)	Soil erosion affects safe and stable crop production (Roy et al. 2006)

significant implications for hunger by increasing food shortages, instability, and malnutrition and by decreasing dietary diversity, income, and overall well-being.

Pollution involves the uncontrolled release of industrial, vehicular, and human waste into the environment, contaminating food and water sources (He et al. 2022). Polluted water bodies damage aquatic ecosystems and decrease fish populations (Liu et al. 2022). Heavy metal from electronic and mining waste dumping contaminate fish meant for human consumption (Hu et al. 2021; Qin et al. 2021), while deforestation and water scarcity from land degradation hinder crop growth (Kumeh, Bieling and Birner 2022). Communities near industrial waste sites that rely on aquatic systems for protein and nutrition face pollution-related health issues (He et al. 2022; Liu et al. 2022). Countries experiencing high hunger and food insecurity are particularly vulnerable to rising pollution, land degradation, and waste.

7.2.3 SDG 3. Good Health and Well-Being

The interconnected environmental crises and the declining health of the planet hinder progress towards achieving healthy lives and well-being for everyone (SDG 3). About 25 per cent of the global disease burden stems from environmental risks, such as climate-related non-communicable diseases (NCDs), infectious diseases, malnutrition, mental health issues (**Table 7.2**), and exposure to pollution and toxic chemicals via air, food, and water (WHO 2023).

Climate change is leading to increasing health and environmental risks, including premature mortality, heat-related illnesses, climate-sensitive NCDs, infectious diseases like zoonoses, malnutrition, and mental health threats, all exacerbated by rising temperatures (Intergovernmental Panel on Climate Change [IPCC] 2022). Rising temperatures, shifts in precipitation, flooding, heatwaves, droughts, and wildfires heighten dangers, such as heat-related health issues, food insecurity, malnutrition, vector-borne diseases like dengue, malaria, chikungunya, yellow fever, Zika, and water- and food-borne illnesses, as shown in **Table 7.2** (FAO 2020; IPCC 2022). Climate-related risks to animal and plant health are also emerging, with the increased use of antimicrobials and pesticides for managing these issues contributing to antimicrobial and pesticide resistance (FAO 2020; EFSA 2021). Vulnerable groups – including people living in poverty, children, women and girls, Indigenous Peoples, displaced persons, the impoverished, the undernourished, persons with disability, homeless individuals, and those in insecure or degraded environments – face greater risks due to limited access to resources, education, and health care, which significantly reduces their resilience (WHO 2018).

Pollution is responsible for approximately 9 million premature deaths each year, with many more deaths related to other environmental health risks. Over 90 per cent of pollution-induced fatalities occur in low- and middle-income countries (Fuller et al. 2022). In 2021, air pollution alone caused 8.1 million deaths worldwide, ranking as the second leading risk factor for death, including among children under five (Health Effects Institute 2024). Outdoor pollution from fossil fuel combustion and indoor pollution from biomass or traditional stove use contribute to around 7.5 million premature respiratory-related deaths annually, and this threat is expected to persist (UNEP 2021b). Additional health hazards stem from environmental exposure to heavy metals and industrial chemicals through air, water, food, and soil, as well as from climate change interacting with marine food webs (Alava et al. 2017). Chemicals like lead are linked to 1.8 million deaths each year globally (Fuller et al. 2022). Elevated blood lead levels are associated with reduced IQ in children, lower educational achievement, decreased economic productivity, and a global economic loss nearing US$1 trillion annually (Fuller et al. 2022). The widespread presence of emerging contaminants in many water supplies from over 350,000 chemicals poses serious health and environmental risks (Wang et al. 2020). Pollution also damages the stratospheric ozone layer, which is slowly recovering. This damage allows excessive ultraviolet radiation from the sun to reach the Earth's surface, increasing the risk of skin cancer, cataracts, and other health problems in humans (UNEP 2021b).

Natural green and blue spaces significantly contribute to physical and mental health and well-being. The decline in biodiversity and ecosystem services, along with nature's reduced ability to regulate air and water quality, limits opportunities for recreation and relaxation that support health. Biodiversity loss hampers nature's capacity to provide medicines and traditional remedies. Over 4 billion people, more than half of the global population, depend mainly on natural medicines for health care,

and about 70 per cent of cancer treatments derived from natural sources or inspired by nature (UNEP 2021).

The deterioration of land, water, oceans, and ecosystems threatens food and water security, nutrition, human health, and the many benefits that nature provides to billions of people (IPCC 2019; Mbow et al. 2019). Land degradation, droughts, and desertification contribute to desert dust storms, which can spread infectious diseases, affect cardiovascular and respiratory health, and have other long-term consequences (IPCC 2022; Vergadi et al. 2022) (**Table 7.2**). Preventing land degradation, restoring degraded areas, and avoiding deforestation can benefit billions by supporting sustainable food systems, promoting other ecosystem services, and enhancing human health and well-being now and in the future.

Table 7.2: The impacts of environmental crises on SDG 3

	Climate change	Pollution	Biodiversity loss	Land degradation
Reproductive, maternal and child health	Low birth weights, premature births Reduced access to reproductive maternal child health care	Chronic respiratory diseases in children, asthma Reproductive and neurotoxicity from persistent organic pollutants, industrial chemicals (halogenated flame-retardants, plasticizers, dioxins), and toxic metals Water contamination leads to 1.7 million deaths/year from diarrheal diseases, mostly in children under five	Reduced dietary diversity contributes to malnutrition and under-nourishment	Desertification, can lead to desert dust storms and exposure to dust particles which have long-term impacts in pregnancy, cognitive difficulties, and birth problems
Infectious diseases	Increases in vector-borne (dengue, malaria, chikungunya, yellow fever, Zika), waterborne (cholera, vibriosis), and food-borne diseases (salmonellosis)	Air pollution may exacerbate respiratory infections	Loss of biodiversity increases risk of zoonotic diseases (One Health)	Dust storms can contribute to infectious diseases such as pneumonia, tuberculosis coccidioidomycosis, COVID-19 etc.
Non-communicable disases (NCDs)	Climate-sensitive NCDs include cardiovascular disease, cancer, diabetes and chronic respiratory diseases	Air, water and soil pollution causes 9 million premature deaths/year. Millions more die yearly from other environmental health risks	Decreased agrobiodiversity and dietary diversity contribute to NCDs	Dust storms contribute to cardiovascular and respiratory chronic diseases (IPCC 2022)
Mental health	Increased PTSD, depression and anxiety linked to injuries, displacement, loss and disasters	Air pollution from climate-related wildfires worsens mental health outcomes	Positive impact from contact with nature and biodiversity (urban green and blue spaces) and negative impact from loss of natural spaces	Desertification, loss of livelihoods, food insecurity and undernutrition erode mental. health and resilience
Health care systems environmental health and water, sanitation, hygiene	Reduced access to health systems, reproductive services, family planning, vaccines, water, sanitation Increased antimicrobial resistance	Health damage from indoor and outdoor air pollution	Biodiversity loss reduces access to natural medicines, threatening Indigenous Peoples' health and wellness	Land degradation and desertification reduce access to health care and reproductive services, water, and biomass

A healthy planet, achieved by addressing climate change, air and water pollution, and land and ecosystem degradation, is essential for human health, well-being, and achieving the SDGs.

7.2.4 SDG 4. Quality Education

The environmental crises, especially climate change and pollution, undermine the general provision of education as well as equitable access to it.

Climate change affects education by damaging educational infrastructure through events, especially floods, which disrupt all kinds of educational services. For example, in 2022, severe floods and landslides damaged schools, roads and other infrastructure, causing lengthy school closures in some parts of KwaZulu-Natal, South Africa. This area experienced similar disasters in the past (Bopape et al. 2021). These disasters often significantly reduce the incomes of poor households, who frequently respond by pulling their children out of school, for example in Indonesia (Rush 2018).

Such disasters also decrease enrollments at all education levels, adversely affecting lifelong learning. Consequently, this leaves more people vulnerable because fewer individuals have enough knowledge about climate risks and adequate disaster responses (Muttarak and Lutz 2014).

Climate-related disasters disproportionately affect people in vulnerable situations such as Indigenous Peoples as well as local communities, further reducing access to education. In areas inhabited by these groups, weather forecasts are often inaccurate due to sparse distribution of meteorological stations (Reyes-García et al. 2024). This heightens their risk of displacement (UNESCO 2020) and limits their educational opportunities. Exposure to tropical cyclones was linked to an average 2.7 percentage point decline in primary school enrolment by 2010, a 14.2 per cent decrease, with girls more affected than boys (Jing et al. 2024). Over the past 20 years, approximately 410,000 children missed school because of tropical cyclones across low- and middle-income countries, resulting in a loss of over 4.1 million school years (Jing et al. 2024). UNICEF reported that in 2024 extreme climate events disrupted schooling for at least 242 million students in 85 countries (United Nations Children's Fund [UNICEF] 2023). Gender inequalities often increase women's vulnerability to disasters, especially in regions like Bangladesh where women tend to be less educated than men (Juran and Trivedi 2015). Additionally, since vulnerability to environmental crises varies depending on context and conditions (Muttarak and Lutz 2014), wealthier households can often afford online education and homeschooling if meteorological and hydrological hazards damage local schools. However, children from poor families have limited alternatives. Climate change-induced rising temperatures also hinder students' ability to learn at all ages: "Across countries, a 1°F [0.55°C] increase in average annual temperature is associated with 0.02 standard deviation lower math scores for 15-year-olds taking the 2012 Programme for International Student Assessment" (Park et al. 2020).

Pollution, including air and water contamination, also harms quality education by impairing students' ability to learn. Vulnerable populations, often living in polluted environments, are most affected. Landrigan et al. (2019) explain, "In children, early-life exposures to neurotoxic pollutants can permanently impair cognitive function thus contributing to school failure and reduced lifetime earnings." Balakrishnan and Tsaneva (2021) found that "air pollution is negatively correlated with academic performance" among children in rural India. Similarly, Mizen et al. (2020) described the academic effects as including "forgetfulness, inattentiveness and careless errors," which are critical for learning and exams. They also linked air pollution to increased school absences and found that children with lung diseases are more vulnerable. Additionally, Zhang et al. (2018) observed that the adverse effect of air pollution on cognitive performance worsens with age, limiting lifelong learning, especially in health and welfare decision-making. A study by Claudia Persico (2019) in Florida found that prenatal exposure to toxic wastes may have long-term consequences that could affect academic achievement in school, leading to grade repetition or even cognitive disabilities.

Biodiversity loss indirectly affects education by limiting opportunities to learn about various species. Access to such knowledge becomes difficult for future generations if biodiversity declines (Børresen et al. 2022). Additionally, biodiversity loss reduces access to Indigenous Knowledge and local solutions, leading to an increased dependence on solutions developed elsewhere.

Land degradation reduces ecological productivity and biodiversity (Ekka et al. 2023), which affects sustainable

education for future generations. Additional research is necessary to increase understanding of land degradation's effect on quality education.

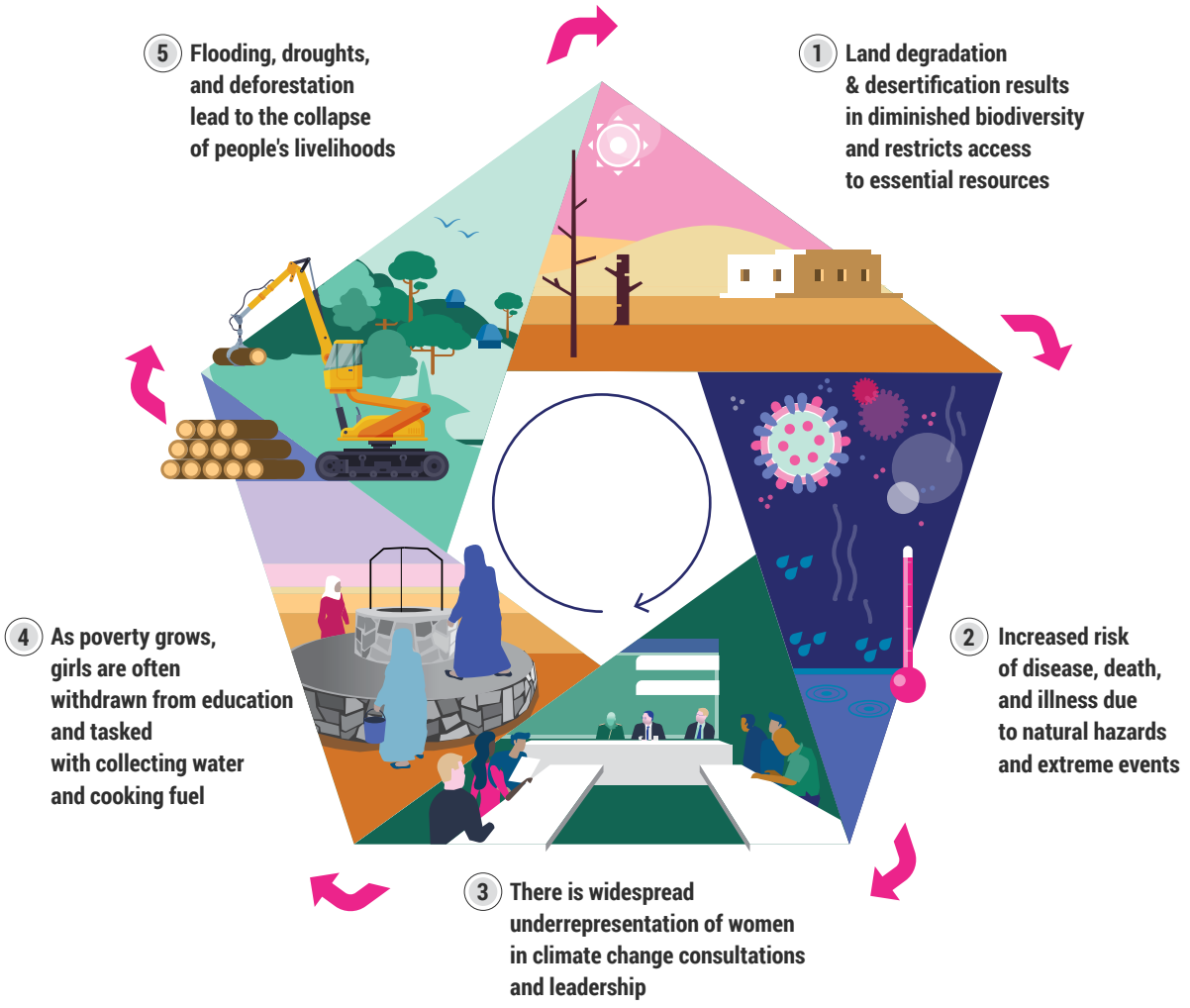
7.2.5 SDG 5. Gender Equality

Research indicates that women and girls are disproportionately affected by environmental crises (Goh 2012; Sardar and Bhaduri 2022). These unequal effects hinder progress towards gender equality.

Climate change affects women's access to and control over essential resources like land and property and puts additional pressure on tasks traditionally carried out by women, such as cooking and collection of water and fuel. These effects significantly limit their ability to cope with adverse outcomes. Women and girls are especially vulnerable to extreme weather events, facing higher risks of death, illness, and livelihood loss. Examples include climate-induced weather events increasing gender-based violence, climate-related income reductions disrupting girls' education because families pull girls out of school first, droughts and floods leading to loss of livelihoods and a rise in child marriages, biodiversity decline harming women's health and eroding traditional knowledge, and under-representation in environmental decision-making marginalizing women's concerns in developing low-carbon economies (IUCN 2021; Anderson and Fisher 2022; OECD 2023; UNDP 2023). A 2019 United Nations Development Programme (UNDP) report states that over 60 per cent of deaths linked to extreme climate events in the past two decades involved women (Escovar and Balduzzi 2024). During disasters, women and children are 14 times more likely to die than men. For example, in the 2004 Indian Ocean Tsunami, out of 230,000 fatalities, 70 per cent were women (UNDRR 2023).

Figure 7.1 highlights the gender-specific effects of climate change across five key areas: land degradation and desertification; adverse health outcomes, including mortality and morbidity; marginalization in

Figure 7.1: Gender differential impact of climate change



climate change consultation and decision-making; increasing poverty and crises related to fuel and water collection; and loss of livelihoods. The figure also illustrates how these outcomes are interconnected.

The complexity of gender inequality in climate change and environmental sustainability has also influenced academic and policy discussions related to other environmental crises. Land degradation and desertification disproportionately affect women (UNFCCC 2022), and "women are the major actors in the global efforts to reverse and reduce land degradation" (Gurung et al. 2006).

Household and ambient air pollution was responsible for an estimated 6.7 million deaths worldwide in 2019 (WHO 2024). Women face a 50 per cent higher mortality rate from indoor air pollution compared to men (Rees and Choi 2019). In India, approximately 30 per cent of ambient air pollution originates from cooking with solid biomass, leading to 1.3 million deaths annually due to household air pollution.

Women around the world serve as farmers, herders, forest gatherers, water collectors, food processors, soil conservationists, and keepers of natural and built environments. However, their progress is often hindered by restricted rights to productive resources, limiting their ability to fulfil increasing roles in conserving biodiversity and preventing land degradation (Rocheleau 1995; Kelkar and Nathan 2024; UN Women 2024).

An OECD study highlights the interconnectedness of environmental crises and gender inequality, emphasizing that empowering women and girls (SDG 5) "not only helps reduce the disproportionate exposure but can help drive positive change and enhance the impact of these agendas" (OECD 2023).

7.2.6 SDG 6. Clean Water and Sanitation

The environmental crises, especially climate change and pollution, are threatening the achievement of SDG 6 and water security.

Increasing frequency, duration, and intensity of droughts, worsened by climate change, contribute to water scarcity (SDG 6.4) and threaten the supply of safe and affordable water (SDG 6.1) (Mishra et al. 2021; Visser-Quinn et al. 2021). Additionally, increased flooding caused by climate change endangers essential drinking water and wastewater infrastructure needed for SDGs 6.1 and 6.2 (Salameh 2023), while sea level rise is causing salinization of some coastal aquifers. Climate change is stressing the reliable supply of fresh water for all uses – such as food, energy, manufacturing, and drinking water – further contributing to water scarcity (SDG 6.4).

Water pollution is a major threat to safe drinking water (SDG 6.1) (WHO 2023). Key sources include untreated sewage (SDG 6.2), inadequate sanitation, and industrial wastewater (Schwarzenbach et al. 2010). The health implications of contaminated drinking water are well-documented (Wolf et al. 2023; Li et al. 2024). In 2019 alone, an estimated 1.4 million deaths and 74 million disability-adjusted life years could have been prevented through safe water, sanitation, and hygiene (Wolf et al. 2023). Poor water, sanitation, and hygiene are also linked to 69 per cent of diarrheal disease, 14 per cent of acute respiratory infections, and 10 per cent of undernutrition (Wolf et al. 2023).

Land degradation can worsen the effects of drought, leading to water scarcity, especially in arid regions, with negative consequences for food security and rural livelihoods (Hermans and McLeman 2021). It also speeds up soil erosion, which damages some surface water sources used for drinking (Bower et al. 2009). Additionally, soil compaction decreases infiltration and the recharge of certain groundwater sources (Bower et al. 2009). Sediment run-off, pesticides, and heavy metals are carried into water supplies through agricultural intensification, deforestation, and urban expansion (Mateo-Sagasta et al. 2017), thus polluting drinking water. As desertification advances, water supplies vital for agricultural production and community needs diminish, until the land can no longer support farming, natural vegetation, or daily life (Andreeva et al. 2022) . Urbanization increases impervious surfaces, which can slow the recharge of shallow aquifers and threaten the sustainability of some water sources (Wakode et al. 2018).

Biodiversity loss affects water supply and increases water stress in some regions due to systemic disruptions caused by invasive species. Worldwide, aquatic invasive species have caused US$345 billion of economic damage since 1971, with the largest cost linked to invasive mussels in North America that have damaged water and energy infrastructure (Cuthbert et al. 2021). Invasive species can also disturb the hydrology of freshwater systems by interfering with

natural infiltration and evapotranspiration processes. For instance, invasions of *Tamarix sp.* and *eucalyptus* have led to reduced stream flow in arid climates already experiencing water stress (Catford 2017; Le Maitre et al. 2023).

There are gender disparities in water collection: In 2022, 2.2 billion people lacked safely managed drinking water. In two-thirds of households, women are mainly responsible for collecting water, which has broader socioeconomic effects (WHO and UNICEF 2023). Also, in 2022, 152 countries had over 75 per cent of their populations with improved water access on premises. However, 41 countries had less than 50 per cent coverage, including 17 countries with less than 25 per cent coverage (WHO and UNICEF 2023). The lack of water on premises disproportionately affects women and girls.

7.2.7 SDG 7. Affordable and Clean Energy

Environmental crises are increasingly disrupting energy production and distribution, hindering SDG 7 and broader energy security, affecting both fossil fuel production and the transition to net-zero energy (**Table 7.3**). These crises are particularly worsening energy poverty and limiting energy access in low-income countries (Biswas et al. 2022, Khoday 2021).

Climate change negatively affects both fossil and renewable energy sources. Recent studies show that a 1°C increase above the optimal panel temperature of 25°C can cause about a 0.5 per cent decrease in photovoltaic or solar energy efficiency (Ebhota and Tabakov 2023; Saxena et al. 2024; Bamisile et al. 2025). Additionally, climate-induced droughts can disrupt electricity generation from hydroelectric, nuclear, and thermal power plants that depend heavily on water for steam production and cooling (In et al. 2022; Shuai et al. 2024). This leads to greater reliance on fossil fuels and portable generators, which in turn raises greenhouse gas emissions and air pollution. Gernaat et al. (2021) noted that under a high emissions scenario, global hydropower potential could decline by up to 10 per cent by 2100, with regional differences, and decrease further by 2050. The interconnected food-energy-water nexus worsens these challenges. For example, in countries like India and China, new coal-fired power plants compete with agriculture for water resources (Alkon et al. 2019; Singh and Tayal 2021). Simultaneous heat waves and droughts boost electricity demand for cooling, straining power grids, particularly in less developed regions (Leichenko and Silva 2014; Kapeller et al. 2024).

The economic costs from supply shocks and health impacts are about 2.5 times higher than the direct costs of energy production (Qiu et al. 2023). Consequently, electricity prices increase, disproportionately affecting marginalized and vulnerable groups by reducing access to affordable energy and elevating energy poverty risks (Byrne and Portanger 2016).

Biodiversity loss has mostly indirect effects on energy access by reducing plant species essential for biomass production. While this is a global issue, it is more pronounced in tropical regions (CBD 2020). Additionally, yields of energy crops are likely to decline as ecosystems degrade and natural flood defences weaken due to biodiversity loss. Under the worst climate change scenarios, crop yields – including those of energy crops – could decrease by up to 23 per cent (Izumi et al. 2020; Wing et al. 2021; Minoli et al. 2022). Biodiversity loss also indirectly affects pipeline stability through changes in vegetation that compromise land and soil integrity (US Department of Transportation 2022). This results in greater operational monitoring requirements for pipeline assets.

Pollution damages both grid and non-grid energy sources. For instance, acid rain contributes to solar panel corrosion, while airborne particulate matter reduces their productivity. In urban and industrial regions of the United States of America and Türkiye, PM_{10} has lowered the average annual solar transmittance – also known as "PM dimming" – by about 10 per cent, and up to 4 per cent in parts of East, Central, and South Asia, the Arabian peninsula, and Western Siberia (Özdemir 2019; Amini et al. 2024; Oh 2025), thus decreasing solar power output.

Pollution also indirectly damages wind farms. Acid rain corrodes turbine components, erodes metal surfaces and damages protective coatings, leading to reduced efficiency, higher maintenance costs, and shorter equipment lifespans. Consequently, air pollution reduces overall energy production efficiency. Achieving up to a 50 per cent reduction in yearly carbon emissions could boost power generation by

Table 7.3: The impacts of environmental crises on various energy sources

Energy source	Climate change	Air pollution	Biodiversity loss	Land degradation
Hydropower	Droughts reduce water availability (Shuai et al. 2024)		Vegetation loss reduces river flows, increasing soil erosion, impacting turbines (Obahoundje and Diedhiou 2022)	Erosion, water scarcity, and landslides impact infrastructure (Wasti, et al. 2022)
Nuclear	Droughts reduce cooling water availability (Gernaat et al. (2021)	Particulates, acid rain risk ineffective air filtration, corrosion, poor cooling		
Wind farms	Sea level rise, heat waves, and cyclones cause unpredictable wind patterns, affecting offshore wind farm infrastructure and power generation (Rapella et al. 2024; Gonçalves et al. 2024)	Corrosion from acid rain affects wind turbine machinery		Land degradation reduces land availability for onshore wind farm sites (Dhar et al. 2020; Tercan 2021)
Biomass and biofuels	Droughts reduce water availability for energy crops	Poor soil health reduces energy crop yields (Izumi et al. 2020; Wing et al. 2021; Minoli et al. 2022)	Deforestation disrupts ecosystems (CBD 2020)	
Solar	Extreme weather, hurricanes, hailstorms damage panels	Reduced solar intensity due to smog particulates (Özdemir 2019; Amini 2024; Oh 2025)		Reduced suitable land for solar farms (Dhar et al. 2020; Tercan 2021)
Oil pipelines	Structural damage from melting permafrost (Li et al. 2021; Wang et al. 2023; Zhang et al. 2024)	Acid rain corrodes machinery and components, and increases risks to worker health	Degradation of land and soil supporting pipelines (US Department of Transportation 2022)	Erosion and landslides damage pipelines
Power grids	Heat waves cause power spikes which stress power grids (Leichenko and Silva 2014; Kapeller et al. 2024)			Land degradation affects land availability for power grid infrastructure (Dhar et al. 2020; Tercan 2021)
Refineries	Sea level rise, storms and extreme weather disrupts operations and risks infrastructure damage, especially in coastal areas	Acid rain corrodes machinery, components and poses worker health risks	Soil erosion and habitat destruction increases landslides and flooding risks	Erosion and landslides damage infrastructure

approximately 10.3 terawatt hours/year in China and 2.5 terawatt hours/year in India, valued at roughly US$880 million and US$200 million annually.

Land degradation diminishes the supply and quality of biomass energy sources like firewood, which are commonly used in low-income countries, thereby worsening energy poverty. It also decreases the amount of suitable land available for solar and wind farms (Dhar et al. 2020; Tercan 2021). Land degradation severely disrupts the soil's structural integrity and water retention capacity, both of which are essential for supporting the infrastructure of renewable energy installations.

Environmental crises are increasingly disrupting energy production, distribution, and security, affecting both fossil fuels and renewables. These issues worsen

energy poverty and access, especially in low-income countries. Rising temperatures reduce solar panel efficiency, while water shortages impair hydroelectric, thermal, and nuclear plants. Droughts and heatwaves increase electricity demand, overloading power grids and prompting a shift back to fossil fuels, which exacerbates greenhouse gas emissions and air pollution. Melting Arctic permafrost and ice threaten oil and gas pipelines, increasing spill risks. Biodiversity loss reduces the yields of energy crops. Air pollution decreases the efficiency and lifespan of solar panels and wind turbines. Urgent actions are needed to mitigate these impacts and ensure equitable, clean, and affordable energy worldwide.

7.2.8 SDG 8. Decent Work and Economic Growth

Environmental crises are undermining economic development and employment (UNEP 2021b). While growth-focused economic systems significantly contribute to these crises, they are now also being weakened by them (UNEP 2019).

Climate change is causing significant economic harm, which is expected to grow, reducing "average global incomes by approximately 23 per cent by 2100" (Burke et al. 2015). Countries most affected will be those least responsible and with the fewest resources for adaptation.

Climate change impacts on jobs and work productivity are already being felt and are forecasted to worsen (ILO 2018a). Heat stress is expected to cut total working hours worldwide by 2.2 per cent and reduce global GDP by US$ 2.4 trillion by 2030 (ILO 2019), with low- and middle-income countries suffering the most (ILO 2019). Heat stress is especially challenging for outdoor workers such as in construction, "1 billion agricultural workers and 66 million textile workers, many working inside factories and workshops without air conditioning", and workers engaged in "refuse collection, emergency repair work, transport, tourism, and sport" (ILO 2019). Heat stress is more common in countries facing "decent work deficits", and excessive heat levels will worsen inequalities among nations and social groups (ILO 2019). Each year, on average, natural disasters caused or worsened by humans lead to the loss of 23 million working-life years, or about 0.8 per cent of a year's work (ILO 2018b).

Over the past 20 years, climate-related extreme weather has caused annual costs of US$143 billion (Newman and Noy 2023). The benefits of early action exceed the costs of inaction (Stern 2007; Heal 2009). Prevention costs are much lower than cleanup costs, as assets become stranded, leading to irreversible damage that adversely affects human health, economies, and productivity.

Climate change also damages critical infrastructure. The costs of the infrastructure damage along with required maintenance and repair costs exceed current levels by multiple times (IPCC 2022). These consequences disrupt lives, livelihoods, and well-being for a growing number of people, significantly undermining economic growth and development (IPCC 2022).

Pollution's economic costs are very high, far exceeding the costs of pollution reduction measures, in addition to harming health. Air pollution resulted in an estimated 6.4 million deaths and 93 billion days with illness in 2019 (World Bank 2021). The health-related costs reached approximately US$8.1 trillion in 2019, accounting for 6.1 per cent of global GDP (PPP adjusted) (World Bank Group 2022). For low- and middle-income countries, the cost was 8.9 per cent of GDP, while it was 3.0 per cent for high-income countries (World Bank Group 2022). The global cost of air pollution from fossil fuels is estimated at US$8 billion daily, or 3.3 per cent of global GDP (Farrow et al. 2020).

Land degradation also results in economic costs by decreasing land productivity, which affects food security, agricultural output, and overall economic development, particularly for vulnerable populations. The extent of land degradation has expanded, with at least 100 million hectares of healthy, productive land degraded annually between 2015 and 2019, directly affecting 1.3 billion people. This degradation has caused significant economic harm, and climate change is expected to further worsen these conditions (IPCC 2019).

Losses in biodiversity and ecosystems also lead to significant economic losses. Between 1997 and 2011, land-use changes caused an estimated decline of US$4.3 to 20.2 trillion annually in ecosystem services, depending on the valuation method (Costanza et al. 2014). Environmental degradation contributes to pollinator declines, putting global crop yields at risk

(UNEP 2021b), and causes a 3-5 per cent annual decline in the production of fruits, vegetables, and nuts (Smith et al. 2022). Climate-related extreme weather events further threaten ecosystem services (ILO 2018a). About 1.2 billion jobs – primarily in Africa, Asia, and the Pacific, where 80 per cent of the world's Indigenous Peoples as well as local communities live, depend directly on ecosystem services, representing roughly 40 per cent of global employment (ILO 2018b). However, all humans, in some way, rely on these services.

SDG 8.4 aims to decouple economic growth from environmental degradation, but progress remains limited. Research suggests that the prospect of achieving necessary absolute or relative decoupling is unlikely without significant reductions in material and energy consumption by high-consumption countries and social groups (Ward et al. 2016; Hickel and Kallis 2020; et al.Vaden et al. 2020; Parrique et al. 2019), while still maintaining human well-being (Jackson 2016; Lorek and Fuchs 2013). Without this action, there is a high risk that the economic growth will increasingly undermine its own foundation.

Alternative approaches to organizing economies are possible which can promote prosperity without relying on continuous economic growth while reducing environmental impacts (Raworth 2012; Jackson 2016; Hickel et al. 2022). Many Indigenous Peoples consider themselves prosperous without depending on economic growth (Kelly and Woods 2021). They effectively care for their living territories (Prosper et al. 2011; UNEP 2019; Hill et al. 2022) and resist resource extraction (Etchart 2017). Numerous Indigenous and decolonization movements critique the concept of perpetual economic growth, considering their challenges to be rooted in global economic systems (IPBES 2022), colonial modernities (Quijano 2000; Kimerling 2012; Arora and Stirling 2021), and green colonialism in conservation. Indigenous Peoples can develop new transformational pathways that transcend the framework of sustainable development centred on economic growth (Burke et al. 2023). Their ontologies and values can inspire global action (Bryer 2023), fostering well-being in harmony with nature (UNEP 2024). Current economic models are based on individualism and consumerism. However, there are alternative, sustainable economic models that emphasize the ethics of care as a way to build economies based on social justice, environmental sustainability, and collective well-being (IPBES 2022). The IPBES Transformative Change Assessment Report highlights systemic reforms in global economies, transforming governance, and shifting values to emphasize nature-connectedness as a crucial strategy (IPBES 2024).

7.2.9 SDG 9. Infrastructure, Industry and Innovation

Environmental crises are impacting industry and infrastructure and disrupting supply chains (World Economic Forum 2020). These sectors are vital for economic growth, employment, and poverty alleviation, as they rely heavily on natural resources and ecosystem services. In 2020, approximately half of global GDP – around US$44 trillion – was moderately or highly dependent on nature, and the top sectors were construction at US$4 trillion, agriculture at US$2.5 trillion, and food and beverages at US$1.4 trillion.

7.2.9.1 Impact on infrastructure

Extreme weather events linked to climate change, such as floods and droughts, are damaging infrastructure and production facilities, resulting in an estimated US$700 billion in related losses in 2022 (Coalition for Disaster Resilient Infrastructure and UNDP 2023). In low- and middle-income countries, these events result in approximately US$18 billion in annual direct damage to power generation and transportation infrastructure (Hallegatte 2019). For instance, a sea level rise of just 0.5 metres could interrupt electricity production at around 6,700 coastal thermoelectric power plants (C40 Cities 2018). **Figures 7.2** and **7.3** illustrate the effects of climate change on various infrastructure sectors.

Increased air pollution damages infrastructure, including the erosion of building materials and the deterioration of existing structures. Acid rain, a consequence of higher air pollution levels, is especially damaging to older infrastructure (Environment and Climate Change Canada 2018).

Biodiversity loss can lead to shortages and price fluctuations of raw materials needed for construction, infrastructure maintenance, and other industries. Biodiversity losses and changes can also disrupt supply chains (Principals for Responsible Investment

Figure 7.2: Climate impacts on the infrastructure sectors

	Sea level rise				Rainfall						Temperature						Other				
Infrastructure Sector	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Rail transport	X			X	X	X	X	X		X	X	X	X	X		X	X	X			X
Road transport	X			X	X	X		X		X	X	X	X	X		X		X		X	X
Inland waterway transport	X	X			X	X	X			X	X	X	X	X		X					
Ports and marine transport	X	X		X		X					X	X	X							X	X
Potable water	X		X	X	X	X	X	X	X		X	X	X	X	X	X					X
Waste water sanitation	X	X	X		X	X	X		X		X	X	X	X	X						
Flood and coastal erosion management	X	X		X	X	X				X	X			X	X						X
Information and communication technology	X				X	X	X	X			X	X	X				X	X			X
Solid waste	X			X	X	X	X		X	X	X		X		X						X
Nuclear, coal, oil, and gas energy	X			X	X	X	X			X	X	X	X								X
Renewable energy generation	X				X	X	X	X					X						X		X
Power systems, transmission and distribution	X				X	X					X		X				X				X
Energy demand	X				X	X	X				X	X				X			X		

Key

1 Damage or disruption from coastal flooding
2 Tidelocking
3 Saline intrusion
4 Coastal erosion
5 Damage or disruption from river flooding
6 Damage or disruption from fluvial flooding
7 Droughts and low precipitation
8 Altered capability or efficiency
9 Biological processes and/or disease
10 Stability of earthworks
11 Severe heat
12 Severe cold, snow, and ice
13 Altered capacity or efficiency
14 Subsidence and/or desiccation
15 Biological processes and/or disease
16 Demand for service
17 Lightning strikes
18 Humidity
19 Solar radiation
20 Fog
21 Storm and wind damage

Source: UNEP (2021a)

2023). Land degradation and soil erosion can change land topography, degrading roads, utility networks, and other infrastructure.

7.2.9.2 Impact on industries

Extreme weather events disrupt supply chains by reducing the availability of resources, raw materials, and labour, leading to significant production disruptions and potential relocations due to the amplification of existing socioeconomic inequalities among vulnerable worker communities, especially in natural resource-intensive industries such as fisheries and agriculture (Tchonkouang, Onyeaka and Nkoutchou 2024).

Water pollution poses a major threat to industrial production. Many industries, ranging from the tannery and fashion sectors to semiconductors, require large amounts of clean water for their operations. The food industry is one of the highest water-consuming sectors, using about two quadrillion gallons annually (Balsam 2020), followed by the textile industry, which requires approximately 79 trillion litres of clean water as of 2020 (Milton 2023). Excessive pesticide use also contaminates water supplies, disrupting industrial processes.

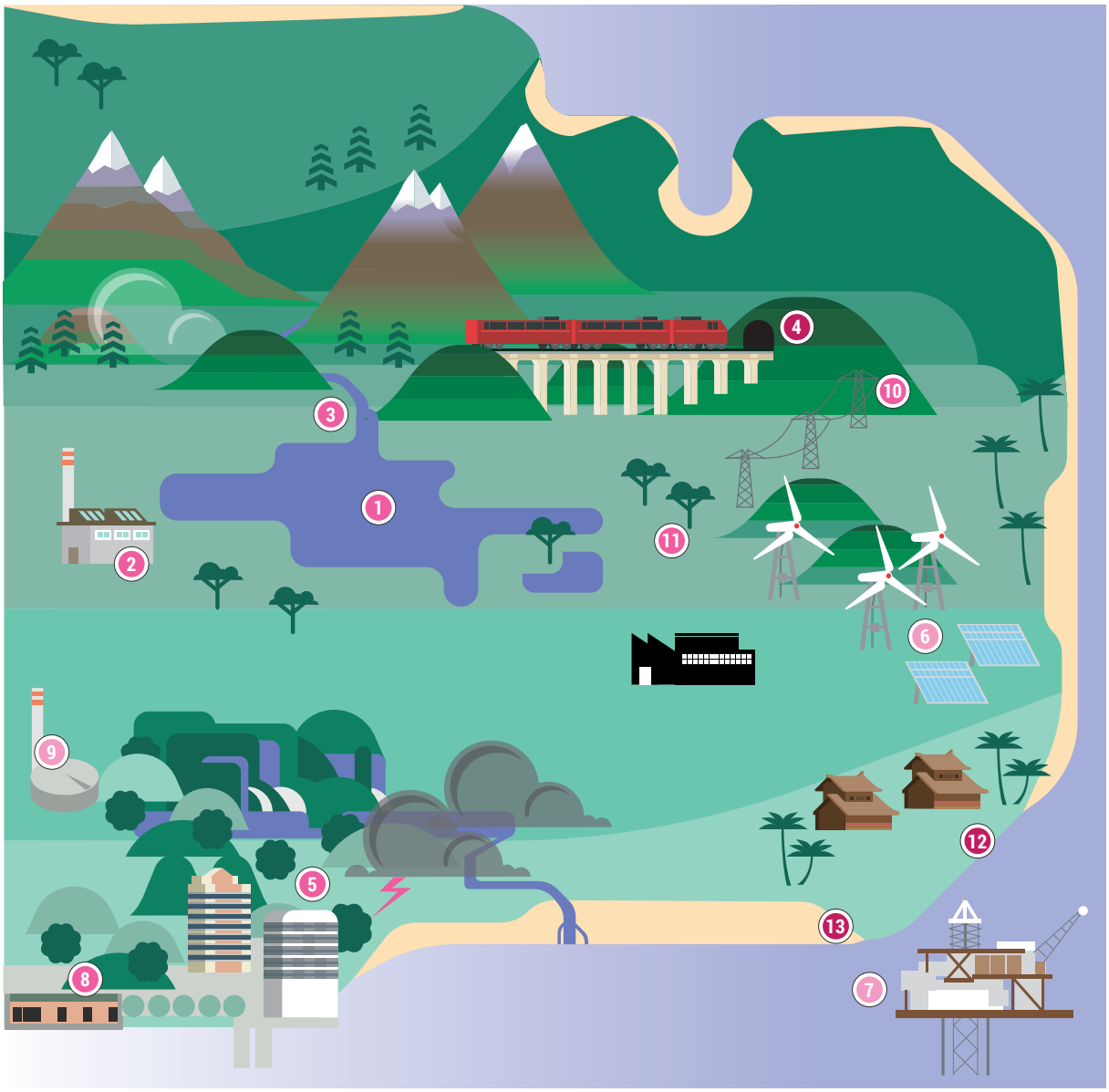
Tropospheric ozone results in annual losses of about 110 million tons of major staple crops, representing roughly 4 per cent of global crop production (CCAC, 2024).

7.2.9.3 Impact on small-scale enterprises

Many small-scale enterprises are particularly vulnerable to the impacts of climate change because

Figure 7.3: Examples of climate change impacts on infrastructure

High confidence Medium confidence Low confidence



1. Disruption of public water supply due to lower summer rainfall
2. Increased wind damage to above ground infrastructure
3. Increased frequency of river and surface water flooding
4. Increased delays and safety risks due to rail track damage during heatwaves
5. Increased ICT faults due to lightning strikes
6. Changes in yield from renewable 11 energy sources (onshore and offshore)
7. Disruption to offshore operations including energy extraction/ generation
8. Increased subsidence disrupting subterranean infrastructure
9. Reduced efficiency of waste treatment processes
10. Reduced power line capacity
11. Changes to vegetation and to performance of natural or 'green infrastructure'
12. Increased frequency of coastal flooding due to rising sea levels
13. Loss of beaches that provide natural protection to low-lying coastal areas

Source: UNEP (2021a)

of limited production capacity and narrow profit margins. They have very limited financial resources to relocate or rebuild after climate-induced disasters. About 30 per cent of small businesses are already affected by climate-related disasters, suffering from facility damage, loss of industrial symbiosis, disrupted supply chains, and workflow interruptions (Deloitte 2021, WTO 2022). Small-scale impacts of climate change on SMEs can have devastating consequences due to their limited production capacity. For instance, many smallholder farms are only marginally productive so even minor climate-related crop damage can lead to immediate and severe production and income losses (Lario 2022).

7.2.9.4 Impact on the industry retrofitting

Environmental crises impede sustainable industrial retrofitting (SDG 9.3) in ways similar to broader industry and infrastructure impacts. These include structural damage, supply chain disruptions, shortages of resources and labour, heightened occupational hazards for workers, and the need for relocation. Overall, such crises adversely affect many industries and their infrastructure (**Table 7.4**), as well as supply chains. The resulting economic costs decrease GDP, lead to job losses, and hinder economic development, ultimately undermining human well-being.

7.2.10 SDG 10. Reduced Inequalities

Interconnected global environmental crises disproportionately impact marginalized groups, obstructing progress towards SDG 10 (**Figure 7.4**) (Field and Barros 2014; WHO 2016; UNDP 2018; UNEP 2019; CBD 2020; Tessum et al. 2021; UNCCD 2022; Wagner et al. 2023).

Climate change disproportionately impacts marginalized groups, especially those residing in low-income areas, small island developing states, arable farmers, pastoralists, and Indigenous Peoples (IPCC 2022). These groups endure the harshest effects of extreme weather events, rising sea levels, and resource shortages, particularly those with limited adaptive capacities who live in informal urban settlements. Climate-related events, such as droughts, floods, and storms, worsen existing inequalities, and historical injustices amplify these vulnerabilities (IPCC 2018; CBD 2020; Marí Dell'Olmo et al. 2022).

Pollution disproportionately affects low-income and marginalized communities that do not generate it, especially those near hazardous sites like industrial zones, where dumpsites and landfills are often located close to their homes. These communities face higher rates of respiratory and other health issues, such as heart disease, due to greater exposure to air pollution. Other forms of pollution such as water pollution, soil contamination, and chemical exposure also worsen health risks. For example, contaminated water and hazardous waste contribute to long-term health problems and deepen socioeconomic disparities, widening inequality (WHO 2016; Mianabadi et al. 2022, 2023). Indoor air pollution from energy use also disproportionately affects marginalized groups (WHO 2016). Tackling these pollution-related inequalities is crucial for SDG 10 to promote health equity and ensure marginalized communities have equal access to clean air, water, and a healthy environment.

Biodiversity loss greatly affects vulnerable populations, including marginalized groups and Indigenous Peoples, who depend on natural resources for their livelihoods, cultural traditions, and overall well-being (Nkuba et al. 2020; Hoffmann 2022; Pirali Zefrehei et al. 2022a, 2022b). Biodiversity loss worsens food insecurity, erodes traditional knowledge, and can lead to displacement of these groups (IPBES 2019; Amini et al. 2023). Additionally, insufficient recognition of land rights makes Indigenous communities especially susceptible to dispossession, threatening their livelihoods, cultural identity, and increasing gender inequalities (Quiroga Eróstegui 2022; Bohman 2024). The effects of biodiversity loss are disproportionately felt by those who depend heavily on ecosystem services, such as low-income rural communities, making them particularly vulnerable to these changes (Davies et al. 2018).

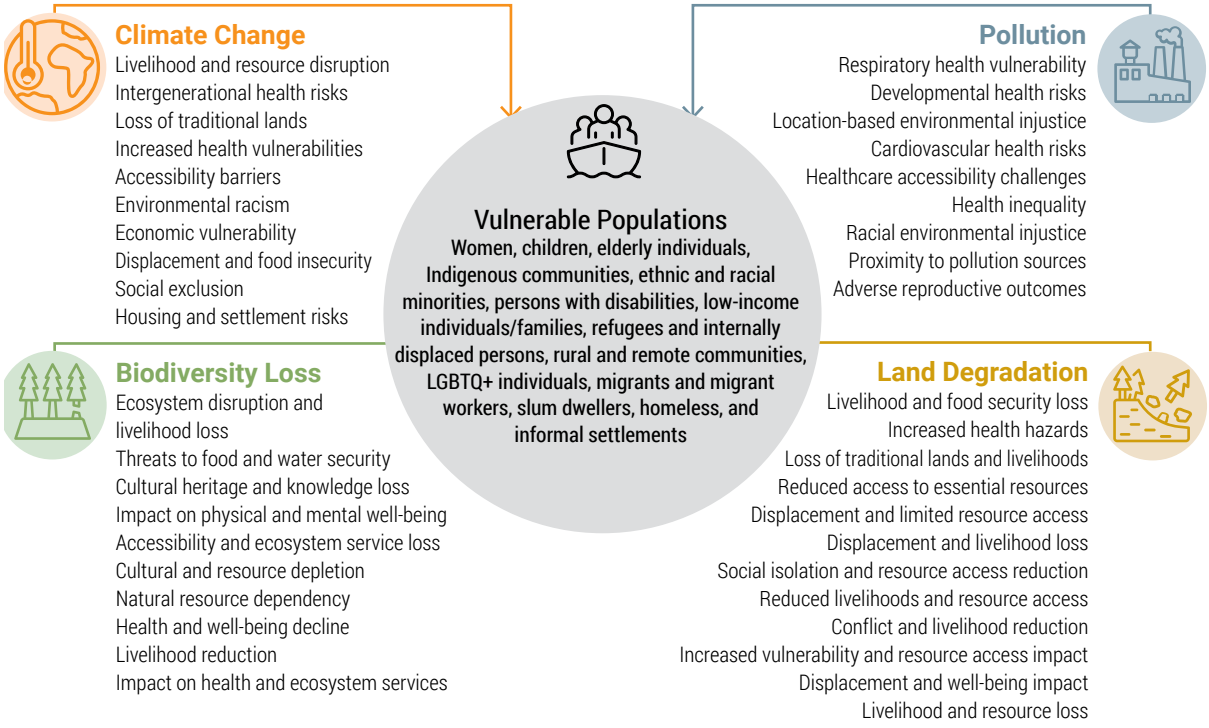
Land degradation disproportionately affects vulnerable populations, worsening inequality by disrupting their livelihoods. The reduction of arable land and limited resource access increase food insecurity and economic hardship for marginalized and low-income groups that depend heavily on natural resources (UNCCD 2022).

Environmental racism intensifies existing inequalities by exposing disadvantaged groups, particularly people of colour and low-income groups, to higher ecological risks. This worsens

Table 7.4: Impacts of global environmental crises on infrastructure and industries

SDG9 Impacts			9.1 Infrastructure					9.2 Industries						9.3 Small scale enterprises					9.4 Industrial retrofitting	
			Damage to structures and production facilities	Accelerated ageing of structures	Disruption in value chains including transportation	Changes in energy demand	Reduced raw material availability	Disruption in value chains including transportation	Reduced raw material availability	Need for locational changes	Reduced labor availability	Damage to structures and production facilities	Reduced production efficiency	Damage to structures and production facilities	Reduced labor availability	Increased occupational hazards	Reduced raw material availability	Disruption in value chains including transportation	Reduced raw material availability	Changes in infrastructure demand
Climate impacts	Sea level rise	Damage and destruction from coastal flooding	x	x	x		x	x	x	x	x	x		x	x	x	x	x	x	
		Tidelocking					x		x								x		x	
		Saline intrusion	x	x	x		x	x	x	x		x		x			x	x	x	
		Coastal erosion					x		x	x							x		x	
	Rainfall	Damage and destruction from pluvial and river flooding	x	x	x		x	x	x	x	x	x		x	x		x	x	x	
		Droughts and low percipitation					x		x	x	x		x		x		x		x	x
	Temperature	Severe heat	x	x		x	x		x	x	x	x	x	x	x	x	x		x	x
		Severe cold, snow and ice	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
		Subsidence and/or desiccation	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x
	Other	Lightning strikes	x	x	x		x	x	x			x	x	x			x	x	x	
		Humidity	x	x			x		x			x	x	x			x		x	
		Solar radiation		x	x	x	x	x	x	x	x		x		x	x	x	x	x	x
		Fog			x		x	x	x				x				x	x	x	
		Storm and wind damage	x	x	x		x	x	x	x	x	x	x	x	x		x	x	x	
Impact of pollution		Air pollution	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x
		Water pollution					x		x	x	x		x		x	x	x		x	x
		Soil pollution	x	x			x		x	x		x		x		x	x		x	x
Biodiversity loss		Biodiversity loss					x		x	x			x				x		x	
		Changes in biological processes					x		x	x			x				x		x	
		Diseases					x		x	x	x		x		x	x	x		x	
Land degradation		Changes in water availability					x		x	x	x		x		x	x	x		x	x
		Changes in topography and stability of earthworks	x	x	x		x	x	x	Xs		x	x	x		x	x	x	x	x

Figure 7.4: Impact of global environmental crises on vulnerable populations (SDG 10)



Sample Data:
- Double victimization
- Suffering more than 80% of illnesses, injuries, and deaths attributable to climate change
- 80% of the world's remaining biodiversity resides in Indigenous homelands
- A 1°C temperature increase can impact elderly health and mortality
- Disability increases disaster mortality 4 times
- 56% and 63% excess $PM_{2.5}$ exposure in Black and Hispanic minorities
- 80% of urban greenhouse gas emissions linked to high climate exposure in the poor
- 15.4 million refugees and 43.7 million displaced people in search of solutions amid environmental crises
- 15% higher suicide risk in rural Australian males during drought
- LGBTQ+ individuals exhibit stronger environmental preferences
- 10-30 million people annually
- Massive transformations: environmental impact on Majuli Island, India - A reduction from 1,255 sq km to 421 sq km

Sources: McMichael et al. (2004); McAdam (2012); Bunker et al. (2016); Chappell (2018); UNHCR (2018); Izutsu et al. (2019); Tessum et al. (2019); Hantscher & Hantscher (2019); Kang et al. (2019); Kolahi & Payeste (2020); Kaczan and Orgill-Meyer (2020); Moradi & Kolahi (2020); Balvin & Christie (2020); Desai & Mandal (2021); Hunter & Simon (2021); Nyahunda et al. (2021); Walker et al. (2021); Bjork-James et al. (2022); IPCC (2022); Wang et al. (2022); Stein & Stein (2022); Berberian et al. (2022); Oreffice & Sansone (2022); Arora (2022); Klaproth (2023); Sejil (2023); Baruah (2023); Joseph & Doon (2023)

disparities in health, employment, and overall well-being (Mohai and Saha 2015; Gutterman 2022; Khine and Langkulsen 2023).

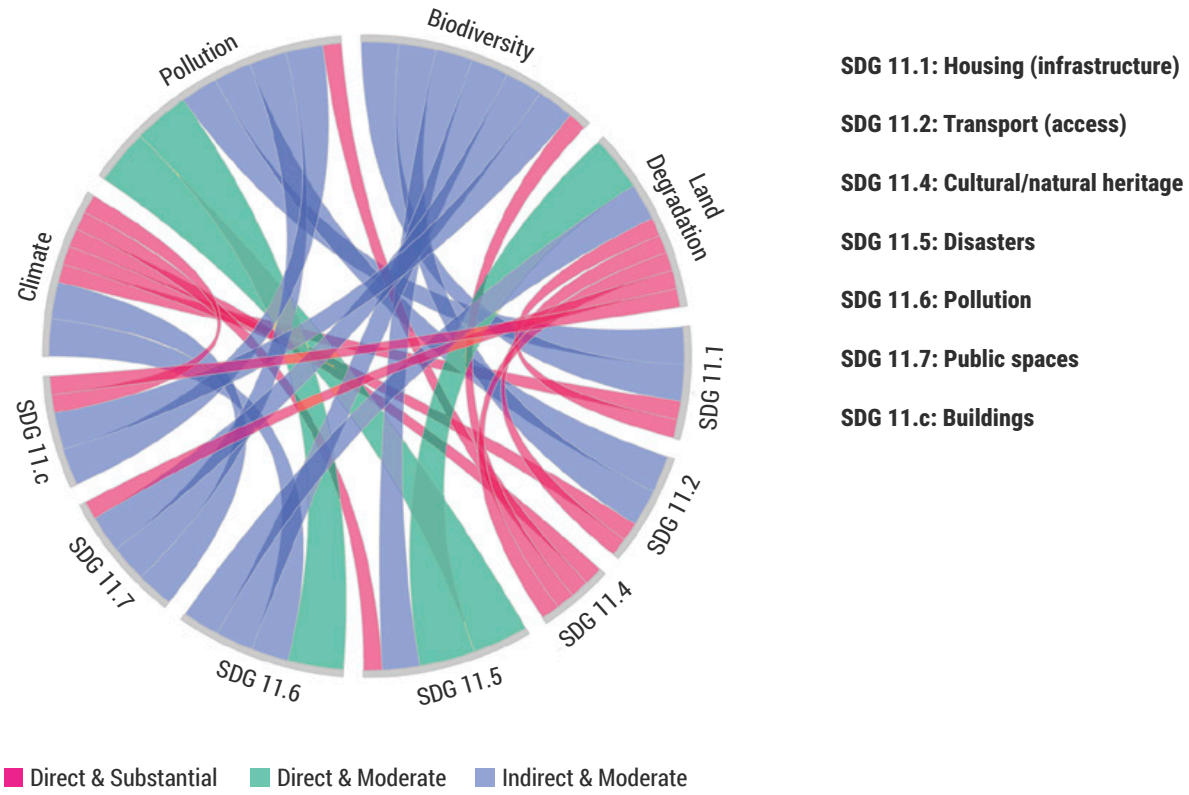
Addressing global environmental crises is crucial for reducing inequality and advancing justice. Immediate, comprehensive measures are needed to ensure that marginalized communities do not bear a disproportionate burden of environmental damage (UNEP 2019).

7.2.11 SDG 11. Sustainable Cities and Communities

Overall, environmental crises threaten both current and future progress towards SDG 11 (**Figure 7.5**). As these crises worsen, the existing progress on SDG 11 could potentially be reversed.

Climate change will hinder SDG targets related to housing, transport, heritage, and buildings due to increased flooding, drought, urban heat island effects, and sea level rise (Elmqvist and Andersson et al. 2019; Lin and Cao et al. 2021; Ozturk and Bozzolan et al. 2022; Lin and Melbourne-Thomas et al. 2023; Zhang and Cao et al. 2023). Additionally, heritage sites and buildings will suffer damage from extreme weather and air pollutants, such as sulfur dioxide and ozone (Xiao and Ning et al. 2022). Biodiversity loss will harm the ecosystem services of heritage and reduce their appeal to humans (Cave 2022). The proportion of the world's urban population breathing polluted air increased from 90 per cent in 2016 to 99 per cent in 2021, based on WHO air quality guidelines (UN 2019; UN 2022). Land degradation will seriously damage sociocultural values, slow economic development, threaten food and

Figure 7.5: Overview of environmental crises' impact on SDG 11 targets



water security, increase communities' vulnerability to natural hazards, and could potentially compromise geopolitical stability and security (Salehi et al. 2017). Some impacts, such as the effect of climate change on the urban environmental microbiome and its influence on SDG 11, require additional assessment (Zhu and Penuelas 2020).

The environmental crises impact SDG 11 differently across and within countries, with cities in developing countries and vulnerable urban populations bearing the heaviest burden. Coastal and island cities are particularly vulnerable to climate change (Xiao and Ning et al. 2022; Lin and Melbourne-Thomas et al. 2023). Approximately 1 billion people live in urban slums, mainly in low-income developing countries, which are some of the most environmentally sensitive and at-risk areas (UN 2022). Significant global disparities in greenspace exposure and inequality exist; for example, Asian cities have the lowest human exposure to greenspace at 13.49 per cent, which is much less than North American cities' 53.45 per cent, European cities' 39.25 per cent, and Australian and Oceanian cities' 42.51 per cent (Chen and Wu et al. 2022). Additionally, access to urban facilities varies widely among different groups, often disadvantaging large, vulnerable populations (Dadashpoor and Rostami et al. 2016).

Biodiversity provides essential ecosystem services for urban living environments, particularly for microorganisms. However, the diversity and abundance of microorganisms in affluent urban areas have noticeably declined (Alenius and Pakarinen et al. 2009). Global biodiversity loss may contribute to the development of allergic and autoimmune diseases because pollution reduces urban microbial diversity, which, according to the hygiene hypothesis, helps protect human immune systems (Zhu and Penuelas 2020; von Hertzen et al. 2011).

Regional natural ecosystems are vital for maintaining cities' resilience against environmental crises (Wendling and Garcia et al. 2021). For instance, nutrient cycling of food between urban areas and their surroundings directly influences urban sustainability (Lin and Gibson et al. 2014). The loss of natural landscapes within cities and the increase of surfaces, such as roads and rooftops, which absorb and emit heat more than natural surfaces, lead to heat islands and cause economic and health issues. Urban forests and trees are very important in reducing heat islands,

enhancing air and water quality, and supporting biodiversity (Grote and Samson et al. 2016; Manoli and Fatichi et al. 2019; Bux and Anderson et al. 2021; Cuthbert and Rau et al. 2022). Nature-based solutions should be emphasized in response strategies to the environmental crises.

7.2.12 SDG 12 Responsible Consumption and Production

Environmental crises hinder efforts to promote sustainable consumption and production, undermining the sustainable management and efficient use of natural resources.

Climate change threatens progress on the targets for sustainable waste management (12.4, 12.5), reduction of food waste and loss (12.3), resource efficiency (12.2), and sustainable practices (12.1, 12.6, 12.8, 12.a, 12.b, 12.c). It speeds up the release, redistribution, and remobilization of legacy pollutants and industrial contaminants, weakens current control measures, and challenges the enforcement of multilateral environmental agreements. Additionally, the climate crisis influences the longevity and spatial spread of volatile persistent organic pollutants (POPs), halogenated organic chemicals, and heavy metals (Nadal et al. 2015; Wagner et al. 2019 Zhang et al. 2021; Chai et al. 2022; Bolan et al. 2023; Langer et al. 2023). Melting ice – from ice caps, glaciers, sea ice – and thawing permafrost release legacy contaminants, such as industrial chemicals and heavy metals (Potapowicz et al. 2019; Kibria et al. 2021; Miner et al. 2021; Borgå et al. 2022; De Wit et al. 2022; Hung et al. 2022; Christensen 2024). Higher temperatures accelerate the release of POPs from ice, soil, and other environments, raising their levels in the atmosphere and helping them travel long distances. This includes higher amounts of polybrominated diphenyl ethers (Rigét et al. 2019; Zhang et al. 2021; Gong & Wang 2022). Increased climate-related wildfires and land degradation generate new POPs and polycyclic aromatic hydrocarbons (PAHs) from burning organic material. Intense fires remobilize pollutants like DDT and hexachlorocyclohexanes trapped in foliage, litter, and surface soil, causing them to volatilize back into the atmosphere. Deforestation, reforestation, and disruptions of contaminated sites release stored POPs and produce new POPs and PAHs (Gong et al. 2021; Li et al. 2024; Zhu et al. 2024). Rising temperatures also speed up pesticide breakdown and decrease their effectiveness, leading to more frequent applications and increased environmental contamination. Shifts in climate patterns can boost pesticide use in farming and introduce new chemicals and waste streams, resulting in more pollution (Pérez-Lucas et al. 2024).

Climate-related extreme weather events, along with mitigation and adaptation efforts, increase material demand by requiring climate-resilient infrastructure, population relocation, and pollution-control facilities. This leads to a larger material footprint, more raw material extraction, and higher per capita and GDP-linked consumption (Wang et al. 2020), thereby undermining target (12.2) on the efficient use of natural resources.

Climate-induced disruptions compromise waste-disposal infrastructure and the management of municipal, industrial, and hazardous waste by weakening sustainable waste practices, recycling systems, and secondary resource markets, thus hindering progress towards targets 12.4 and 12.5 (Amato et al. 2020; Brand and Spencer 2020; Kumar and Reddy 2020; Summers et al. 2021; Lincoln et al. 2023; Lebu et al. 2024; MacAfee and Löhr 2024).

Climate impacts and extreme weather events disrupt global supply chains (Tchonkouang et al. 2024), leading to material shortages that hinder sustainable consumption and production practices, making it more difficult to achieve targets related to material footprint and domestic material consumption (Gonzalez et al. 2019). They heighten the vulnerability of cross-border agrifood supply chains by disrupting transportation systems through delays, rerouting, and infrastructure stress, while also damaging postharvest storage and transport facilities; rising temperatures and heat stress accelerate food spoilage, reducing market value, and increasing waste (du Plessis, Goedhals-Gerber, and van Eeden 2024). Extreme weather events hinder green innovation by slowing economic growth, restricting financial development, widening income inequality, eroding human capital, and escalating political risks (Wen et al. 2023).

The biodiversity loss crisis, especially changes in species distribution and abundance – such as the decline of pollinators or the spread of invasive species and pests – disrupts food supply chains (Sabbahi et al. 2022). This situation leads to increased dependence on chemical inputs, which in turn increases resource use and hinders the effective management of chemicals.

Land degradation leads to an increased use of fertilizers, pesticides, and water to sustain agricultural productivity. It also changes soil properties – including pH, organic matter content, and moisture retention – affecting the soil's capacity to absorb, mobilize, and break down POPs (Tao et al. 2019; Gong et al. 2021et al.). Furthermore, activities such as deforestation, afforestation, and disturbance of contaminated sites release stored pollutants, creating new POPs and PAHs (Gong et al. 2021;et al. Li et al. 2024; Zhu et al. 2024).

The pollution and waste crisis contaminates crops, livestock, and aquatic resources with harmful substances such as POPs, heavy metals, and pesticides. This contamination forces the disposal of agrifood products, leading to increased food waste and hindering resource use reduction efforts (Tigchelaar et al. 2021; Cao 2023; Fred-Ahmadu et al. 2024). Additionally, pollution and higher temperatures accelerate the spoilage of fruits and vegetables (Wafula, Ouna, and Kamiri 2024). Pollution also poses challenges to sustainable manufacturing in the agrifood sector, obstructing progress toward target 12.3 on food waste (Fróna et al. 2021; Kumar et al. 2022; Onyeaka et al. 2023).

7.2.13 SDG 14 Life Below Water

Environmental crises weaken progress towards the sustainable use of oceans, seas, and marine resources for all, including Indigenous Peoples as well as local communities (SDG 14). Target 14.7 emphasizes the economic benefits for small island developing states (SIDS) of the sustainable use of marine resources, while 14.b focuses on providing small-scale artisanal fishers access to marine resources and markets. The 58 SIDS (UNEP 2019; Glass et al. 2022), along with small-scale and artisanal fishers (FAO 2016; FAO 2022), supply around 60 per cent of protein in some developing countries, including SIDS themselves (United Nations 2016). Their livelihoods largely depend on healthy marine ecosystems (Techera and Appadoo 2020). Nonetheless, SIDS' vulnerability is increased by factors such as low elevation of their islands, their geographic remoteness, and their small population and land size (Vousdoukas et al. 2023).

Climate change and coral reef loss harm food security, coastal protection, and the tourism industry (Bindoff et al. 2019; Eddy et al. 2021). The loss of coral reefs, especially in SIDS, significantly disrupts fish habitats, reducing fishing grounds (Thomas 2020). The forced migration of fish and ocean species from warming waters to more suitable habitats may cause severe economic losses for fishing communities. These include tuna, with a projected 17 per cent reduction in annual government revenue, and migratory oceanic pelagic fish near the Caribbean islands (Oxenford and Monnereau 2017). SIDS lost approximately US$153 billion from 1970 to 2020 due to extreme weather events, water hazards, and climate change – equivalent to about 11 times the average GDP of SIDS (WMO 2020). It is also projected that SIDS will face US$56 billion in losses from climate-related disasters such as floods and storms by 2050 under a 2°C warming scenario (Panwar et al. 2023).

Climate change has contributed to declines in the reproduction and size of several species, such as crustaceans and molluscs. This has affected 12 million artisanal fishers and their livelihoods in coastal African communities, pushing fishing communities to diversify their sources of income and adapt their fishing practices (Coalition for Fair Fisheries Arrangements 2021). The growth, reproduction, and survival of marine species are at risk due to lower oxygen levels, a problem worsened by climate change and nutrient pollution (Rose et al. 2019; Appadoo et al. 2022), which in turn reduces harvest yields.

Plastic debris, including fishing gear, food packaging, and single-use plastics, is a primary cause of marine pollution. Plastics damage the health of marine species and humans. For example, entanglement reduces the efficiency and productivity of commercial fisheries and aquaculture (Yang 2021; Marcharla et al. 2024), while consuming contaminated seafood poses health risks to people (Beaumont et al. 2019). Artisanal fishers in both SIDS and least developed countries (LDCs) are particularly vulnerable (Barrowclough and Eugui 2021). SIDS are often located near ocean gyres, resulting in debris accumulating on their shores (Lachmann et al. 2017), such as in Caribbean islands (Monsanto et al. 2023). Marine pollution also causes long-term damage to coral reef ecosystems, as seen on the Republic of the Marshall Islands.

Depletion of shallow water ecosystems, including habitats such as mangroves, seagrass beds, and estuaries, caused by offshore oil platforms and coastal refineries (Andrews et al 2021), harms the livelihoods and incomes of small-scale and artisanal fishers and coastal communities.

Pollution and climate change decrease fish stocks, lowering potential global food supplies and forcing small-scale and artisanal fishers to compete with larger fishers and tourism industries. Additionally, these fishers face economic losses from fish contaminated by land-based pollution (Nair and Nayak 2023).

Biodiversity loss and marine habitat degradation, driven by human activities such as overfishing and the use of harmful fishing gear, significantly reduce fish biomass and negatively affect food security and the livelihoods of coastal communities (Sumaila and Tai 2020). Reef fish and coastal species are also increasingly depleted due to rising global fishing pressures. SIDS rely heavily on fisheries, aquaculture, and tourism, earning about US$55 billion in 2019 from tourism alone (Mead 2021; UNESCO 2022). Maintaining high-quality marine and coastal ecosystems is crucial for sustaining these industries. The degradation of marine ecosystems can expose SIDS to natural disasters and diminish their ability to fully realize economic benefits (Martyr-Koller et al. 2021). Biodiversity loss also economically disadvantages women and small-scale fishers who supply fish to local markets.

Land and coastal degradation are driven by human activities like dam building, deforestation, and farming, which contribute to coastal erosion and change shoreline features (Mentaschi et al. 2018). Nearly half of the world's coastal wetlands have disappeared over the past century, making communities more vulnerable to flooding (Jungwiwattanaporn et al. 2023). Rising sea levels worsen the effects of coastal erosion and flooding from tropical storms and cyclones. This endangers large coastal megacities and also threatens small fisheries and local livelihoods. Climate change-driven land degradation speeds up the decline of vital coastal habitats such as corals, seagrasses, and mangroves, which support fisheries, aquaculture, tourism, and the marine food web in SIDS, mainly due to excessive sedimentation. Sea walls built to counter coastal erosion have often worsened coastal degradation by causing beach erosion, coastal squeeze, and loss of coastal biodiversity, affecting countries like Tuvalu, Kiribati, and the Bahamas (Martyr-Koller et al. 2021).

7.2.14 SDG 15. Life on Land

Although SDG 15 is considered as an "environmental" goal, its targets emphasize human needs, particularly 15.4, sustainable use of mountain ecosystems, and 15.6, access to genetic resources. The benefits of the environment for human well-being are reflected in ecosystem services, which include "provisioning services like food and water; regulating services such as flood and disease control; cultural benefits including spiritual, recreational, and cultural values; and supporting services like nutrient cycling that sustain life on Earth" (Millennium Assessment 2005). All these services rely on Earth's biodiversity (Millennium Assessment 2005; Diaz and Moore 2017).

The global environmental crises affect land and the communities reliant on land systems, including humans and all other living beings. These crises lead to a decline in biodiversity across genetic, species, and ecosystem levels (Sections 4.3.4, 4.3.5), which in turn degrades ecosystem services. The growing demand for these services accelerates these negative trends (Marques et al. 2019).

Mountain ecosystems (SDG 15.4) are key to terrestrial vertebrate diversity (Rahbek et al. 2019). Although they cover only 25 per cent of Earth's land (excluding Antarctica), they host 87 per cent of amphibian, bird, and mammal species (Rahbek et al. 2019).

Climate-linked shifts in temperature and precipitation (Habibullah et al. 2022) – intensified by economic development, habitat fragmentation, and intensive agriculture – lead to a decline in insect species' abundance and diversity in disturbed sites (Outhwaite et al. 2022), outbreaks of agricultural pests, such as locusts in Eastern Africa (Salih et al. 2020), forest pests (Jactel et al. 2019), and disruptions in pollination and seed dispersal (Teixido et al. 2022). These effects weaken the ability of land ecosystems to provide essential services to local communities (Mooney et al. 2009).

Pollution poses a significant global challenge to biodiversity, with approximately 10 million potentially contaminated sites identified worldwide. The full impact on biodiversity remains largely unknown (Chapter 4.3.1). Toxic chemicals accumulate in the environment and enter the food chain, exposing organisms to substances like heavy metals, pesticides, and radioactive elements (WHO 2022). In agriculture, pollutants decrease crop yields (Naidu et al. 2021) and cause "nutritional stress" due to excess chemicals (Zhu et al. 2020). Soil pollution is worsened by air pollution, further diminishing food production (Burney and Ramanathan 2014; Liu and Desai 2021).

Land degradation has already affected 25 per cent of the Earth's land, including 40 per cent of agricultural land (Pacheco 2018). Soil erosion decreased soil fertility, and habitat fragmentation result in biodiversity loss and the decline of ecosystem services such as food and water production, water purification, tourism, and spiritual benefits.

Biodiversity loss directly affects SDG 15.6, which focuses on sharing benefits derived from genetic resources. It also offers additional benefits for human well-being (Houlden et al. 2021). Floral biodiversity has been linked to better well-being and subjective health, such as reduced depression (Cox et al. 2017), lower blood pressure (Lindemann-Matthies and Matthies 2018), perceived restoration (Hoyle et al. 2019; Hussain et al. 2019), and overall well-being (Mavoa et al. 2019). These benefits tend to be more significant for disadvantaged socioeconomic groups and many Indigenous Peoples as well as local communities, whose health and well-being are deeply rooted in their relationship with land and nature (Rigolon et al. 2021). Furthermore, disparities exist in greenspace access among different social groups, influenced by socioeconomic status, race, ethnicity, or religion (et al.Sikorska et al. 2020; Laan and Piersma 2021; Liu et al. 2021; Sun et al. 2022).

The environmental crises interact and reinforce each other, creating a vicious cycle of degradation. For instance, climate change accelerates land degradation, while pollution contributes to biodiversity loss, both of which weaken the resilience of land systems. The decline in biodiversity and land health has significant economic and social impacts, particularly for Indigenous Peoples as well as local communities, who rely on land and its ecosystems for their well-being (Chapter 4.4).

7.2.15 SDG 16. Peace, Justice and Strong Institutions

The path to achieving SDG 16 on peace, justice, and strong institutions faces global challenges, including ongoing conflict, tension, sociopolitical uprisings, invasions, ethnic cleansing, injustice, riots, and violence within and between countries. These issues are undermining humanity's overall development and well-being (UNDP 2023; UN 2024). These conflicts and acts of violence have multiple causes. However, environmental crises often intensify the root causes of conflict and violence both domestically and internationally. Conflicts often emanate from competition over land and natural resources. Exploitation of natural resources has been associated with the origin of 40 per cent of intrastate conflicts since the mid-twentieth century (UNEP 2021b). Moreover, unsustainable and disproportionate consumption of natural resources results in pollution and environmental degradation, which ultimately hampers social cohesion and fosters injustice.

Environmental degradation resulting from unsustainable consumption and the failure to manage scarce resources fairly and effectively contributes to violence and injustice across national, regional, and international levels. Water resources often span borders, and in areas experiencing water stress, conflicts and violence are more likely to occur when governance and institutional capacity are weak (UNFCCC 2022). For example, in the Nile River basin, conflict has increased in recent years over shared water management to address water insecurity for food production, driven by rapid population growth and climate change (Fernández 2022).

Land degradation can threaten global peace and stability because it undermines food and water security. The gradual degradation of land can lead to the complete loss of people's food sources and livelihoods. This may increase forced migration within and between countries and increase risks to geopolitical stability and security (Gilbert 2017; Salehi et al. 2017).

Climate change indirectly worsens conflict, both within communities and across borders (UNFCCC 2022). The increase in climate-related cases at the United Nations and in arbitration tribunals underscores this trend, with the number of cases globally doubling from 2017 to 2022 (UNEP 2023). Additionally, the UNHCR reported that between 2008 and 2016, over 21.5 million people were displaced annually by sudden weather events – a majority of whom were Indigenous Peoples as well as local communities. The Institute for Economics and Peace forecasts that climate-induced disasters could displace up to 1.2 billion people by 2050 (Kumari et al. 2018; IEP 2020; Han et al. 2024). These displaced individuals often face exclusion, marginalization, inequality, and injustice in host communities. The proportion of refugees and asylum seekers from highly climate-vulnerable countries increased from 61 per cent in 2010 to 84 per cent in 2022, with only 1 per cent able to return home in 2020 due to worsening conditions and limited opportunities in their countries

of origin (UNHCR 2022). Moreover, it is estimated that 143 million people from the three primary climate hotspots – Sub-Saharan Africa, South Asia, and Latin America – may be internally displaced by 2050 (Kumari et al. 2018).

Biodiversity underpins the ecosystem services vital for all. Biodiversity loss and the decline of ecosystem functions can threaten livelihoods and destabilize the environment, potentially causing conflicts, violence, and maladaptive migration (Terton et al. 2022; Rist et al. 2023). Indigenous Peoples as well as local communities living close to nature are especially vulnerable to these risks. Moreover, the severe consequences of climate change, combined with the overexploitation of natural resources, threaten the equitable development of these marginalized groups (ICCA Consortium 2021; IPCC 2022; Reyes-García et al. 2024). The rapid extraction of resources often infringes on Indigenous Peoples' rights over their ancestral lands (Gilbert 2017).

Environmental crises can also destabilize governments by making it harder to meet basic human needs and undermining human well-being (UNDP 2024). A lack of support for inclusivity, equity, social cohesion, and accountability in governance can lead to economic instability, social unrest, geopolitical tensions, and growing scepticism (Lindvall 2021).

7.2.16 SDG 17. Partnerships For the Goals

The environmental crises undermine SDG 17 – the goal focused on the means of implementation – especially its targets on finance, technology, capacity-building, and trade.

A key obstacle to achieving the SDGs is insufficient financing, which reflects the lack of understanding among people and policymakers of the fundamental interdependence between humans and nature. The environmental crises exacerbate this problem by both increasing the overall cost of achieving the goals and reducing available funds to implement the goals because the resources are diverted to address the damages from the environmental crises.

Table 7.5 illustrates estimated SDG funding gaps of US$5 to 7 trillion annually, which is small compared to military spending, the costs of inaction, and the economic losses from climate change. This gap accounts for only about 5 per cent of the global annual value of biodiversity and ecosystems, estimated to be US$125 trillion (Costanza et al. 2014). Therefore, investing in SDGs can be viewed as a strategic approach to environmental protection, safeguarding ecosystem services, and promoting social well-being through a relatively modest investment relative to the value of biodiversity and ecosystems . The value of addressing crises becomes even more apparent when considering the monetary value of ecosystems: insufficient investment in SDGs and environmental sustainability is a poor business choice. Even without additional resources, how existing resources are allocated can greatly affect outcomes. The case for greater investment in the SDGs is even stronger when considering the consequences of inaction. Continued shortfalls in SDG funding will intensify the environmental crises and push systems past tipping points, making solutions more costly or impossible and potentially leading to widespread social disruption – the cost of which is beyond measure.

Table 7.5: SDG funding gap compared to global military spending, economic losses from the climate crisis, and benefits to the global economy from ecosystems

SDGs funding gap (2024 est.)	World total military spending (2023)	Cost of inaction/economic loss (climae change)	Value of biodiversity and ecosystems to the global economy
US$5-7 trillion per year of additional finance needed to achieve SDGs worldwide by 2030	**US$2.4 trillion** in 2023 (highest ever recorded)	**US$178 trillion** in net present value lost (2021-2070) or **US$2.5 trillion** lost per year	Total value of global ecosystem services in 2011 is **US$125 trillion** per year
		Global cost of climate change damage to be between **US$1.7 trillion** and **US$3.1 trillion** per year	

Sources: Costanza et al. (2014); Deloitte (2022); Newman (2023); UNGC (2023); World Economic Forum (2023); Tian et al. (2024)

The increasing costs of climate change and environmental degradation will hinder the implementation of other SDG 17 targets by redirecting resources away from capacity development and innovation (SDG 17.8; SDG 17.9).

Climate change and pollution also affect trade ((SDG 17.10 to SDG 17.12) (Chen et al. 2022). For example, drought is disrupting maritime transportation through key chokepoints, such as the Panama Canal (Gratton et al. 2022; Key et al. 2024), leading to global supply chain delays (SIPRI 2022). Europe's 2022 heatwave softened airport runways, disrupting flights (Burbidge 2018). Pollution can sometimes also disrupt travel (Xu et al. 2021). For example, thick smog caused severe delays and cancellations at New Delhi airport in January 2024 (Saxena 2024). Increasingly, extreme weather events disrupt land connectivity, cutting off access roads for medical facilities and food supplies to Indigenous and rural communities (Sangha et al. 2021; Arslanalp et al. 2023).

Natural disasters adversely affect foreign direct investment, as was illustrated by Anuchitworawong and Thampanishvong (2015) on the example of Thailand. Environmental crises elevate investment risks in developing countries (Chen et al. 2022), which are more susceptible to disasters (Batten et al. 2016). Such outcomes harm the social and economic dimensions of SDGs and threaten progress in technology transfer and innovation that comes with foreign direct investments (SDG 17.6 to SDG 17.8).

Globally, environmental crises are worsening conflicts and resource shortages, shifting attention and funding away from SDG implementation (also SDG 16) (UNSC 2018; World Bank 2022). Climate change and environmental degradation are seen as threat multipliers. Military and security spending have reached record highs of US$ 2.4 trillion in 2023 (SPIRI 2024), along with other expenditures on disaster response and environment-related crises, diverting funds that could otherwise support SDGs. These trends also weaken macroeconomic stability, policy coherence, and multilateral cooperation (SDG 17.13).

7.3 Common Themes

In assessing the effects of environmental crises on the socioeconomic aspects of the SDGs, several common themes emerged regarding the risks and consequences for people, vital infrastructure, the economy, and future development.

1. Consequences for people and their access to basic needs. Environmental crises disrupt access to, availability of, utilization of, and stability and security of resources. Access to food, water, energy, housing, education, land, and even clean air is hindered. These issues contribute to rising poverty and declining human health. They also impact most of the SDGs' socioeconomic targets, especially SDGs 1-7 and 11.

Environmental crises heighten the risk of both gradual and sudden development challenges, such as poverty traps and food insecurity. Climate change, extreme weather events, pollution, biodiversity loss, and land degradation disrupt food production, leading to decreased agricultural yields and increased hunger. Climate change undermines global efforts to address hunger, poverty, ill-health, and improve access to clean water and energy, affecting many aspects of sustainable development (WMO et al. 2020). Nearly 670 million people could face hunger by 2030. (SDGs 2, 3, 6, 7, 11)

Access to clean air is obstructed by air pollution. Air pollution is a significant health threat, particularly in urban areas, and is linked to nearly seven million premature deaths annually. (SDGs 3, 11)

Access to clean water is disrupted by various forms of pollution that make water unsafe. The water supply is also limited by climate impacts such as droughts, infrastructure damage, and land degradation. Managing water resources is difficult due to climate-related issues like floods, droughts, and changing precipitation patterns, as well as pollution and land degradation. (SDG 6)

Access to energy faces challenges from extreme weather events and climate change. These increase energy demand while disrupting supply. This also makes the clean energy transition more difficult and costly. (SDG 7)

Cities, which host over half of the world's population, are vulnerable to rising sea levels, storm surges, heat waves, heavy rainfall, flooding, drought, water shortages, air pollution, and land degradation. (SDG 11)

Climate change and pollution pose threats to oceans, marine ecosystems, and communities depending on them for food and livelihoods. (SDG 14)

Credit: anatolikFOTO/Envato

2. Differentiated burdens on the most vulnerable. The most vulnerable and the world's poorest people, especially women and Indigenous Peoples as well as local communities, are often hardest hit by environmental crises, trapping them in poverty, increasing inequalities, and hindering progress across several SDGs, particularly SDGs 1 to 6, 8, and 10. These impacts disproportionately affect marginalized groups, intensifying inequalities and undermining sustainable development across all regions (IPCC 2023). Importantly, these effects are profound, long-lasting, and multifaceted, threatening people's physical environment, cultural and social systems, local governance, and livelihoods.

In more vulnerable regions like LDCs and SIDS, extreme weather and climate events have an increasing negative effect on GDP due to their rising frequency, impeding overall development. The societal effects of environmental crises – such as deaths from air pollution and climate-related floods and storms – are significantly more severe in areas with larger populations in vulnerable conditions.

3. Impacts on vital infrastructure assets, access and services. Environmental crises, such as extreme weather and climate events, cause immediate physical damage and disrupt infrastructure across sectors. This damage particularly affects essential services and economic activities such as health systems' hospitals (SDG 3), education's schools (SDG 4), energy installations (SDG 7), water and sanitation (SDG 6), industry (SDG 9), transportation, and housing (SDG 11). The damage also disrupts trade (SDG 17). Infrastructure is critically important because it influences the achievement of all SDGs – over 90 per cent of targets, including water (SDG 6), energy (SDG 7), industry and innovation (SDG 9), and educational facilities (SDG 4). Addressing gender considerations (SDG 5) in infrastructure, such as ensuring accessible transportation and sanitation that promotes menstrual hygiene, is essential to enable equitable access to services like education for all. Overall, damage to infrastructure from environmental crises obstructs progress towards many SDG targets.

4. Economic losses from environmental crises are extensive and growing. According to a 2023 WMO report, between 1970 to 2021, nearly 12,000 weather, climate, and water-related disasters were recorded, resulting in over 2 million deaths and US$4.3 trillion in damages. More than 90 per cent of these deaths and 60 per cent of economic losses occurred in developing countries, undermining sustainable development (WMO et al. 2023). Between 2021 and 2070, climate-related damages are projected to rise to about US$ 2.5 trillion annually, totalling US$178 trillion in net present value (Deloitte 2022). Heat

stress is expected to cut global working hours by 2.2 per cent and reduce global GDP by US$2.4 trillion in 2030 (ILO 2019). Air pollution-related health damages amounted to approximately US$8.1 trillion in 2019, or about 6.1 per cent of global GDP (PPP adjusted) (World Bank Group 2022).

The economic value of ecosystems and biodiversity was estimated at US$125 to 145 trillion per year in 2011, with an annual loss of US$4.2 to 20.2 trillion (Costanza et al. 2014), representing 5.7-27.3 per cent of that year's US$74 trillion global GDP. Extrapolated to 2022, the estimated economic value of ecosystems and biodiversity would have ranged from US$172 to 198 trillion, while annual losses would have ranged from US$ 5.7-27.3 trillion (Elder 2024). Approximately 1.2 billion jobs depend directly on ecosystem services, accounting for about 40 per cent of global employment (ILO 2018b). These jobs, along with indirectly related jobs, are at risk from ecosystem degradation.

Many industries experience economic damage from environmental crises, affecting sectors like agriculture, fishing, energy, manufacturing, transport, and buildings. These damages include infrastructure destruction from climate disasters and loss or deterioration of raw materials and inputs due to pollution and ecosystem degradation. They also include decreased worker availability and productivity caused by heat stress, health issues, and degraded educational outcomes, in addition to those resulting from disruptions in supply chains.

Environmental crises cause disproportionately high economic damage to developing nations, especially LDCs and SIDS. The 2022 Vulnerable Twenty Group Report highlights that the 55 most vulnerable countries lost US$525 billion from climate disasters between 2000 and 2019. Additionally, climate change reduced their annual GDP per capita growth by 25 per cent (Baarsch et al. 2022).

The UNEP adaptation gap report estimated that the average annual adaptation finance costs for LDCs and SIDS are around US$41 billion, ranging from US$16 to 83 billion, which is roughly 2 per cent of their GDP, with a range of 0.80 to 4 per cent (UNEP 2023).

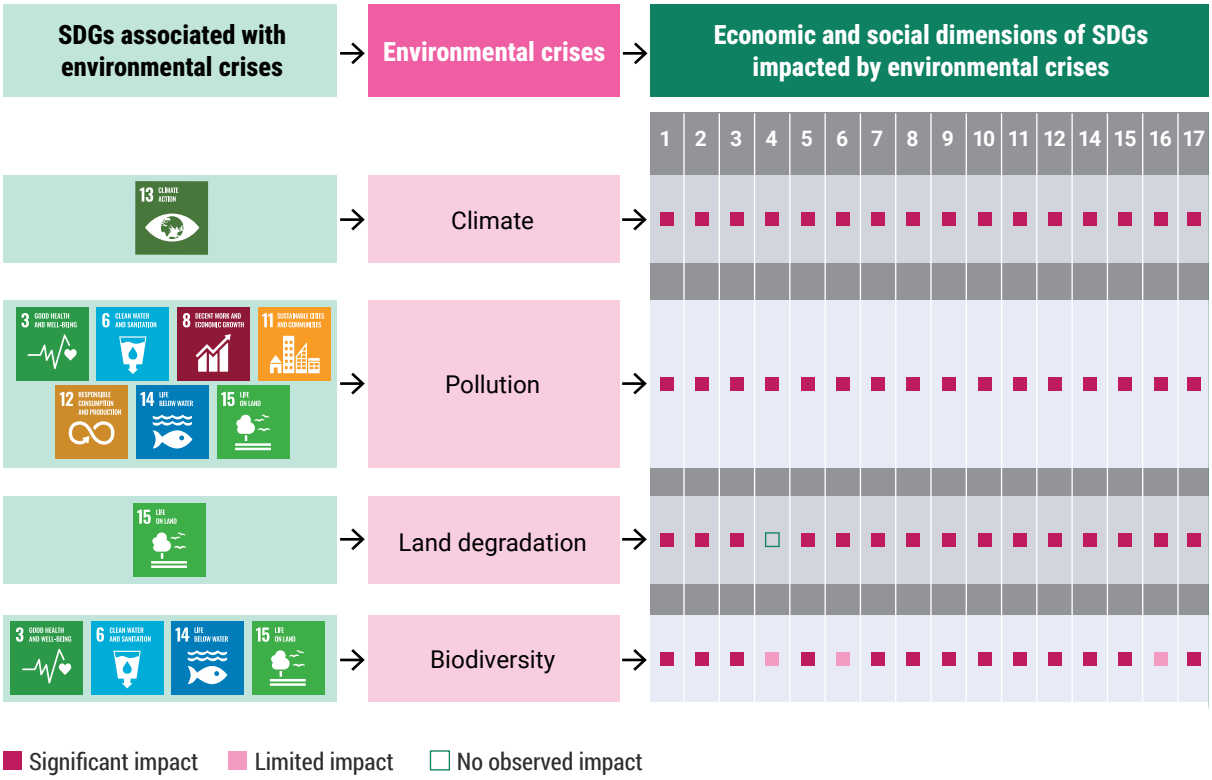
5. Cascading and compounding adverse effects of environmental crises on the interconnected socioeconomic aspects of the SDGs reinforce and worsen each other. This is sometimes called a poly crisis (Lawrence et al. 2024). There are extensive interlinkages among SDGs which can magnify these adverse effects as well as potential synergies (Pradhan et al. 2017; Kroll et al. 2019; Independent Group of Scientists 2023). The food-energy-water nexus illustrates these connections among socioeconomic SDGs (FAO 2014; D'Odorico et al. 2018; Di Martino et al. 2023). For instance, disruptions in water production due to environmental crises have a compounding effect, negatively affecting food and energy production. Economic impacts also cascade – damage to infrastructure in one industry can disrupt supply chains across others, reducing economic growth and employment. These cascading effects increase vulnerabilities among Indigenous Peoples as well as local communities, severely affecting their ability to sustain their ways of life. Wars, conflicts, natural disasters, economic shocks, and pandemics further intensify the crises.

6. Overview of the impacts of environmental crises. This chapter concludes that the economic and social aspects of all SDGs were adversely affected by the environmental crises. The main findings are summarized in **Figure 7.6**. The climate and pollution crises impacted the socioeconomic aspects of every SDG, whereas land degradation primarily affected all but one (SDG 4). The biodiversity crisis had an adverse effect on all SDGs, although its impact on three specific SDGs (4, 6, 16) was limited. **Figure 7.6** also illustrates that many SDGs include targets reflecting environmental conditions and trends, many of which are in crisis, along with socioeconomic targets that suffer adverse effects from these environmental crises.

7.4 Conclusion

The environmental crises are undermining progress towards the economic and social dimensions of the SDGs, harming human well-being. These crises are imposing significant economic and social costs. They threaten energy, food, safe water, and housing. They damage human health and increase inequality and inequity. Environmental crises also exacerbate gender inequality and disproportionately affect women, girls, children in rural areas of developing countries,

Figure 7.6: SDGs Associated with Environmental Crises



Indigenous Peoples as well as local communities, and other people in vulnerable situations. As environmental crises worsen, their costs, damages, and inequities will continue to rise.

The socioeconomic effects of environmental crises will affect everyone, including the middle class, working people, and those in developed countries. While impacts will vary regionally and nationally, no group or area will be immune to the socioeconomic consequences of the environmental crises.

The implication is that significant effort is required to address the environmental crises, not only to accelerate progress in achieving SDGs by 2030 but also to prevent jeopardizing current levels of development. Therefore, the environment-related goals and targets of the SDGs need much higher prioritization to put the social and economic-related goals and targets on track. The scale and costs of damage from the environmental crises should be substantially reduced to minimize the resulting economic and social harm that undermines human well-being. A healthy environment forms the foundation for the economic and social aspects of the SDGs (UNEP 2019), so alleviating the environmental crises is essential for achieving the SDGs' economic and social objectives.

At the same time, environmental solutions should be designed and managed to directly support economic and social goals and targets, especially jobs, decent work, and poverty eradication (Matsushita et al. 2023; Elder 2024). As unsustainable industries are phased out, a clear pathway for displaced workers to find decent employment in sustainable industries is essential. Environmental solutions should support social and economic goals, such as poverty eradication, food security, and gender equality, while also providing decent work opportunities.

Crises such as wars and pandemics exacerbate the social and economic damage caused by environmental crises, making environmentally sustainable solutions even more urgent. Wars and pandemics are not reasons to delay action (Mori et al. 2021; Elder et al. 2022).

The primary implication for the post-2030 sustainable development agenda is that greater efforts are required to ensure environmental

Credit: Gorlovkv/Envato

sustainability – the foundation of economic prosperity and human well-being – and to tackle the root causes of environmental crises. It is widely recognized that traditional resource-intensive economic growth is a key driver of these crises (2.2.2, 2.2.5), and SDG 8.1, on economic growth, is considered one of the most significant trade-offs among the SDGs (Spaiser et al. 2017; Pradhan 2017; Kroll et al. 2019), as it conflicts with achieving other goals, particularly those related to the environment. Additionally, this chapter's discussion of SDGs 7, 8, 9, and 11 shows that the economic consequences of the environmental crises have become so severe that they are now hindering economic growth itself, through damage to infrastructure and economic assets and through reduced worker productivity and capacity to work. Governments committed to decouple economic growth from environmental harm in target 8.4, although it may not be fully achievable. To date, efforts to decouple have not significantly reduced the adverse impacts of traditional economic growth. This suggests that future discussions should focus on ways to directly meet socioeconomic needs – such as decent work, food security, housing, and transportation – rather than indirectly relying solely on economic growth, which has often left many behind.

References

Afifi, T. (2011). Economic or environmental migration? The push factors in Niger. International Migration 49, e95-e124. https://doi.org/10.1111/j.1468-2435.2010.00644.x

Alava J.J., Cheung W.W.L., Ross P.S., Sumaila U.R. (2017). Climate Change-Contaminant Interactions in Marine Food Webs: Toward a Conceptual Framework. Global Change Biology, no. 23:3984-4001. https://doi.org/10.1111/gcb.13667

Alenius, H., Pakarinen, J., Saris, O., Andersson, M.A., Leino, M., Sirola, K. et al. (2009). Contrasting immunological effects of two disparate dusts–preliminary observations. International archives of allergy and immunology 149(1), 81-90. https://doi.org/10.1159/000176310

Alkon, M., He, X., Paris, A.R., Liao, W., Hodson, T., Wanders, N. et al. (2019). Water security implications of coal-fired power plants financed through China's Belt and Road Initiative. Energy policy 132, 1101-1109. https://doi.org/10.1016/j.enpol.2019.06.044

Allendorf, T.D. (2022). A global summary of local residents' perceptions of benefits and problems of protected areas. Biodiversity and Conservation 31(2), 379-396. https://doi.org/10.1007/s10531-022-02359-z

Amato, A., Gabrielli, F., Spinozzi, F., Magi Galluzzi, L., Balducci, S. and Beolchini, F. (2020). Disaster waste management after flood events. Journal of Flood Risk Management 13, e12566. https://doi.org/10.1111/jfr3.12566

Amini, A., Abedi, M., Nesari, E., Daryadel, E., Kolahi, M., Mianabadi, H. et al. (2023). The Paris Agreement's approach toward climate change loss and damage. World Affairs 186(1), 46-80. https://doi.org/10.1177/00438200221147936

Amiraslani, F. (2021). Tackling rural health, energy,… and technological issues all at once: A call for a global interdisciplinary platform for strengthening rural setting amid the COVID-19 pandemic. Challenges 12(2), 16. https://doi.org/10.3390/challe12020016

Anderson, T. and Fisher, S. (2022). Gender equality and informality in low-carbon transitions: a review of evidence to identify transformative outcomes. International Institute for Environment and Development. https://www.iied.org/sites/default/files/pdfs/2022-10/21116iied.pdf

Andreeva, O., Sebentsov, A., Kust, G. and Kolosov, V. (2022). The Nexus Between Land Degradation, Climate Change and Migration in Central Asia. United Nations Convention to Combat Desertification, Institute of Geography of Russian Academy of Sciences. https://www.unccd.int/sites/default/files/2023-08/Study%20migration%20Central%20Asia%20full%20ENG.pdf

Andrews, N., Bennett, N. J., Le Billon, P., Green, S. J., Cisneros-Montemayor, A. M., Amongin, S., . . . Sumaila, U. R. (2021). Oil, fisheries and coastal communities: A review of impacts on the environment, livelihoods, space and governance. Energy research & social science, 75, 102009. doi:https://doi.org/10.1016/j.erss.2021.102009

Angon, P.B., Islam, M.S., Kc, S., Das, A., Anjum, N., Poudel, A. et al. (2024). Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. Heliyon. https://www.cell.com/heliyon/fulltext/S2405-8440(24)04388-3

Appadoo, C., Sultan, R., Simier, M., Tandrayen-Ragoobur, V. and Capello, M. (2022). Artisanal fishers in small island developing states and their perception of environmental change: the case study of Mauritius. Rev Fish Biol Fish, 1-18. https://doi.org/10.1007/s11160-022-09735-6

Arora, P. (2022). Rainbow Operations: Let's Add LGBTQ Colors to 'Doing Good with Good Operations'. Available at SSRN. http://dx.doi.org/10.2139/ssrn.4225261

Arora, S. and Stirling, A. (2021). Degrowth and the pluriverse: Continued coloniality or intercultural revolution. STEPS Centre Blog, Brighton UK. https://www.researchgate.net/profile/Andy-Stirling/publication/352789556_Degrowth_and_the_pluriverse_continued_coloniality_or_intercultural_revolution/links/60d9c69292851ca9449083fa/Degrowth-and-the-pluriverse-continued-coloniality-or-intercultural-revolution.pdf

Arslanalp, S., Koepke, R., Sozzi, A. and Verschuur, J. (2023). Climate Change is Disrupting Global Trade. https://www.imf.org/en/Blogs/Articles/2023/11/15/climate-change-is-disrupting-global-trade

Asafu-Adjaye, J. (2003). Biodiversity Loss and Economic Growth: A Cross-Country Analysis. Contemporary Economic Policy. 21 (2): 173-85. https://doi.org/10.1093/cep/byg003

Anuchitworawong, C. and Thampanishvong, K. (2015). Determinants of foreign direct investment in Thailand: Does natural disaster matter? International Journal of Disaster Risk Reduction. https://doi.org/10.1016/j.ijdrr.2014.09.001

Baarsch, F., Awal, I. and Schaeffer, M. (2022). Climate Vulnerable Economies Loss Report 2000-2019. Vulnerable Twenty Group. https://www.v-20.org/wp-content/uploads/2022/06/Climate-Vulnerable-Economies-Loss-Report_June-14_compressed-1.pdf

Balakrishnan, U. and Tsaneva, M. (2021). Air Pollution and Academic Performance: Evidence from India. World Development. https://doi.org/10.1016/j.worlddev.2021.105553

Balsam, P. (2020). Water Usage in The Agricultural Industry. https://htt.io/water-usage-in-the-agricultural-industry

Balvin, N. and Christie, D.J. (2020). Children and peace: From research to action. Springer Nature. https://doi.org/10.1007/978-3-030-22176-8

Banerjee, A. v. and Duflo, E. (2011). Poor Economics: A Radical Rethinking of the Way to Fight Global Poverty. Population and Development Review. https://doi.org/10.1111/j.1728-4457.2011.00462.x

Barbier, E.B. and Hochard, J.P. (2016). Does land degradation increase poverty in developing countries? PloS one 11(5), e0152973. https://doi.org/10.1371/journal.pone.0152973

Baruah, M. (2023). The Political Ecology of an Environmental Crisis in the Brahmaputra Valley, Assam. Ecology, Economy and Society–the INSEE Journal 6(2), 121-145. https://doi.org/10.37773/ees.v6i2.1054

Bamisile, O., Acen, C., Cai, D., Huang, Q., and Staffell, I. (2025). The environmental factors affecting solar photovoltaic output. Renewable and Sustainable Energy Reviews, 20. https://doi.org/10.1016/j.rser.2024.115073

Barrowclough, D. and Vivas Eugui, D. (2021), 'Plastic Production and Trade in Small States and SIDS: The Shift Towards a Circular Economy', International Trade Working Paper 2021/01, Commonwealth Secretariat, London.https://production-new-commonwealth-files.s3.eu-west-2.amazonaws.com/migrated/inline/ITWP%202021_01_0.pdf

Batten, S., Sowerbutts, R. and Tanaka, M. (2016). Let's talk about the weather: the impact of climate change on central banks. http://dx.doi.org/10.2139/ssrn.2783753

Beaumont, N.J., Aanesen, M., Austen, M.C., Börger, T., Clark, J.R., Cole, M. et al. (2019). Global ecological, social and economic impacts of marine plastic. Marine pollution bulletin 142, 189-195. https://doi.org/10.1016/j.marpolbul.2019.03.022

Berberian, A.G., Gonzalez, D.J. and Cushing, L.J. (2022). Racial disparities in climate change-related health effects in the United States. Current environmental health reports 9(3), 451-464. https://doi.org/10.1007/s40572-022-00360-w

Bindoff, N.L., Cheung, W.W., Kairo, J.G., Arístegui, J., Guinder, V.A., Hallberg, R. et al. (2019). Changing ocean, marine ecosystems, and dependent communities. https://doi.org/10.1017/9781009157964.007

Biswas, S., Echevarria, A., Irshad, N., Rivera-Matos, Y., Richter, J., Chhetri, N. et al. (2022). Ending the energy-poverty nexus: an ethical imperative

for just transitions. Science and engineering ethics 28(4), 36. https://doi.org/10.1007/s11948-022-00383-4

Bjork-James, C., Checker, M. and Edelman, M. (2022). Transnational social movements: environmentalist, indigenous, and agrarian visions for planetary futures. Annual review of environment and resources 47, 583-608. https://doi.org/10.1146/annurev-environ-112320-084822

Bohman, E. (2024). A Cry for Justice by "Invisible Squatters": Colonial Legacy, Local Democracy, and the Quest for Human Rights in Land Dispossession by Kakuzi PLC in Makuyu, Murang'a County, Kenya. https://liu.diva-portal.org/smash/get/diva2:1919128/FULLTEXT01.pdf

Bolan, S., Padhye, L.P., Jasemizad, T., Govarthanan, M., Karmegam, N., Wijesekara, H. et al. (2024). Impacts of climate change on the fate of contaminants through extreme weather events. Science of The Total Environment 909, 168388. https://doi.org/10.1016/j.scitotenv.2023.168388

Bopape M., Taillie L.S., Frank T., Murukutla N., Cotter T., Majija L., et al. (2021). South African consumers' perceptions of front-of-package warning labels on unhealthy foods and drinks. PLoS ONE 16(9): e0257626. https://doi.org/10.1371/journal.pone.0257626

Borgå, K., McKinney, M.A., Routti, H., Fernie, K.J., Giebichenstein, J., Hallanger, I. et al. (2022). The influence of global climate change on accumulation and toxicity of persistent organic pollutants and chemicals of emerging concern in Arctic food webs. Environmental Science: Processes & Impacts 24(10), 1544-1576. https://doi.org/10.1039/D1EM00469G

Børresen, S.T., Ulimboka, R., Nyahongo, J., Ranke, P.S., Skjaervø, G.R. and Røskaft, E. (2022). The role of education in biodiversity conservation: Can knowledge and understanding alter locals' views and attitudes towards ecosystem services? Environmental Education Research 29. https://doi.org/10.1080/13504622.2022.2117796

Bower, A., Lozier, M., Gary, S. et al. (2009). Interior pathways of the North Atlantic meridional overturning circulation. Nature 459, 243–247. https://doi.org/10.1038/nature07979

Brand, J.H. and Spencer, K.L. (2020). Will flooding or erosion of historic landfills result in a significant release of soluble contaminants to the coastal zone? Science of The Total Environment 724, 138150. https://doi.org/10.1016/j.scitotenv.2020.138150

Bryer, A. (2023). Critical accounting as an indigenous project. Critical Perspectives on Accounting 93, 102579. https://doi.org/10.1016/j.cpa.2023.102579

Burbidge, R. (2018). Adapting aviation to a changing climate: Key priorities for action. Journal of Air Transport Management 71, 167-174. https://doi.org/10.1016/j.jairtraman.2018.04.004

Burke, M., Hsiang, S.M. and Miguel, E. (2015). Global non-linear effect of temperature on economic production. Nature527(7577), 235-239. https://doi.org/10.1038/nature15725

Bunker, A., Wildenhain, J., Vandenbergh, A., Henschke, N., Rocklöv, J., Hajat, S. et al. (2016). Effects of air temperature on climate-sensitive mortality and morbidity outcomes in the elderly; a systematic review and meta-analysis of epidemiological evidence. EBioMedicine 6, 258-268. https://doi.org/10.1016/j.ebiom.2016.02.034

Burke, L., Díaz-Reviriego, I., Lam, D. P. M., & Hanspach, J. (2023). Indigenous and local knowledge in biocultural approaches to sustainability: A review of the literature in Spanish. Ecosystems and People, 19(1), 1–15. https://doi.org/10.1080/26395916.2022.2157490

Burney, J. and Ramanathan, V. (2014). Recent climate and air pollution impacts on Indian agriculture. Proceedings of the National Academy of Sciences 111(46), 16319-16324. https://doi.org/10.1073/pnas.1317275111

Bux, Q., Anderson, P. and O'Farrell, P. J. (2021). Understanding the local biodiversity and open space strategies in two South African cities. Ecology and Society 26(3):4. https://doi.org/10.5751/ES-12498-260304

Byrne, J. and Portanger, C. (2016). Climate change, energy policy and justice: a systematic review. Analyse & Kritik 36(2), 315-344. https://doi.org/10.1515/auk-2014-0207

C40 Cities (2018). Sea level rise and energy systems. https://www.c40.org/what-we-do/scaling-up-climate-action/water-heat-nature/the-future-we-dont-want/sea-level-rise-and-energy-systems/

Cao, L., Halpern, B.S., Troell, M., Short, R., Zeng, C., Jiang, Z. et al. (2023). Vulnerability of blue foods to human-induced environmental change. Nature Sustainability 6(10), 1186-1198. https://doi.org/10.1038/s41893-023-01156-y

Cao, Y., Li, G., Ma, W., Chen, D., Shang, Y., Wu, G. et al. (2023). Permafrost degradation induced by warm-oil pipelines and analytical results of thermosyphon-based thawing mitigation. Energy 269, 126836. https://doi.org/10.1016/j.energy.2023.126836

Catford, J.A. (2017). Hydrological Impacts of Biological Invasions. In: Vilà, M., Hulme, P. (eds) Impact of Biological Invasions on Ecosystem Services. Invading Nature - Springer Series in Invasion Ecology, vol 12. Springer, Cham. https://doi.org/10.1007/978-3-319-45121-3_5

Cave, C. (2022). Climate Change and World Heritage: An Introduction. In: Albert, MT., Bernecker, R., Cave, C., Prodan, A.C., Ripp, M. (eds) 50 Years World Heritage Convention: Shared Responsibility – Conflict & Reconciliation. Heritage Studies. Springer, Cham. https://doi.org/10.1007/978-3-031-05660-4_17

Chai, L., Zhou, Y. and Wang, X. (2022). Impact of global warming on regional cycling of mercury and persistent organic pollutants on the Tibetan Plateau: current progress and future prospects. Environmental Science: Processes & Impacts 24(10), 1616-1630. https://doi.org/10.1039/D1EM00550B

Chappell, C. (2018). Climate change in the US will hurt poor people the most, according to a bombshell federal report. CNBC, November 26. https://www.cnbc.com/2018/11/26/climate-change-will-hurt-poor-people-the-most-federal-report.html

Chen, B., Wu, S., Song, Y., Webster, C., Xu, B. and Gong, P. (2022). Contrasting inequality in human exposure to greenspace between cities of Global North and Global South. Nat. Commun. 13, 4636. https://doi.org/10.1038/s41467-022-32258-4

Chen, Y., Zhang, D., Wu, F. and Ji, Q. (2022). Climate risks and foreign direct investment in developing countries: the role of national governance. Sustainability Science 17(5), 1723-1740. https://doi.org/10.1007/s11625-022-01199-8

Christensen, K. (2024). Thawing permafrost releases industrial contaminants into Arctic communities. https://doi.org/10.1289/EHP13998

Climate and Clean Air Coalition. (2024) Short-lived climate pollutants and food security. https://www.ccacoalition.org/content/short-lived-climate-pollutants-and-food-security. Accessed 01 July 2025.

Coalition for Fair Fisheries Arrangements. (2021). Living on the frontline: Climate change will first impact African coastal fishing communities. https://www.cffacape.org/publications-blog/climate-change-also-impacts-small-scale-fisheries-in-africa#:%E2%88%BC:text=Artisanal%20fishing%20communities%20in%20African,to%20deal%20with%20this%20phenomenon%20Accessed%20date%2010/3/2022. Accessed 2 July 2025.

Costanza, R., De Groot, R., Sutton, P., Van der Ploeg, S., Anderson, S.J., Kubiszewski, I. et al. (2014). Changes in the global value of ecosystem services. Global environmental change 26, 152-158. https://doi.org/10.1016/j.gloenvcha.2014.04.002

Cox, D. T., Shanahan, D. F., Hudson, H. L., Plummer, K. E., Siriwardena, G. M., Fuller et al. (2017). Doses of neighborhood nature: The benefits for mental health of living with nature. AIBS Bulletin, 67(2), 147–155. https://doi.org/10.1093/biosci/biw173

Cuthbert, M.O., Rau, G., Ekström, M., O'carroll, D. and Bates, A. (2022). Global climate-driven trade-offs between the water retention and cooling benefits of urban greening. Nature communications 13(1), 518. https://doi.org/10.1038/s41467-022-28160-8

Cuthbert, R. N., Pattison, Z., Taylor, N. G., Verbrugge, L., Diagne, C., Ahmed, D. A. et al. (2021). Global economic costs of aquatic invasive alien species. Science of the total environment, 775, 145238. https://doi.org/10.1016/j.scitotenv.2021.145238

Dadashpoor, H., Rostami, F. and Alizadeh, B. (2016). Is inequality in the distribution of urban facilities inequitable? Exploring a method for identifying spatial inequity in an Iranian city. Cities 52, 159-172. https://doi.org/10.1016/j.cities.2015.12.007

Davies, K., Rajvanshi, A., Yeo-Chang, Y., Choe, J.C., Choi, A.S., Cooney, R. et al. (2018). Nature's contributions to people and quality of life. In The IPBES regional assessment report on biodiversity and ecosystem services for Asia and the Pacific.Intergovernmental Science-Policy Platform on

Biodiversity and Ecosystem. 84-219. https://researchers.mq.edu.au/en/publications/natures-contributions-to-people-and-quality-of-life

De Wit, C.A., Vorkamp, K. and Muir, D. (2022). Influence of climate change on persistent organic pollutants and chemicals of emerging concern in the Arctic: state of knowledge and recommendations for future research. Environmental Science: Processes & Impacts 24(10), 1530-1543. https://doi.org/10.1039/D1EM00531F

Deloitte (2022). The Turning Point: A Global Summary.https://www2.deloitte.com/content/dam/Deloitte/global/Documents/gx-global-turning-point-report.pdf

Deb, P. (2018). Chapter 14 - Environmental Pollution and the Burden of Food-Borne Diseases. In Foodborne Diseases. Holban, A.M. and Grumezescu, A.M. (eds.). Academic Press. 473-500. https://www.sciencedirect.com/science/article/pii/B9780128114445000142

Desai, B.H. and Mandal, M. (2021). Role of climate change in exacerbating sexual and gender-based violence against women: A new challenge for international law. Environmental Policy and Law 51(3), 137-157. https://doi.org/10.3233/EPL-210055

Dhar, A., Naeth, M.A., Jennings, P.D. and El-Din, M.G. (2020). Perspectives on environmental impacts and a land reclamation strategy for solar and wind energy systems. Science of the Total Environment 718, 134602. https://doi.org/10.1016/j.scitotenv.2019.134602

Di Martino, M., Linke, P. and Pistikopoulos, E.N. (2023). A comprehensive classification of food-energy-water nexus optimization studies: state of the art. Journal of Cleaner Production, 138293. https://doi.org/10.1016/j.jclepro.2023.138293

Diaz, D. and Moore, F. (2017). Quantifying the economic risks of climate change. Nature Climate Change 7(11), 774-782. https://doi.org/10.1038/nclimate3411

Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R.T., Molnár, Z. et al..al (2018). Assessing nature's contributions to people. Science 359(6373), 270-272. https://www.science.org/doi/abs/10.1126/science.aap8826

D'Odorico, P., Davis, K.F., Rosa, L., Carr, J.A., Chiarelli, D., Dell'Angelo, J. et al. (2018). The global food-energy-water nexus. Reviews of geophysics 56(3), 456-531. https://doi.org/10.1029/2017RG000591

Dumenu, W.K. and Obeng, E.A. (2016). Climate Change and Rural Communities in Ghana: Social Vulnerability, Impacts, Adaptations and Policy Implications. Environmental Science and Policy, 55, 208-217. https://doi.org/10.1016/j.envsci.2015.10.010

du Plessis, F., Goedhals-Gerber, L. and van Eeden, J. (2024). The impacts of climate change on marine cargo insurance of cold chains: A systematic literature review and bibliometric analysis. Transportation Research Interdisciplinary Perspectives 23, 101018. https://doi.org/10.1016/j.trip.2024.101018

Ebhota, W. S., and Tabakov, P. Y. (2023). Influence of photovoltaic cell technologies and elevated temperature on photovoltaic system performance. In Ain Shams Engineering Journal (Vol. 14, Issue 7, p. 101984). Elsevier BV. https://doi.org/10.1016/j.asej.2022.101984

Eddy, T.D., Lam, V.W., Reygondeau, G., Cisneros-Montemayor, A.M., Greer, K., Palomares, M.L.D. et al. (2021). Global decline in capacity of coral reefs to provide ecosystem services. One Earth 4(9), 1278-1285. https://doi.org/10.1016/j.oneear.2021.08.016

Ekka, P., Patra, S., Upreti, M., Kumar, G., Kumar, A. and Saikia, P. (2023). Land Degradation and its impacts on Biodiversity and Ecosystem services. Land and Environmental Management through Forestry, 77-101. https://doi.org/10.1002/9781119910527.ch4

Elder, M. and Olsen, S.H. (2019). The Design of Environmental Priorities in the SDGs. Global Policy. 10(S1), pp. 70–82. https://doi.org/10.1111/1758-5899.12596

Elder, M. et al. (2022) 'Environmental and Sustainability Implications of the Ukraine War for East and South Asia: Sustainability and Decarbonisation Should be Accelerated Not Paused', IGES Issue Brief, December. https://www.iges.or.jp/en/pub/env-sust-implications-ukraine/en

Elder, M. (2024). Integration versus Prioritization in the Sustainable Development Goals: An Argument to Prioritize Environmental Sustainability and a Just Transition. Sustainable Development. https://doi.org/10.1002/sd.3130

Elmqvist, T., et al. (2019). Sustainability and resilience for transformation in the urban century. Nature Sustainability (2 (4)), 267-273. https://doi.org/10.1038/s41893-019-0250-1

Environment and Climate Change Canada (2010). Air pollution damage to infrastructure and industry. https://www.canada.ca/en/environment-climate-change/services/air-pollution/quality-environment-economy/economic-issues/damage-infrastructure-industry.html

Escovar, M. A and Balduzzi, S. (2024) International Women's Day: The Unequal Impact of Disasters on Women. International Development Bank. Accessed 24 September 2025. https://blogs.iadb.org/sostenibilidad/en/international-womens-day-the-unequal-impact-of-disasters-on-women/?utm_source=chatgpt.com

Etchart, L. (2017). The role of indigenous peoples in combating climate change. Palgrave Communications 3(1), 1-4. https://doi.org/10.1057/palcomms.2017.85

European Food Safety Authority (2021). The 2021 European Union report on pesticide residues in food. European Commission. https://efsa.onlinelibrary.wiley.com/doi/pdf/10.2903/j.efsa.2023.7939?_ga=2.82827030.1896508861.1685013740-252894506.1684424716

Fanzo, J., Davis, C., McLaren, R. and Choufani, J. (2018). The effect of climate change across food systems: Implications for nutrition outcomes. Global Food Security 18, 12-19. https://doi.org/10.1016/j.gfs.2018.06.001

Farrow, A., Miller, K.A. and Myllyvirta, L. (2020). Toxic air: the price of fossil fuels. https://policycommons.net/artifacts/2391360/the-price-of-fossil-fuels-full-report/3412789/

Fernández, S. (2022). Water conflict analysis: The Nile River dispute. Análisis Jurídico - Político 4, 83-112. https://doi.org/10.22490/26655489.5877

Field, C.B. and Barros, V.R. (2014). Climate change 2014–Impacts, adaptation and vulnerability: Regional aspects. Cambridge University Press. https://doi.org/10.1017/CBO9781107415386

Food and Agriculture Organization of the United Nations (2014). The Water-Energy-Food Nexus—A New Approach in Support of Food Security and Sustainable Agriculture. Rome: FAO. https://openknowledge.fao.org/server/api/core/bitstreams/86fe97cc-4a38-4511-a37f-8eb8ea8fe941/content

Food and Agriculture Organization of the United Nations (2016). The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/20e618b3-93a1-488a-9697-798f6b6c6b35/content

Food and Agriculture Organization of the United Nations (2020). Unpacking the burden on food safety. FAO—Food and Agriculture Organization of the United Nations: Rome, Italy. https://doi.org/10.4060/ca8185en

Food and Agriculture Organization of the United Nations (2022). The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. Rome, FAO. https://doi.org/10.4060/cc0461en

Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, United Nations Children's Fund, World Food Programme and World Health Organization. (2022). The State of Food Security and Nutrition in the World 2022. Repurposing food and agricultural policies to make healthy diets more affordable. Rome: FAO. https://doi.org/10.4060/cc0639en

Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, United Nations Children's Fund, World Food Programme and World Health Organization. (2023). The State of Food Security and Nutrition in the World 2023. Urbanization, agrifood systems transformation and healthy diets across the rural–urban continuum. Rome: FAO. https://doi.org/10.4060/cc3017en

Fred-Ahmadu, O.H., Ahmadu, F.O., Adedapo, A.E., Oghenovo, I., Ogunmodede, O.T. and Benson, N.U. (2024). Microplastics and chemical contamination in aquaculture ecosystems: The role of climate change and implications for food safety—a review. Environmental Sciences Europe 36(1), 181. https://doi.org/10.1186/s12302-024-00995-6

Fróna, D., Szenerák, J. and Harangi-Rákos, M. (2021). Economic effects of climate change on global agricultural production. Nature Conservation 44,

117-139. https://natureconservation.pensoft.net/article/64296/download/pdf/

Fujii, T. (2016). Climate Change and Vulnerability to Poverty: An Empirical Investigation in Rural Indonesia. Adbi Working Paper 622. https://www.adb.org/publications/climate-change-vulnerability-poverty-indonesia

Fuller, R., Landrigan, P., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M. et al. (2022). Pollution and health: a progress update. Lancet Planet Health. 6 (6): e535–47. https://doi.org/10.1016/S2542-5196(22)00090-0

Gernaat, D.E.H.J., de Boer, H.S., Daioglou, V., Yalew, S.G., Müller, C. and van Vuuren, D.P. (2021). Climate change impacts on renewable energy supply. Nature Climate Change 11(2), 119-125. https://doi.org/10.1038/s41558-020-00949-9

Gilbert, J. (2017). Land grabbing, investments & indigenous peoples' rights to land and natural resources.https://pure.roehampton.ac.uk/ws/portalfiles/portal/2333439/IWGIA_Land_Grabbing.pdf

Glass, J.R., Belle, K., Berke, G., Bodin, N., Burt, A.J., Duncan, M.I. et al. (2022). Evaluating the Feasibility of Sustainable Seafood Labelling Programmes in Small Island Developing States: A Pilot Study of Artisanal Fisheries in Seychelles. Frontiers in Marine Science Volume 9 - 2022. https://doi.org/10.3389/fmars.2022.931407

Godde, C.M., Mason-D'Croz, D., Mayberry, D.E., Thornton, P.K., Herrero, M. (2021). Impacts of climate change on the livestock food supply chain; a review of the evidence. Global Food Security, 28. https://doi.org/10.1016/j.gfs.2020.100488

Goh, A.H. (2012). A literature review of the gender-differentiated impacts of climate change on women's and men's assets and well-being in developing countries. https://www.worldagroforestry.org/sites/default/files/4.pdf.

Gojon, A., Cassan, O., Bach, L., Lejay, L. and Martin, A. (2023). The decline of plant mineral nutrition under rising CO2: physiological and molecular aspects of a bad deal. Trends in Plant Science 28(2), 185-198. https://doi.org/10.1016/j.tplants.2022.09.002

Gonçalves, A.C.R., Costoya, X., Nieto, R. et al. Extreme weather events on energy systems: a comprehensive review on impacts, mitigation, and adaptation measures. Sustainable Energy res. 11, 4 (2024). https://doi.org/10.1186/s40807-023-00097-6

Gong, P., Xu, H., Wang, C., Chen, Y., Guo, L. and Wang, X. (2021). Persistent organic pollutant cycling in forests. Nature Reviews Earth & Environment 2(3), 182-197. https://doi.org/10.1038/s43017-020-00137-5

Gong, P. and Wang, X. (2022). Critical roles of secondary sources in global cycling of persistent organic pollutants under climate change. Journal of Hazardous Materials Advances 6, 100064. https://doi.org/10.1016/j.hazadv.2022.100064

Gonzalez, F.R., Raval, S., Taplin, R., Timms, W. and Hitch, M. (2019). Evaluation of impact of potential extreme rainfall events on mining in Peru. Natural Resources Research 28, 393-408. https://doi.org/10.1007/s11053-018-9396-1

Goulart, H., van der Wiel, K., Folberth, C., Boere, E., van den Hurk, B. (2023). Increase of Simultaneous Soybean Failures Due To Climate Change. Earth's Future 11 (4), https://doi.org/10.1029/2022EF003106

Gratton, G.B., Williams, P.D., Padhra, A. and Rapsomanikis, S. (2022). Reviewing the impacts of climate change on air transport operations. The Aeronautical Journal 126(1295), 209-221. https://www.cambridge.org/core/journals/aeronautical-journal/article/reviewing-the-impacts-of-climate-change-on-air-transport-operations/2B77B76330330CFBA4FADF75A728BBE3

Grote, R., Samson, R., Alonso, R., Amorim, J.H., Cariñanos, P., Churkina, G. et al. (2016). Functional traits of urban trees: air pollution mitigation potential. Frontiers in Ecology and the Environment 14(10), 543-550. https://doi.org/10.1002/fee.1426

Gurung, J., Mwanundu, S., Lubbock, A., Hartl, M. and Firmian, I. (2006). Gender and Desertification: Expanding Roles for Women to Restore Dryland Areas.". International Fund for Agricultural Development (IFAD), Romer, http://www.ifad.org/pub/gender/desert/gender_desert.pdf

Gutterman, A.S. (2022). Intersectionality, Climate Change and Climate Justice. Available at SSRN 4306987. http://dx.doi.org/10.2139/ssrn.4306987

Habibullah, M.S., Din, B.H., Tan, S.-H. and Zahid, H. (2022). Impact of climate change on biodiversity loss: global evidence. Environmental Science and Pollution Research 29(1), 1073-1086. https://doi.org/10.1007/s11356-021-15702-8

Hallegatte, S., Rozenberg, J., Rentschler, J., Nicolas, C., and Fox, C. (2019). Strengthening New Infrastructure Assets- A Cost-Benefit Analysis. Retrieved from https://documents1.worldbank.org/curated/en/962751560793977276/pdf/Strengthening-New-Infrastructure-Assets-A-Cost-Benefit-Analysis.pdf

Han, Q., Kumar, R. and Kumar, D. (2024). Climate change and human migration: Perspectives for environmentally sustainable societies. Journal of Geochemical Exploration 256, 107352. https://doi.org/10.1016/j.gexplo.2023.107352

He, M., Xu, Z., Hou, D., Gao, B., Cao, X., Ok, Y. S., ... & Tsang, D. C. (2022). Waste-Derived Biochar for Water Pollution Control and Sustainable Development. Nature Reviews Earth & Environment, no. 3 (7) (2022): 444-60. https://doi.org/10.1038/s43017-022-00306-8

Heal, G. (2009). The economics of climate change: a post-stern perspective. Climatic Change 96(3), 275-297. https://doi.org/10.1007/s10584-009-9641-z

Health Effects Institute. (2024). State of Global Air 2024. Boston: Health Effects Institute. https://www.stateofglobalair.org/resources/report/state-global-air-report-2024

Hermans, K. and McLeman, R. (2021) Climate Change, Drought, Land Degradation and Migration: Exploring the Linkages. Current Opinion in Environmental Sustainability, 50, 236-244. https://doi.org/10.1016/j.cosust.2021.04.013

Heywood, V.H. (2013). Overview of agricultural biodiversity and its contribution to nutrition and health. In Diversifying food and diets. Routledge. 35-67. https://www.taylorfrancis.com/chapters/edit/10.4324/9780203127261-4/overview-agricultural-biodiversity-contribution-nutrition-health-vernon-heywood

Hickel, J. and Kallis, G. (2020). Is green growth possible? New political economy 25(4), 469-486. https://doi.org/10.1080/13563467.2019.1598964

Hickel, J., Kallis, G., Jackson, T., O'neill, D.W., Schor, J.B., Steinberger, J.K. et al. (2022). Degrowth can work—here's how science can help. Nature 612(7940), 400-403. https://www.nature.com/articles/d41586-022-04412-x

Hill, R., Harkness, P., Raisbeck-Brown, N., Lyons, I., Álvarez-Romero, J.G., Kim, M.K. et al. (2022). Learning together for and with the Martuwarra Fitzroy River. Sustainability Science 17(2), 351-375. https://doi.org/10.1007/s11625-021-00988-x

Hoffmann, S. (2022). Challenges and opportunities of area-based conservation in reaching biodiversity and sustainability goals. Biodiversity and Conservation 31(2), 325-352. https://doi.org/10.1007/s10531-021-02340-2

Hossain, A., Knorr, G., Lohmann, G., Stärz, M., Jokat, W. (2020). Climate model results of Fram Strait and Greenland-Scotland Ridge gateway sensitivity studies of COSMOS, PANGAEA. https://doi.org/10.1594/PANGAEA.915548

Houlden, V., Jani, A., and Hong, A. (2021). Is biodiversity of greenspace important for human health and wellbeing? A bibliometric analysis and systematic literature review. Urban Forestry & Urban Greening, 66, 127385. https://doi.org/10.1016/j.ufug.2021.127385

Hoyle, H., Jorgensen, A. and Hitchmough, J.D. (2019). What determines how we see nature? Perceptions of naturalness in designed urban green spaces. People and nature 1(2), 167-180. https://doi.org/10.1002/pan3.19

Hu, C., Shui, B., Yang, X., Wang, L., Dong, J., & Zhang, X. (2021). Trophic transfer of heavy metals through aquatic food web in a seagrass ecosystem of Swan Lagoon, China. The Science of the total environment, 762, 143139. https://doi.org/10.1016/j.scitotenv.2020.143139

Hung, H., Halsall, C., Ball, H., Bidleman, T., Dachs, J., De Silva, A. et al. (2022). Climate change influence on the levels and trends of persistent organic pollutants (POPs) and chemicals of emerging Arctic concern (CEACs) in the Arctic physical environment–a review. Environmental Science: Processes & Impacts 24(10), 1577-1615. https://doi.org/10.1039/D1EM00485A

Hunter, L.M. and Simon, D.H. (2021). Environmental Demography. Handbook of Environmental Sociology, 405-423. https://doi.org/10.1007/978-3-030-77712-8_19

Hussain, R. I., Walcher, R., Eder, R., Allex, B., Wallner, P., Hutter et al. (2019). Management of mountainous meadows associated with biodiversity attributes, perceived health benefits and cultural ecosystem services. Scientific Reports, 9(1), 14977. https://doi.org/10.1038/s41598-019-51571-5

ICCA Consortium. 2021. Territories of Life: 2021 Report. ICCA Consortium: worldwide. https://report.territoriesoflife.org/wp-content/uploads/2021/09/ICCA-Territories-of-Life-2021-Report-FULL-150dpi-ENG.pdf

Iizumi, T., Shen, Z., Furuya, J., Koizumi, T., Furuhashi, G., Kim, W. et al. (2020). Climate change adaptation cost and residual damage to global crop production. Climate Research 80(3), 203-218. https://doi.org/10.3354/cr01605

In, S.Y., Manav, B., Venereau, C.M. and Weyant, J.P. (2022). Climate-related financial risk assessment on energy infrastructure investments. Renewable and Sustainable Energy Reviews 167, 112689. https://doi.org/10.1016/j.rser.2022.112689

Independent Group of Scientists appointed by the Secretary-General. (2023). Global Sustainable Development Report 2023: Times of crisis, times of change: Science for accelerating transformations to sustainable development. New York: United Nations. https://sdgs.un.org/sites/default/files/2023-09/FINAL%20GSDR%202023-Digital%20-110923_1.pdf

Institute for Economics and Peace (2020). IEP: Over one billion people at threat of being displaced by 2050 due to environmental change, conflict and civil unrest. https://www.prnewswire.com/news-releases/iep-over-one-billion-people-at-threat-of-being-displaced-by-2050-due-to-environmental-change-conflict-and-civil-unrest-301125350.html

Intergovernmental Panel on Climate Change. (2018). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. https://www.ipcc.ch/sr15/

Intergovernmental Panel on Climate Change. (2019). Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. https://www.ipcc.ch/site/assets/uploads/2019/11/SRCCL-Full-Report-Compiled-191128.pdf

Intergovernmental Panel on Climate Change. (2022). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A. et al. (eds.). Cambridge University Press. https://doi.org/10.1017/9781009325844

Intergovernmental Panel on Climate Change (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115. https://www.ipcc.ch/report/ar6/syr/

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Brondizio, E.S., Settele, J., Díaz, S. and T., N.H. (eds.). Bonn, Germany: IPBES secretariat. https://doi.org/10.5281/zenodo.3831673

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. (2022). Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Balvanera, P., Pascual, U., Christie, M., Baptiste, B. and González-Jiménez, D. (eds.). Bonn, Germany: IPBES secretariat. https://doi.org/10.5281/zenodo.6522522

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. (2024). Summary for Policymakers of the Thematic Assessment Report on the Underlying Causes of Biodiversity Loss and the Determinants of Transformative Change and Options for Achieving the 2050 Vision for Biodiversity of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. O'Brien, K., Garibaldi, L., Agrawal, A., Bennett, E., Biggs, O., Calderón Contreras, R., Carr, E., Frantzeskaki, N., Gosnell, H., Gurung, J., Lambertucci, S., Leventon, J., Liao, C., Reyes García, V., Shannon, L., Villasante, S., Wickson, F., Zinngrebe, Y., and Perianin, L. (eds.). IPBES Secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.11382230

International Labour Organization. (2018a). The employment impact of climate change adaptation. Input Document for the G20 Climate Sustainability Working Group. Geneva: ILO. https://www.ilo.org/sites/default/files/wcmsp5/groups/public/@ed_emp/documents/publication/wcms_645572.pdf

International Labour Organization. (2018b). World Employment and Social Outlook 2018: Greening with jobs. Geneva: ILO. https://webapps.ilo.org/weso-greening/documents/WESO_Greening_EN_web2.pdf

International Labour Organization. (2019). Working on a warmer planet: the impact of heat stress on labour productivity and decent work. International Labour Office Geneva, https://www.ilo.org/wcmsp5/groups/public/---dgreports/---dcomm/---publ/documents/publication/wcms_711919.pdf

International Union for Conservation of Nature and Natural Resources. (2021). Marine Plastic Pollution. IUCN issues briefs. https://iucn.org/sites/default/files/2023-11/marine-plastic-pollution-issues-brief_nov21-nov-2023-correction.pdf

Islam, M. J., Kunzmann, A., & Slater, M. J. (2022). Responses of aquaculture fish to climate change-induced extreme temperatures: A review. Journal of the World Aquaculture Society, 53(2), 314–366. https://doi.org/10.1111/jwas.12853

Izutsu, T., Tsutsumi, A., Lu, X., Hashimoto, J., Allotey, P., Dakkak, H. et al. (2019). Disability-inclusive disaster risk reduction and humanitarian action: An urgent global imperative. United Nations World Conference on Disaster Risk Reduction and the Progress Thereafter. https://www.un.org/development/desa/disabilities/wp-content/uploads/sites/15/2020/03/Final-Disability-inclusive-disaster.pdf

Jackson, T. (2016). Prosperity without growth: Foundations for the economy of tomorrow. Routledge. https://doi.org/10.4324/9781315677453

Jactel, Hervé & Koricheva, Julia & Castagneyrol, Bastien. (2019). Responses of forest insect pests to climate change: not so simple. Current Opinion in Insect Science. 35. https://doi.org/10.1016/j.cois.2019.07.010

Jing, R., Heft-Neal, S., Wang, Z., Chen, J., Qiu, M., Opper, I. et al. (2024). Loss of Schooling from Tropical Cyclones: Evidence from 13 Low-and Middle-income Countries. https://doi.org/10.26300/cm2h-ns20

Joseph, D.D. and Doon, R.A. (2023). The Social and Economic Inequalities of Climate Change Events on the Elderly, Disabled and Homeless Societies in the Caribbean. The Impact of Climate Change on Vulnerable Populations, 5. https://library.oapen.org/bitstream/handle/20.500.12657/85272/1/external_content.pdf#page=20

Jungwiwattanaporn, M., McKinney, R., Wozniak, E. and Songco, A.M. (2023). Ocean ecosystem degradation and human populations. Oceans and Human Health, 243-264. https://doi.org/10.1016/B978-0-323-95227-9.00006-3

Juran, L., and Trivedi, J. (2015). Women, gender norms, and natural disasters in Bangladesh. Geographical Review (105 (4)), 601-611. https://doi.org/10.1111/j.1931-0846.2015.12089.x

Kaczan, D.J. and Orgill-Meyer, J. (2020). The impact of climate change on migration: a synthesis of recent empirical insights. Climatic Change 158(3-4), 281-300. https://doi.org/10.1007/s10584-019-02560-0

Kang, Y., Khan S. and Ma, X. (2009). Climate Change Impacts on Crop Yield, Crop Water Productivity and Food Security—A Review. Progress in Natural Science, 19, 1665-1674. https://doi.org/10.1016/j.pnsc.2009.08.001

Kang, J., Fabbre, V.D. and Ekenga, C.C. (2019). Let's talk about the real issue: Localized perceptions of environment and implications for ecosocial work practice. Journal of Community Practice 27(3-4), 317-333. https://doi.org/10.1080/10705422.2019.1657218

Kapeller, R., Bügelmayer-Blaschek, M., Herndler, B., Kranzl, L., Müller, A., Moser, S. et al. (2024). The effects of climate change-induced cooling demand on power grids. Energy Reports 11, 674-691. https://doi.org/10.1016/j.egyr.2023.07.028

Katumo D., Huan Liang, Anne Christine Ochola, Min Lv, Qing-Feng Wang, Chun-Feng Yang. (2022). Pollinator diversity benefits natural and agricultural ecosystems, environmental health, and human welfare. Plant Diversity 44 (5), 429-435. https://doi.org/10.1016/j.pld.2022.01.005

Kelkar, G. and Nathan, D. (2021). Cultural and Economic Barriers in Switching to Clean Cooking Energy: Does Women's Agency Make a Difference? Energies 14(21), 7242. https://doi.org/10.3390/en14217242

Kelly, D. and Woods, C. (2021). Ethical indigenous economies. Engaged Scholar Journal 7(1), 140-158. https://doi.org/10.15402/esj.v7i1.70010

Key, R., Parrado, R., Delpiazzo, E., King, R. and Bosello, F. (2024). Potential climate-induced impacts on trade: the case of agricultural commodities and maritime chokepoints. Journal of Shipping and Trade 9(1), 11. https://doi.org/10.1186/s41072-024-00170-3

Khine, M.M. and Langkulsen, U. (2023). The Implications of Climate Change on Health among Vulnerable Populations in South Africa: A Systematic Review. International Journal of Environmental Research and Public Health 20(4), 3425. https://doi.org/10.3390/ijerph20043425

Khoday, K. (2021). Decolonizing the environment: Third World approaches to the planetary crisis. Indonesian J. Int'l L. 19, 189. https://doi.org/10.17304/ijil.vol19.2.1

Kibria, G., Nugegoda, D., Rose, G. and Haroon, A.Y. (2021). Climate change impacts on pollutants mobilization and interactive effects of climate change and pollutants on toxicity and bioaccumulation of pollutants in estuarine and marine biota and linkage to seafood security. Marine Pollution Bulletin 167, 112364. https://doi.org/10.1016/j.marpolbul.2021.112364

Kimerling, J. (2012). Huaorani land rights in Ecuador: Oil, contact, and conservation. Environmental Justice 5(5), 236-251. https://doi.org/10.1089/env.2011.0034

Klaproth, F. (2023). Indigenous Communities and Climate Change: Portrayal of Environmental (In) justice in Indigenous and Mainstream Media in the US. Ohio University. https://etd.ohiolink.edu/acprod/odb_etd/etd/r/1501/10?clear=10&p10_accession_num=ohiou1671778885659256

Kolahi, M. and Payeste, M. (2020). Impacts of natural resource projects on socioeconomic issues of villagers at ChahNouroz watershed. Journal of Watershed Management Research 11(21), 154-164. https://doi.org/10.52547/jwmr.11.21.154

Kroll, C., Warchold, A. and Pradhan, P. (2019). Sustainable Development Goals (SDGs): Are we successful in turning trade-offs into synergies? Palgrave Communications 5(1). https://doi.org/10.1057/s41599-019-0335-5

Kumar, G. and Reddy, K.R. (2020). Addressing climate change impacts and resiliency in contaminated site remediation. Journal of Hazardous, Toxic, and Radioactive Waste 24(4), 04020026. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000515

Kumar, L., Chhogyel, N., Gopalakrishnan, T., Hasan, M.K., Jayasinghe, S.L., Kariyawasam, C.S. et al. (2022). Climate change and future of agri-food production. In Future foods. Elsevier. 49-79. https://doi.org/10.1016/B978-0-323-91001-9.00009-8

Kumari R.K., Sherbinin, A., Jones, B., Bergmann, J., Clement, V., Ober, K. et al. (2018). Groundswell: Preparing for Internal Climate Migration. Washington, DC: The World Bank. https://documents1.worldbank.org/curated/en/401511522303177090/pdf/124722-BRI-PUBLIC-NEWSERIES-Groundswell-note-PN2.pdf#:~:text=The%20report%20Groundswell:%20Preparing%20for%20Internal%20Climate,forced%20to%20move%20within%20their%20own%20countries

Kumeh, Eric Mensah & Bieling, Claudia & Birner, Regina. (2022). Food-security corridors: A crucial but missing link in tackling deforestation in Southwestern Ghana. Land Use Policy, Elsevier. 112. https://doi.org/10.1016/j.landusepol.2021.105862

Laan, C.M. and Piersma, N. (2021). Accessibility of green areas for local residents. Environmental and Sustainability Indicators 10, 100114. https://doi.org/10.1016/j.indic.2021.100114

Lachmann, F., Carney Almroth, B., Baumann, H., Broström, G., Corvellec, H., Gipperth, L. et al. (2017). Marine plastic litter on Small Island Developing States (SIDS): Impacts and measures. http://dx.doi.org/10.13140/RG.2.2.16168.37121

Landrigan, P.J., Fuller, R., Fisher, S., Suk, W.A., Sly, P., Chiles, T.C. et al. (2019). Pollution and children's health. Science of The Total Environment 650, 2389-2394. https://doi.org/10.1016/j.scitotenv.2018.09.375

Langer, M., von Deimling, T.S., Westermann, S., Rolph, R., Rutte, R., Antonova, S. et al. (2023). Thawing permafrost poses an environmental threat to thousands of sites with legacy industrial contamination. Nature Communications (14(1)), 1721. https://doi.org/10.1038/s41467-023-37276-4

Lario, A. (2022). Small-scale farmers feed the planet. They should not be overlooked in our fight against climate change. [World Economic Forum https://www.weforum.org/agenda/2022/11/the-vital-role-of-small-scale-farmers-climate-change

Lawrence, M., Homer-Dixon, T., Janzwood, S., Rockström, J., Renn, O. and Donges, J.F. (2024). Global polycrisis: the causal mechanisms of crisis entanglement. Global Sustainability 7, e6. https://doi.org/10.1017/sus.2024.1

Lebu, S., Gyimah, R., Nandoya, E., Brown, J., Salzberg, A. and Manga, M. (2024). Assessment of sanitation infrastructure resilience to extreme rainfall and flooding: Evidence from an informal settlement in Kenya. Journal of Environmental Management 354, 120264. https://doi.org/10.1016/j.jenvman.2024.120264

Leichenko, R. and Silva, J.A. (2014). Climate change and poverty: vulnerability, impacts, and alleviation strategies. Wiley Interdisciplinary Reviews: Climate Change 5(4), 539-556. https://doi.org/10.1002/wcc.287

Le Maitre, D. C., Máguas, C., Ulm, F., and Marchante, H. (2023). Ecological impacts and changes in ecosystem services and disservices mediated by invasive Australian Acacia species. In Wattles: Australian Acacia Species around the World (pp. 342-358). https://doi.org/10.1079/9781800622197.0022

Li, Y., Jin, H., Wen, Z., Li, X. and Zhang, Q. (2021). Stability of the foundation of buried energy pipeline in permafrost region. Geofluids 2021(1), 3066553. https://doi.org/10.1155/2021/3066553

Li, Z., Ma, W., Zhong, D., Ma, J., Zhang, Q., Yuan, Y. et al. (2024). Applications of machine learning in drinking water quality management: A critical review on water distribution system. Journal of Cleaner Production 481, 144171. https://doi.org/10.1016/j.jclepro.2024.144171

Lin, B.B. (2011). Resilience in agriculture through crop diversification: adaptive management for environmental change. BioScience 61(3), 183-193. https://doi.org/10.1525/bio.2011.61.3.4

Lin, B.B., Melbourne-Thomas, J., Hopkins, M., Dunlop, M., Macgregor, N.A., Merson, S.D. et al. (2023). Holistic climate change adaptation for World Heritage. Nature Sustainability, 1-9. https://doi.org/10.1038/s41893-023-01153-1

Lin, T., Cao, X., Huang, N., Xu, L., Li, X., Zhao, Y. et al. (2021). Social cognition of climate change in coastal community: A case study in Xiamen City, China. Ocean & Coastal Management 207, 104429. https://doi.org/10.1016/j.ocecoaman.2018.02.025

Lin, T., Gibson, V., Cui, S., Yu, C.-P., Chen, S., Ye, Z. et al. (2014). Managing urban nutrient biogeochemistry for sustainable urbanization. Environmental Pollution 192, 244-250. https://doi.org/10.1016/j.envpol.2014.03.038

Lincoln, S., Chowdhury, P., Posen, P.E., Robin, R.S., Ramachandran, P., Ajith, N. et al. (2023). Interaction of climate change and marine pollution in Southern India: Implications for coastal zone management practices and policies. Science of The Total Environment 902, 166061. https://doi.org/10.1016/j.scitotenv.2023.166061

Lindemann-Matthies, P. and Matthies, D. (2018). The influence of plant species richness on stress recovery of humans. Web Ecology 18(2), 121-128. https://doi.org/10.5194/we-18-121-2018

Lindvall, D. (2021). Democracy and the challenge of climate change. IDEA Publications. https://doi.org/10.31752/idea.2021.88

Liu, X. and Desai, A.R. (2021). Significant reductions in crop yields from air pollution and heat stress in the United States. Earth's Future 9(8). https://doi.org/10.1029/2021EF002000. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2021EF002000

Liu, D., Kwan, M.-P. and Kan, Z. (2021). Analysis of urban green space accessibility and distribution inequity in the City of Chicago. Urban forestry & urban greening 59, 127029. https://doi.org/10.1016/j.ufug.2021.127029

Liu, F., Huang, Y., Zhang, L. and Li, G. (2022). Marine environmental pollution, aquatic products trade and marine fishery Economy—An empirical analysis based on simultaneous equation model. Ocean & Coastal Management 222, 106096. https://doi.org/10.1016/j.ocecoaman.2022.106096

Lu, Y., Song, S., Wang, R., Liu, Z., Meng, J., Sweetman, A.J. et al. (2015). Impacts of soil and water pollution on food safety and health risks in China. Environment International 77, 5-15. https://doi.org/10.1016/j.envint.2014.12.010

Langer, M., Von Deimling, T.S., Westermann, S., Rolph, R., Rutte, R., Antonova, S. et al. (2023). Thawing permafrost poses environmental threat to thousands of sites with legacy industrial contamination. Nature communications 14(1), 1721. https://doi.org/10.1038/s41467-023-37276-4

Lorek, S. and Fuchs, D. (2013). Strong sustainable consumption governance–precondition for a degrowth path? Journal of Cleaner Production 38, 36-43. https://doi.org/10.1016/j.jclepro.2011.08.008

MacAfee, E.A. and Löhr, A.J. (2024). Multi-scalar interactions between mismanaged plastic waste and urban flooding in an era of climate change and rapid urbanization. Wiley Interdisciplinary Reviews: Water 11(2), e1708. https://doi.org/10.1002/wat2.1708

Manoli, G., Fatichi, S., Schläpfer, M. et al. Magnitude of urban heat islands largely explained by climate and population. Nature 573, 55–60 (2019). https://doi.org/10.1038/s41586-019-1512-9

Marcharla, E., Vinayagam, S., Gnanasekaran, L., Soto-Moscoso, M., Chen, W.-H., Thanigaivel, S. et al. (2024). Microplastics in Marine Ecosystems: A Comprehensive Review of Biological and Ecological Implications and its mitigation approach using nanotechnology for the sustainable environment. Environmental Research, 119181. https://doi.org/10.1016/j.envres.2024.119181

Marí-Dell'Olmo, M., Oliveras, L., Barón-Miras, L.E., Borrell, C., Montalvo, T., Ariza, C. et al. (2022). Climate change and health in urban areas with a Mediterranean climate: a conceptual framework with a social and climate justice approach. International Journal of Environmental Research and Public Health 19(19), 12764. https://doi.org/10.3390/ijerph191912764

Marques, A., Martins, I.S., Kastner, T., Plutzar, C., Theurl, M.C., Eisenmenger, N. et al. (2019). Increasing impacts of land use on biodiversity and carbon sequestration driven by population and economic growth. Nature ecology & evolution 3(4), 628-637. https://doi.org/10.1038/s41559-019-0824-3

Martyr-Koller, R., Thomas, A., Schleussner, C.-F., Nauels, A. and Lissner, T. (2021). Loss and damage implications of sea-level rise on Small Island Developing States. Current opinion in environmental sustainability 50, 245-259. https://doi.org/10.1016/j.cosust.2021.05.001

Mateo-Sagasta, J., Zadeh, S. M., Turral, H. and Burke, J. (2017) Water pollution from agriculture: a global review. Executive summary. Rome, Italy: FAO; Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE). https://hdl.handle.net/10568/88070

Mateo-Sagasta, J., Marjani Zadeh, S. and Turral, H. (2018) More people, more food, worse water? a global review of water pollution from agriculture. FAO. https://openknowledge.fao.org/server/api/core/bitstreams/686ea465-7847-428e-b599-b236f2240e47/content

Matsushita, K. et al. (2023). Integrated Approach for Well-Being, Environmental Sustainability, and Just Transition, Think7 Issue Paper. https://www.think7.org/publication/integrated-approach-for-well-being-environmental-sustainability-and-just-transition/

Mavoa, S., Lucassen, M., Denny, S., Utter, J., Clark, T. and Smith, M. (2019). Natural neighbourhood environments and the emotional health of urban New Zealand adolescents. Landscape and urban planning 191, 103638. https://doi.org/10.1016/j.landurbplan.2019.103638

McAdam, J. (2012). Climate change, forced migration, and international law. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199587087.001.0001

Mbow C., C. Rosenzweig, L.G. Barioni, T.G. Benton, M. Herrero, M. Krishnapillai, E. et al. (2019). Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems (2019). https://www.ipcc.ch/srccl/

McDowell, N., Pockman, W.T., Allen, C.D., Breshears, D.D., Cobb, N., Kolb, T. et al. (2008). Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? New Phytologist 178(4), 719-739. https://doi.org/10.1111/j.1469-8137.2008.02436.x

McMichael, A., Campbell-Lendrum, D., Kovats, R.S., Nicholls, R., Edwards, S., Wilkinson, P. et al. (2004). Global climate change. https://eprints.soton.ac.uk/53057/

Mead, L. (2021) Small islands, large oceans: voices on the frontlines of climate change. International Institute for Sustainable Development. Published March 29 2021. https://www.iisd.org/articles/deep-dive/small-islands-large-oceans-voices-frontlines-climate-change. Accessed 22 March 2025.

Mentaschi, L., Vousdoukas, M.I., Pekel, JF. et al. (2018). Global long-term observations of coastal erosion and accretion. Sci Rep 8, 12876. https://doi.org/10.1038/s41598-018-30904-w

Mianabadi, A., Davary, K., Kolahi, M. and Fisher, J. (2022). Water/climate nexus environmental rural-urban migration and coping strategies. Journal of Environmental Planning and Management 65(5), 852-876. https://doi.org/10.1080/09640568.2021.1915259

Millenium Assessment (2005). Chapter 2: Ecosystems and Human Well-being: A Framework for Assessment. https://www.millenniumassessment.org/documents/document.300.aspx.pdf

Milton, L. (2023). Squeezing Us Dry: How The Fashion Industry Pollutes Water. Sustainably Chic https://www.sustainably-chic.com/blog/how-the-fashion-industry-pollutes-water

Miner, K.R., D'Andrilli, J., Mackelprang, R., Edwards, A., Malaska, M.J., Waldrop, M.P. and Miller, C.E. (2021). Emergent biogeochemical risks from Arctic permafrost degradation. Nature Climate Change (11(10)), 809-819. https://doi.org/10.1038/s41558-021-01162-y

Minoli, S., Jägermeyr, J., Asseng, S., Urfels, A. and Müller, C. (2022). Global crop yields can be lifted by timely adaptation of growing periods to climate change. Nature communications 13(1), 7079. https://doi.org/10.1038/s41467-022-34411-5

Mirón I.J, Linares,C. and Díaz, J. (2023). The influence of climate change on food production and food safety. Environmental Research 216, Part 3, 114674. https://doi.org/10.1016/j.envres.2022.114674

Mirzabaev, A., et al. (2023). Severe climate change risks to food security and nutrition. Climate Risk Management 39. https://doi.org/10.1016/j.crm.2022.100473

Mishra, S.K., Wang, H. (2021). Computational Analysis Predicts Hundreds of Coding lncRNAs in Zebrafish. Biology. 10(5). https://doi.org/10.3390/biology10050371

Mishra, R. K. (2023). Fresh Water availability and Its Global challenge. British Journal of Multidisciplinary and Advanced Studies, 4(3), 1–78. https://doi.org/10.37745/bjmas.2022.0208

Mizen, A., Lyons, J., Milojevic, A., Doherty, R., Wilkinson, P., Carruthers, D., Akbari, A. et al. (2020). Impact of air pollution on educational attainment for respiratory health treated students: A cross sectional data linkage study. Health & Place 63. https://doi.org/10.1016/j.healthplace.2020.102355

Mohai, P. and Saha, R. (2015). Which came first, people or pollution? A review of theory and evidence from longitudinal environmental justice studies. Environmental research letters 10(12), 125011. https://doi.org/10.1088/1748-9326/10/12/125011

Monsanto, M., Kohler, P., Binetti, U., Silburn, B., Russell, J., Corbin, C. et al. (2023). A Blue Future: developing a national marine litter action plan in SIDS—lessons learnt in Belize. ICES Journal of Marine Science 80(8), 2171-2182. https://doi.org/10.1093/icesjms/fsac206

Mooney, H., Larigauderie, A., Cesario, M., Elmquist, T., Hoegh-Guldberg, O., Lavorel, S., Mace, G. M., Palmer, M., Scholes, R., & Yahara, T. (2009). Biodiversity, climate change, and ecosystem services. Current Opinion in Environmental Sustainability, 1(1), 46-54. https://doi.org/10.1016/j.cosust.2009.07.006

Moradi, A. and Kolahi, M. (2020). Sustainable rurality in the Mousa Abad watershed of Torbat Jam County. Environmental Sciences 18(4), 183-202. https://doi.org/10.52547/ENVS.18.4.183

Mori, H., Takahashi, Y., Zusman, E., Mader, A., Kawazu, E., Otsuka, T. et al. (2021). Implications of COVID-19 for the Environment and Sustainability. Hayama, Japan: Institute for Global Environmental Strategies. Available at: https://www.iges.or.jp/en/pub/covid19-e/en

Muttarak, R., Lutz, W. (2014). Is education a key to reducing vulnerability to natural disasters and hence unavoidable climate change? Ecology and Society 42(19(1). https://www.jstor.org/stable/26269470

Nadal, M., Marquès, M., Mari, M., & Domingo, J. L. (2015). Climate change and environmental concentrations of POPs: A review. Environmental research, 143(Pt A), 177–185. https://doi.org/10.1016/j.envres.2015.10.012

Naidu, R., Biswas, B., Willett, I. R., Cribb, J., Kumar Singh, B., Paul Nathanail, C., Coulon, F. et al. (2021). Chemical pollution: A growing peril and potential catastrophic risk to humanity. Environment international, 156, 106616. https://doi.org/10.1016/j.envint.2021.106616

Nair, N. and Nayak, P. (2023). Exploring Water Quality as a Determinant of Small-Scale Fisheries Vulnerability. Sustainability. 15. 13238. https://doi.org/10.3390/su151713238

Naorem, A., Jayaraman, S., Dang, Y.P., Dalal, R.C., Sinha, N.K., Rao, C.S. et al. (2023). Soil constraints in an arid environment—challenges, prospects, and implications. Agronomy 13(1), 220. https://doi.org/10.3390/agronomy13010220

Newman, R. and Noy, I. (2023). The global costs of extreme weather that are attributable to climate change. Nature communications 14(1), 6103. https://doi.org/10.1038/s41467-023-41888-1

Nkuba, M. R., Chanda, R., Mmopelwa, G., Mangheni, M. N., Lesolle, D., & Kato, E. (2020). Indigenous knowledge systems and indicators of rain: evidence from Rwenzori Region, Western Uganda. Weather, Climate, and Society, 12(2), 213-234. https://cgspace.cgiar.org/items/2fc6132a-5571-4b52-b3d0-4bcc5cfed227

Nyahunda, L., Makhubele, J.C., Mabvurira, V. and Matlakala, F.K. (2021). Vulnerabilities and inequalities experienced by women in the climate change discourse in South Africa's rural communities: implications for social work. The British Journal of Social Work 51(7), 2536-2553. https://doi.org/10.1093/bjsw/bcaa118

Obahoundje, S. and Diedhiou, A. (2022). Potential impacts of climate, land use and land cover changes on hydropower generation in West Africa: a review. Environmental Research Letters 17(4), 043005. https://doi.org/10.1088/1748-9326/ac5b3b

Oh, J., Hevia-Ramos, G., Ha, E., Hong, Y.-C., Kim, H. and Lim, Y.-H. (2025). A Systematic Review and Meta-Analysis on Long-Term Exposure to Particulate Matter and All-Cause and Cause-Specific Mortality in the Asia-Pacific States. J Korean Med Sci 40(27). https://doi.org/10.3346/jkms.2025.40.e156

Onyeaka, H., Ghosh, S., Obileke, K., Miri, T., Odeyemi, O.A., Nwaiwu, O. et al. (2023). Preventing chemical contaminants in food: Challenges and prospects for safe and sustainable food production. Food Control 155, 110040. https://doi.org/10.1016/j.foodcont.2023.110040

Oreffice, S. and Sansone, D. (2022). Transportation to work by sexual orientation. PloS one 17(2), e0263687. https://doi.org/10.1371/journal.pone.0263687

Organisation for Economic Co-operation and Development. (2023). The Gender Equality and Environment Intersection. https://doi.org/10.1787/c16d8fe8-en

Outhwaite, C.L., McCann, P. and Newbold, T. (2022). Agriculture and climate change are reshaping insect biodiversity worldwide. Nature 605(7908), 97-102. https://doi.org/10.1038/s41586-022-04644-x

Ozturk, U., Bozzolan, E., Holcombe, E.A., Shukla, R., Pianosi, F. and Wagener, T. (2022). How climate change and unplanned urban sprawl bring more landslides. Nature 608(7922), 262-265. https://www.nature.com/articles/d41586-022-02141-9

Oxenford, H. and Monnereau, I. (2017). Impacts of Climate Change on Fish and Shellfish in the Coastal and Marine Environments of Caribbean Small Island Developing States (SIDS). Science Review. 83-114. https://assets.publishing.service.gov.uk/media/5a820ce7e5274a2e87dc0e2e/8._Fish_and_Shellfish.pdf

Özdemir, E.T. (2019). Investigations of a Southerly Non-Convective High Wind Event in Turkey and Effects on PM10 Values: A Case Study on April 18, 2012. Pure and Applied Geophysics 176(10), 4599-4622. https://doi.org/10.1007/s00024-019-02240-1

Pacheco, F.A.L., Fernandes, L.F.S., Junior, R.F.V., Valera, C.A. and Pissarra, T.C.T. (2018). Land degradation: Multiple environmental consequences and routes to neutrality. Current Opinion in Environmental Science & Health 5, 79-86. https://doi.org/10.1016/j.coesh.2018.07.002

Panwar, V., Noy, I., Wilkinson, E., & Corbett, J. (2023). The Costs of Inaction: Calculating climate change-related loss and damage from extreme weather in Small Island Developing States. Overseas Development Institute (ODI). https://odi.org/en/publications/calculating-loss-and-damage-from-extreme-weather-in-sids/

Park Y.S., Konge L. and Artino A.R. Jr. (2020). The Positivism Paradigm of Research. Acad Med. 95(5):690-694. https://doi.org/10.1097/acm.0000000000003093

Parrique T., Barth J., Briens F., C. Kerschner, Kraus-Polk A., Kuokkanen A. and Spangenberg J.H. (2019). Decoupling Debunked: Evidence and Arguments against Green Growth as a Sole Strategy for Sustainability. European Environmental Bureau. https://eeb.org/wp-content/uploads/2019/07/Decoupling-Debunked.pdf

Pérez-Lucas, G., Navarro, G. and Navarro, S. (2024). Adapting agriculture and pesticide use in Mediterranean regions under climate change scenarios: A comprehensive review. European Journal of Agronomy 161, 127337. https://doi.org/10.1016/j.eja.2024.127337

Persico, C. (2019) How exposure to pollution affects educational outcomes and inequality. Brookings, 20 November 2019. Accessed 1 July 2025. https://www.brookings.edu/articles/how-exposure-to-pollution-affects-educational-outcomes-and-inequality/

Pimentel, D. (2006). Soil erosion: a food and environmental threat. Environment, Development and Sustainability 8, 119-137. https://doi.org/10.1007/s10668-005-1262-8

Pickson, R.B., Boateng, E., Gui, P. and Chen, A. (2024) The impacts of climatic conditions on cereal production: implications for food security in Africa. Environ Dev Sustain 26, 18333–18360. https://doi.org/10.1007/s10668-023-03391-x

Pirali Zefrehei, A.R., Kolahi, M. and Fisher, J. (2022a). Ecological-environmental challenges and restoration of aquatic ecosystems of the Middle-Eastern. Scientific reports 12(1), 17229. https://doi.org/10.1038/s41598-022-21465-0

Pirali Zefrehei, A.R., Kolahi, M. and Fisher, J. (2022b). Evaluation of Zayandehroud basin health in the Iranian plateau. Aquatic Sciences 84(4), 64. https://doi.org/10.1007/s00027-022-00896-x

Potapowicz, J., Szumińska, D., Szopińska, M. and Polkowska, Ż. (2019). The influence of global climate change on the environmental fate of anthropogenic pollution released from the permafrost: Part I. Case study of Antarctica. Science of the Total Environment 651, 1534-1548. https://doi.org/10.1016/j.scitotenv.2018.09.168

Pradhan, P., Costa, L., Rybski, D., Lucht, W. and Kropp, J.P. (2017). A systematic study of sustainable development goal (SDG) interactions. Earth's Future 5(11), 1169-1179. https://doi.org/10.1002/2017EF000632.

Prangel, E., Kasari-Toussaint, L., Neuenkamp, L., Noreika, N., Karise, R., Marja, R. et al. (2023). Afforestation and abandonment of semi-natural grasslands lead to biodiversity loss and a decline in ecosystem services and functions. Journal of Applied Ecology, 60, 825–836. https://doi.org/10.1111/1365-2664.14375

Principals for Responsible Investment. (2023). Integrating biodiversity considerations into infrastructure. https://www.unpri.org/infrastructure/integrating-biodiversity-considerations-into-infrastructure/11611.article. Accessed 01 July 2025.

Prosper, K., McMillan, L.J., Davis, A.A. and Moffitt, M. (2011). Returning to Netukulimk. International Indigenous Policy Journal 2(4), 1-17. https://www.jstor.org/stable/48766973

Qin, G., Niu, Z., Yu, J., Li, Z., Ma, J. and Xiang, P. (2021). Soil heavy metal pollution and food safety in China: Effects, sources and removing technology. Chemosphere 267, 129205. https://doi.org/10.1016/j.chemosphere.2020.129205

Qiu, M., Ratledge, N., Azevedo, I.M., Diffenbaugh, N.S. and Burke, M. (2023). Drought impacts on the electricity system, emissions, and air quality in the western United States. Proceedings of the National Academy of Sciences 120(28), e2300395120. https://doi.org/10.1073/pnas.2300395120

Quijano, A. (2000). Coloniality of power and Eurocentrism in Latin America. International sociology 15(2), 215-232. https://doi.org/10.1177/0268580900015002005

Quiroga Eróstegui, C. (2022). Use of and access to land for peaceful transformation: a socio-legal perspective on human rights of indigenous women of the Cochabamba Upper Valley. University of Antwerp https://repository.uantwerpen.be/docstore/d:irua:17876

Rapella, L., Faranda, D., Gaetani, M., Drobinski, P. and Ginesta, M. (2023). Climate change on extreme winds already affects off-shore wind power availability in Europe. Environmental Research Letters 18(3), 034040. https://doi.org/10.1088/1748-9326/acbdb2

Raworth, K. (2012). A safe and just space for humanity: can we live within the doughnut? Oxfam. https://policy-practice.oxfam.org/resources/a-safe-and-just-space-for-humanity-can-we-live-within-the-doughnut-210490/.

Rahbek, C., Borregaard, M.K., Colwell, R.K., Dalsgaard, B., Holt, B.G., Morueta-Holme, N. et al. (2019). Humboldt's enigma: What causes global patterns of mountain biodiversity? Science 365(6458), 1108-1113. https://doi.org/10.1126/science.aax0149

Rees N. Wickham A; Choi Y. (2019). Silent suffocation in Africa air pollution is growing menace affecting the poorest children the most. https://www.Unicef.org/media/55081/file/silent. Accessed 1 July 2025.

Reyes-García, V., García-del-Amo, D., Álvarez-Fernández, S., Benyei, P., Calvet-Mir, L., Junqueira, A.B. et al. (2024). Indigenous Peoples and local communities report ongoing and widespread climate change impacts on local social-ecological systems. Communications earth & environment 5(1), 29. https://doi.org/10.1038/s43247-023-01164-y

Rezaei, E. E., Webber, H., Asseng, S., Boote, K., Durand, J. L., Ewert, F. et al. (2023). Climate change impacts on crop yields. Nature Reviews Earth and Environment, 4(12), 831-846. https://doi.org/10.1038/s43017-023-00491-0

Rigét, F., Bignert, A., Braune, B., Dam, M., Dietz, R., Evans, M. et al. (2019). Temporal trends of persistent organic pollutants in Arctic marine and freshwater biota. Science of the Total Environment 649, 99-100. https://doi.org/10.1016/j.scitotenv.2018.08.268

Rigolon, A., Browning, M.H., McAnirlin, O. and Yoon, H. (2021). Green space and health equity: a systematic review on the potential of green space to reduce health disparities. International Journal of Environmental Research and Public Health 18(5), 2563. https://doi.org/10.3390/ijerph18052563

Rist, L., Norström, A. and and Queiroz, C. (2023). Biosphere Security: Understanding the Connections between Conflict and Biodiversity. https://www.sipri.org/sites/default/files/2023-12/the_stockholm_hub_no_3_biosphere_security.pdf

Robinson, E.A., Ryan, G.D. and Newman, J.A. (2012). A meta-analytical review of the effects of elevated CO2 on plant–arthropod interactions highlights the importance of interacting environmental and biological variables. New Phytologist 194(2), 321-336. https://doi.org/10.1111/j.1469-8137.2012.04074.x

Rocheleau, Dianne E. (2009). Gender and Biodiversity: A Feminist Political Ecology Perspective, IDS Bulletin, Volume 26, No. 1, pp – 9-16.

Rockström, J., Gupta, J., Qin, D., Lade, S.J., Abrams, J.F., Andersen, L.S. et al. (2023). Safe and just Earth system boundaries. Nature 619(7968), 102-111. https://doi.org/10.1038/s41586-023-06083-8

Roe, D., Walpole, M. and Elliott, J. (2010) Summary report of a symposium held at the Zoological Society of London. https://www.iied.org/sites/default/files/pdfs/migrate/G02779.pdf

Rose, K. A., Gutiérrez, D., Breitburg, D., Conley, D., Craig, J. K., Froehlich, H. E. et al. (2019). Impacts of ocean deoxygenation on fisheries. In D. Laffoley & J. M. Baxter (Eds.), Ocean deoxygenation: Everyone's problem – Causes, impacts, consequences and solutions (pp. 519–544). Gland, Switzerland: IUCN. https://portals.iucn.org/library/sites/library/files/documents/10%20DEOX.pdf

Roy, R.N., Finck, A., Blair, G. and Tandon, H. (2006). Plant nutrition for food security. A guide for integrated nutrient management. FAO Fertilizer and Plant Nutrition Bulletin 16(368), 201-214. https://www.fao.org/fileadmin/templates/soilbiodiversity/Downloadable_files/fpnb16.pdf

Rush, J.V. (2018). The Impact of Natural Disasters on Education in Indonesia. Economics of Disasters and Climate Change 137(2 (2), 58. https://doi.org/10.1007/s41885-017-0022-1

Sabbahi, R. (2022). Effects of Climate Change on Insect Pollinators and Implications for Food Security—Evidence and Recommended Actions. The Food Security, Biodiversity, and Climate Nexus. 143-163. https://doi.org/10.1007/978-3-031-12586-7_8

Sachs, J.D., Lafortune, G. and Fuller, G. (2024). The SDGs and the UN Summit of the Future. Sustainable Development Report 2024. https://doi.org/10.25546/108572

Salehi, P., Woodbridge, M. and Arikan, Y. (2017). Land degradation and cities: The essential role of local and regional governments. CLEI Briefing Sheet. https://iclei.org/e-library/land-degradation-and-cities-the-essential-role-of-local-and-regional-governments/.

Salih, A.A.M., Baraibar, M., Mwangi, K.K. et al. (2020). Climate change and locust outbreak in East Africa. Nat. Clim. Chang. 10, 584–585 (2020). https://doi.org/10.1038/s41558-020-0835-8

Sangha, K.K., Russell-Smith, J., Edwards, A.C. and Surjan, A. (2021). Assessing the real costs of natural hazard-induced disasters: A case study from Australia's Northern Territory. Natural hazards 108, 479-498. https://doi.org/10.1007/s11069-021-04692-y

Salameh, E. (2023). Water resources and water services infrastructure and its vulnerability to extreme events—The case of Jordan. Journal of Geoscience and Environment Protection, 11(2), 30–45. https://doi.org/10.4236/gep.2023.112003

Sardar, S. and Bhaduri, S.K. (2022). An exploratory analysis of the differential climate change impact on women in India. Materials Today: Proceedings 60, 827-833. https://doi.org/10.1016/j.matpr.2021.09.418

Saxena, R. (2024). Delhi Smog Sparks Travel Chaos Angering Passengers. Bloomberg. https://www.bloomberg.com/news/articles/2024-01-16/travellers-face-13-hour-delay-flight-diversions-as-smog-blankets-delhi

Scheper, J., Badenhausser, I., Kantelhardt, J., Kirchweger, S., Bartomeus, I., Bretagnolle, V. et al. (2023). Biodiversity and pollination benefits trade off against profit in an intensive farming system. Wageningen University. https://doi.org/10.5061/dryad.j6q573nkr.

Schwarzenbach, R.P., Egli, T., Hofstetter, T.B., Von Gunten, U. and Wehrli, B. (2010). Global Water Pollution and Human Health. Annual Review of Environment and Resources, 35, 109-136. http://dx.doi.org/10.1146/annurev-environ-100809-125342

Schweikert, A., Chinowsky, P., Espinet, X. and Tarbert, M. (2014). Climate Change and Infrastructure Impacts: Comparing the Impact on Roads in ten Countries through 2100. Procedia Engineering 78, 306-316. https://doi.org/10.1016/j.proeng.2014.07.072

Secretariat of the Convention on Biological Diversity. (2010). Linking Biodiversity Conservation and Poverty Alleviation: A State of Knowledge Review. https://www.cbd.int/doc/publications/cbd-ts-55-en.pdf

Secretariat of the Convention on Biological Diversity. (CBD 2020). Global Biodiversity Outlook 5 – Summary for Policy Makers. Montréal, Canada: Secretariat of the Convention on Biological Diversity. https://www.cbd.int/gbo/gbo5/publication/gbo-5-spm-en.pdf

Sejil, R. (2023). Rethinking Refugee Protection: Navigating the Complexities of Humanitarian Crises and the Need for Adaptive Solutions. https://doi.org/10.13140/RG.2.2.30351.56481

Shaheryar, M., Hayat, M., Shah, M.N., Hayat, H.S., Rehman, H.U., Sheryar, A. et al. (2025). Agricultural Pollution and Its Relation to Climate Change. In Bioremediation and Nanotechnology for Climate Change Mitigation. Abdel Latef, A.A.H., Zayed, E.M. and Omar, A.A. (eds.). Singapore: Springer Nature Singapore. 137-155. https://doi.org/10.1007/978-981-96-3069-1_6

Shuai Z., Jiating Z., Lizhong Z. (2024). Predicting removal efficiency of organic pollutants by soil vapor extraction based on an optimized machine learning method. Science of The Total Environment, 927. https://doi.org/10.1016/j.scitotenv.2024.172438

Sikorska, D., Łaszkiewicz, E., Krauze, K. and Sikorski, P. (2020). The role of informal green spaces in reducing inequalities in urban green space availability to children and seniors. Environmental science & policy 108, 144-154. https://doi.org/10.1016/j.envsci.2020.03.007

Singh, D.K. and Tayal, S. (2021). Assessment of regional water demand for coal-based power plants in India: exploring its regional impact on other cross-sectoral water stress. Environmental Monitoring and Assessment 193(8), 503. https://doi.org/10.1007/s10661-021-09298-2

Smith, M.R., Mueller, N.D., Springmann, M., Sulser, T.B., Garibaldi, L.A., Gerber, J. et al. (2022). The lost opportunity from insufficient pollinators for global food supplies and human health. The Lancet Planetary Health 6, S3. https://doi.org/10.1016/S2542-5196(22)00265-0

Spaiser, V., Ranganathan, S., Swain, R.B. and Sumpter, D.J. (2017). The sustainable development oxymoron: quantifying and modelling the incompatibility of sustainable development goals. International Journal of Sustainable Development & World Ecology 24(6), 457-470. https://doi.org/10.1080/13504509.2016.1235624

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M. et al. (2015). Planetary boundaries: Guiding human development on a changing planet. Science 347(6223), 1259855. https://doi.org/10.1126/science.1259855

Stein, P.J. and Stein, M.A. (2022). Climate change and the right to health of people with disabilities. The Lancet Global Health10(1), e24-e25. https://doi.org/10.1016/S2214-109X(21)00542-8

Stern, N. (2007). The economics of climate change: the Stern review. American Economic Review. https://www.aeaweb.org/articles?id=10.1257/aer.98.2.1

Stockholm International Peace Research Institute. (2022). World Military Expenditure Passes $2 Trillion for First Time. https://www.sipri.org/media/press-release/2022/world-military-expenditure-passes-2-trillion-first-time

Sumaila, U.R. and Tai, T.C. (2020). End overfishing and increase the resilience of the ocean to climate change. Frontiers in Marine Science 7, 523. https://doi.org/10.3389/fmars.2020.00523

Summers, K., Lamper, A. and Buck, K. (2021). National hazards vulnerability and the remediation, restoration and revitalization of contaminated sites—1. superfund. Environmental management 67(6), 1029-1042. https://doi.org/10.1007/s00267-021-01459-w

Sun, Y., Saha, S., Tost, H., Kong, X. and Xu, C. (2022). Literature review reveals a global access inequity to urban green spaces. Sustainability 14(3), 1062. https://doi.org/10.3390/su14031062

Tao, Y., Zhang, Y., Cao, J., Wu, Z., Yao, S. and Xue, B. (2019). Climate change has weakened the ability of Chinese lakes to bury polycyclic aromatic hydrocarbons. Environmental Pollution 255, 113288. https://doi.org/10.1016/j.envpol.2019.113288

Taub, D.R., Miller, B. and Allen, H. (2008). Effects of elevated CO2 on the protein concentration of food crops: a meta-analysis. Global Change Biology 14(3), 565-575. https://doi.org/10.1111/j.1365-2486.2007.01511.x

Tchonkouang, R.D., Onyeaka, H. and Nkoutchou, H. (2024). Assessing the vulnerability of food supply chains to climate change-induced disruptions. Science of The Total Environment 920, 171047. https://doi.org/10.1016/j.scitotenv.2024.171047

Techera, E., and Appadoo, K. (2020). Achieving SDG 14 in the African Small Island Developing States of the Indian Ocean. In D. Mickler, and M. Ramutsindela (Eds.), Africa and the Sustainable Development Goals (pp. 219-227). (Sustainable Development Goals Series; Vol. Part F2651). Springer. https://doi.org/10.1007/978-3-030-14857-7_21

Teixido, A.L., Fuzessy, L.F., Souza, C.S., Gomes, I.N., Kaminski, L.A., Oliveira, P.C. et al. (2022). Anthropogenic impacts on plant-animal mutualisms: A global synthesis for pollination and seed dispersal. Biological Conservation 266, 109461. https://doi.org/10.1016/j.biocon.2022.109461

Tercan, E. (2021). Land suitability assessment for wind farms through best-worst method and GIS in Balıkesir province of Turkey. Sustainable Energy Technologies and Assessments 47, 101491. https://doi.org/10.1016/j.seta.2021.101491

Terton, A., Tadgell, A., Crawford, A. and and Gout, E. (2022). A Natural Path to Conflict Prevention: Unpacking the nature–security nexus. https://www.iisd.org/articles/insight/natural-path-conflict-prevention

Tessum, C.W., Apte, J.S., Goodkind, A.L., Muller, N.Z., Mullins, K.A., Paolella, D.A. et al. (2019). Inequity in consumption of goods and services adds to racial–ethnic disparities in air pollution exposure. Proceedings of the National Academy of Sciences 116(13), 6001-6006. https://doi.org/10.1073/pnas.1818859116

Tessum, C.W., Paolella, D.A., Chambliss, S.E., Apte, J.S., Hill, J.D. and Marshall, J.D. (2021). PM2. 5 polluters disproportionately and systemically affect people of color in the United States. Science Advances 7(18), eabf4491. https://doi.org/10.1126/sciadv.abf4491

Thomas, A., Baptiste, A., Martyr-Koller, R., Pringle, P. and Rhiney, K. (2020). Climate Change and Small Island Developing States. Annual Review of Environment and Resources 45 (Volume 45, 2020), 1-27. https://www.scirp.org/reference/referencespapers?referenceid=4050545.

Tian, N., Lopes, D., Liang, X. and Scarazzato, L. (2024). Trends in World Military Expenditure, 2023. April, 2024 (SIPRI Fact Sheet). https://www.sipri.org/sites/default/files/2024-04/2404_fs_milex_2023.pdf

Tigchelaar, M., Cheung, W. W., Mohammed, E. Y., Phillips, M. J., Payne, H. J., Selig, E. R. et al. (2021). Compound climate risks threaten aquatic food system benefits. Nature Food (2(9), 673-682. https://doi.org/10.1038/s43016-021-00368-9

Tirado M.C., R. Clarke, L.A. Jaykus, A. McQuatters-Gollop, J.M. Frank. (2010). Climate change and food safety: A review. Food Research International 43 (7), 1745-1765. https://doi.org/10.1016/j.foodres.2010.07.003

United Nations (2016) The First Global Integrated Marine Assessment World Ocean Assessment I. https://www.un.org/regularprocess/sites/www.un.org.regularprocess/files/woacompilation.pdf

United Nations. (2019). The Sustainable Development Goals Report 2019. https://unstats.un.org/sdgs/report/2019/The-Sustainable-Development-Goals-Report-2019.pdf

United Nations. (2022). The Sustainable Development Goals Report 2022. https://unstats.un.org/sdgs/report/2022/

United Nations. (2024). The Sustainable Development Goals Report 2024. https://unstats.un.org/sdgs/report/2024/

United Nations Children's Fund (2023). Global snapshot of climate-related school disruptions in 2024. https://www.unicef.org/media/168311/file/Global-snapshot-climate-related-school-disruptions-2024.pdf

United Nations Convention to Combat Desertification. (2019). Land Degradation, Poverty and Inequality. https://www.unccd.int/sites/default/files/documents/2020-09/200909_08_Brief%20note%20%E2%80%93%20Poverty%20and%20Inequality.pdf

United Nations Convention to Combat Desertification. (2022). The Global Land Outlook, second edition. Bonn: UNCCD. https://www.unccd.int/sites/default/files/2022-04/UNCCD_GLO2_low-res_2.pdf

United Nations Development Programme. (2018). Sustainable Development Goals: Goal 10—Reduced Inequalities. https://www.undp.org/sustainable-development-goals/reduced-inequalities

United Nations Development Programme. (2023a). 2023 Gender Social Norms Index (GSNI): Breaking down gender biases: Shifting social norms towards gender equality. New York. https://hdr.undp.org/system/files/documents/hdp-document/gsni202303.pdf

United Nations Development Programme. (2023b). Human Impact Assessment. United Nations Development Programme (2023). Human Impact Assessment. https://www.undp.org/sites/g/files/zskgke326/files/2023-09/undp-ua-hia-3.pdf

United Nations Development Programme. (2024). Strengthening environmental governance. Environmental Governance. https://www.undp.org/nature/our-work-areas/environmental-governance

United Nations Educational, Scientific and Cultural Organization (2020). The impact of climate displacement on the right to education. https://unesdoc.unesco.org/ark:/48223/pf0000374966

United Nations Educational, Scientific and Cultural Organization (2022). Cutting Edge: Small Island Developing States:Cultural diversity as a driver of resilience and adaptation. https://www.unesco.org/en/articles/cutting-edge-small-island-developing-statescultural-diversity-driver-resilience-and-adaptation

United Nations Environment Programme. (2019). Global Environment Outlook – GEO-6: Healthy Planet, Healthy People. https://doi.org/10.1017/9781108627146

United Nations Environment Programme (2021a). Future proofing infrastructure to address the climate, biodiversity and pollution crises. https://wedocs.unep.org/bitstream/handle/20.500.11822/37563/GFB5.pdf.

United Nations Environment Programme. (2021b). Making Peace with Nature: A scientific blueprint to tackle the climate, biodiversity and pollution emergencies. Nairobi. https://www.unep.org/resources/making-peace-nature

United Nations Environment Programme. (2023). Adaptation Gap Report 2023: Underfinanced. Underprepared. Inadequate investment and planning on climate adaptation leaves world exposed. Nairobi. https://doi.org/10.59117/20.500.11822/43796

United Nations Framework Convention on Climate Change. (2018). Considerations regarding vulnerable groups, communities and ecosystems in the context of the national adaptation plans. United Nations Framework Convention on Climate Change. https://unfccc.int/sites/default/files/resource/Considerations%20regarding%20 vulnerable.pdf

United Nations Framework Convention on Climate Change. (2022a). Dimensions and examples of the gender-differentiated impacts of climate change, the role of women as agents of change and opportunities for women. https://unfccc.int/sites/default/files/resource/sbi2022_07.pdf

United Nations Framework Convention on Climate Change. (2022b). Conflict and Climate. https://unfccc.int/blog/conflict-and-climate

United Nations Global Compact. (2023). UN Alliance for SDG Finance. https://unglobalcompact.org/take-action/action/globalallianceforsdgfinance

United Nations High Commissioner for Refugees (2022). UNHCR's Global Trends Report 2022. https://www.unhcr.org/global-trends-report-2022

United Nations High Commissioner for Refugees. (2018). Global trends in forced displacement in 2017. Geneva. https://doi.org/10.1080/09584939308719709

United Nations Office for Disaster Risk Reduction. (2023) World Tsunami Awarness Day. Theme of the day: fighting inequality for a resilient future. https://tsunamiday.undrr.org/2023/learn-wtad. Accessed 1 July 2025

United Nations Security Council. (2018). States Must Transform Natural Resources from Driver of Conflict into Development Tool to Foster Peace, Cooperation, Secretary-General Tells Security Council. https://press.un.org/en/2018/sc13540.doc.html

United Nations Women. (2024). Gender Equality at the Intersection of Climate Change, Biodiversity Loss and Land Degradation, https://unwomen.org/sites/default/files/202411/un_women_uncbd_cop16_and_synergies.pdf

United States of America, Department of Transportation. (2022). Pipeline Safety: Potential for Damage to Pipeline Facilities Caused by Earth Movement and Other Geological Hazards. https://www.federalregister.gov/documents/2022/06/02/2022-11791/pipeline-safety-potential-for-damage-to-pipeline-facilities-caused-by-earth-movement-and-other

Vadén, T., Lähde, V., Majava, A., Järvensivu, P., Toivanen, T., Hakala, E. et al. (2020). Decoupling for ecological sustainability: A categorisation and review of research literature. Environmental Science & Policy 112, 236-244. https://doi.org/10.1016/j.envsci.2020.06.016

Vergadi E,. Rouva G., Angeli M., Galanakis E. (2022) Infectious Diseases Associated with Desert Dust Outbreaks: A Systematic Review. Int J Environ Res Public Health. 19(11): 6907. https://doi.org/10.3390/ijerph19116907

Vargas, E.M. (2011). Climate change and food crisis. Perspectives, (27), 147-160.

Visser-Quinn, A., Beevers, L., Lau,T. and Gosling, R. (2021). Mapping future water scarcity in a water abundant nation: Near-term projections for Scotland. Climate Risk Management, 32. https://doi.org/10.1016/j.crm.2021.100302

Von Hertzen, L., Hanski, I. and Haahtela, T. (2011). Natural immunity: biodiversity loss and inflammatory diseases are two global megatrends that might be related. EMBO reports 12(11), 1089-1093. https://doi.org/10.1038/embor.2011.195

Vousdoukas, M.I., Athanasiou, P., Giardino, A., Mentaschi, L., Stocchino, A., Kopp, R.E. et al. (2023). Small Island Developing States under threat by rising seas even in a 1.5 °C warming world. Nature Sustainability 6(12), 1552-1564. https://doi.org/10.1038/s41893-023-01230-5

Wakode, Hemant & Baier, Klaus & Jha, Ramakar & Azzam, Rafig. (2018). Impact of urbanization on groundwater recharge and urban water balance for the city of Hyderabad, India. International Soil and Water Conservation Research. 6. https://doi.org/10.1016/j.iswcr.2017.10.003

Wafula, G.W., Ouna, T., and Kamiri, H. (2024). Temporal changes in rainfall and temperature influence on solid waste generation in Bungoma County urban centres, Kenya. Eastern African Journal of Humanities and Social Sciences, 3(2), pp.75-83. http://dx.doi.org/10.58721/eajhss.v3i2.646

Wagner, C.C., Amos, H. M., Thackray, C. P., Zhang, Y., Lundgren, E. W., Forget, G. et al. (2019). A Global 3-D Ocean Model for PCBs: Benchmark Compounds for Understanding the Impacts of Global Change on Neutral Persistent Organic Pollutants. Global Biogeochemical Cycles (33(3), 469-481. https://doi.org/10.1029/2018GB006018

Wagner, V., Pascal, M., Corso, M., Alari, A., Benmarhnia, T. and Le Tertre, A. (2023). On the supra-linearity of the relationship between air pollution, mortality and hospital admission in 18 French cities. International Archives of Occupational and Environmental Health 96(4), 551-563. https://doi.org/10.1007/s00420-022-01948-3

Walker, S.E., Bruyere, B.L., Yasin, A., Lenaiyasa, E. and Lolemu, A. (2021). The good life in the face of climate change: understanding complexities of a well-being framework through the experience of pastoral women. The Journal of Development Studies 57(7), 1120-1137. https://doi.org/10.1080/00220388.2021.1881493

Wang, F., Li, G., Alexander, F., Ma, W., Chen, D., Wu, G. et al. (2023). Applicability analysis of thermosyphon for thermally stabilizing pipeline foundation permafrost and its layout optimization. Cold Regions Science and Technology 208, 103769. https://doi.org/10.1016/j.coldregions.2022.103769

Wang, Z., Walker, G.W., Muir, D.C.G. and Nagatani-Yoshida, K. (2020). Toward a Global Understanding of Chemical Pollution: A First Comprehensive Analysis of National and Regional Chemical Inventories. Environmental Science & Technology 54(5), 2575-2584. https://doi.org/10.1021/acs.est.9b06379

Wang, Z., Xu, N., Wei, W. and Zhao, N. (2020). Social inequality among elderly individuals caused by climate change: Evidence from the migratory elderly of mainland China. Journal of Environmental Management 272, 111079. https://doi.org/10.1016/j.jenvman.2020.111079

Wang, T., Qu, Z., Yang, Z., Nichol, T., Clarke, G., and Ge, Y. (2020). Climate change research on transportation systems: Climate risks, adaptation and planning. Transportation Research 88. https://doi.org/10.1016/j.trd.2020.102553

Ward, J.D., Sutton, P.C., Werner, A.D., Costanza, R., Mohr, S.H. and Simmons, C.T. (2016). Is decoupling GDP growth from environmental impact possible? PloS one 11(10), e0164733. https://doi.org/10.1371/journal.pone.0164733

Wasti, A., Ray, P., Wi, S., Folch, C., Ubierna, M. and Karki, P. (2022). Climate change and the hydropower sector: A global review. Wiley Interdisciplinary Reviews: Climate Change 13(2), e757. https://doi.org/10.1002/wcc.757

Wen, J., Zhao, X., Fu, Q. and Chang, C.-P. (2023). The impact of extreme weather events on green innovation: Which ones bring to the most harm? Technological Forecasting and Social Change 188, 122322. https://doi.org/10.1016/j.techfore.2023.122322

Wendling, L., Garcia, J., Descoteaux, D., Sowińska-Świerkosz, B., McPhearson, T., Frantzeskaki, N. et al. (2021). Introduction to the Nature-Based Solutions journal. Nature-Based Solutions 1(C). http://dx.doi.org/10.1016/j.nbsj.2021.100003

Wing, I. S., De Cian, E., & Mistry, M. N. (2021). Global vulnerability of crop yields to climate change. Journal of Environmental Economics and Management, 109, 102462. https://doi.org/10.1016/j.jeem.2021.102462

Wolf, J., Johnston, R.B., Ambelu, A., Arnold, B.F., Bain, R., Brauer, M. et al. (2023). Burden of disease attributable to unsafe drinking water, sanitation, and hygiene in domestic settings: a global analysis for selected adverse health outcomes. Lancet 401(10393), 2060-2071. https://doi.org/10.1016/s0140-6736(23)00458-0

World Bank. (2015). Poverty and climate change: reducing the vulnerability of the poor through adaptation. World Bank. https://documents1.worldbank.org/curated/en/534871468155709473/pdf/521760WP0pover1e0Box35554B01PUBLIC1.pdf

World Bank (2021). The Global Health Cost of PM2.5 Air Pollution: A Case for Action Beyond 2021.International Development in Focus. Washington, DC: World Bank. https://doi.org/10.1596/978-1-4648-1816-5

World Bank. (2022a). Poverty and Shared Prosperity 2022: Correcting Course. Washington, DC: World Bank. http://hdl.handle.net/10986/37739

World Bank. (2022b). The Global Health Cost of PM2. 5 Air Pollution: A Case for Action Beyond 2021. The World Bank. https://doi.org/10.1596/978-1-4648-1816-5

World Economic Forum (2020). Nature Risk Rising: Why the Crisis Engulfing Nature Matters for Business and the Economy. https://www3.weforum.org/docs/WEF_New_Nature_Economy_Report_2020.pdf

World Economic Forum. (2023). The Global Risks Report 2023. https://www3.weforum.org/docs/WEF_Global_Risks_Report_2023.pdf

World Health Organization. (2022). Ambient (outdoor) air pollution. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

World Health Organization. (2016). Ambient air pollution: A global assessment of exposure and burden of disease. https://apps.who.int/iris/handle/10665/250141

World Health Organization. (2016). Burning opportunity: clean household energy for health, sustainable development, and wellbeing of women and children. https://www.who.int/publications/i/item/9789241565233

World Health Organization. (2018). Climate Change and Health: Fact Sheet on Sustainable Development Goals (SDGs): Health Targets. https://iris.who.int/bitstream/handle/10665/340820/WHO-EURO-2018-2374-42129-58024-eng.pdf?sequence=1

World Health Organization. (2023). World health statistics 2023: monitoring health for the SDGs, Sustainable Development Goals. Geneva: World Health Organization; 2023. Licence: CC BY-NC-SA 3.0 IGO. https://cdn.who.int/media/docs/default-source/gho-documents/world-health-statistic-reports/2023/world-health-statistics-2023_20230519_.pdf

World Health Organization. (2024). World Health Statistics 2024 Monitoring health for the SDGs, Sustainable Development Goals, Geneva. https://digitallibrary.un.org/record/4050651?ln=en&v=pdf

World Health Organization and Secretariat of the Convention on Biological Diversity. (2015). Connecting global priorities: biodiversity and human health: a state of knowledge review. https://iris.who.int/bitstream/handle/10665/174012/9789241508537_eng.pdf.

World Health Organization and United Nations Children's Fund (2023). Progress on household drinking water, sanitation and hygiene: 2000 – 2022. https://cdn.who.int/media/docs/default-source/wash-documents/jmp-2023_layout_v3launch_5july_low-reswhowebsite.pdf

World Meteorological Organization. (2020). 2020 State of climate services risk information and early warning systems. https://library.wmo.int/viewer/57191/download?file=1252_9-October_en.pdf&type=pdf&navigator=1

World Meteorological Organization. (2023). Atlas of mortality and economic losses from weather, climate and water-related hazards (1970–2021). https://wmo.int/publication-series/atlas-of-mortality-and-economic-losses-from-weather-climate-and-water-related-hazards

World Trade Organizations (2022). Small Business and Climate Change. https://www.wto.org/english/tratop_e/msmes_e/ersd_research_note3_small_business_and_climate_change.pdf

Xiao B, Ning L, Lin Z, Wang S, Zang H. (2022). The Impact of Air Pollution on the Protection of World Cultural Heritage in China. Int J Environ Res Public Health. 2022 Aug 17;19(16):10226. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9408473/

Xu, Y., Liu, Y., Chang, X. and Huang, W. (2021). How does air pollution affect travel behavior? A big data field study. Transportation Research Part D: Transport and Environment 99, 103007. https://doi.org/10.1016/j.trd.2021.103007.

Yang, H., Chen, G. and Wang, J. (2021). Microplastics in the marine environment: Sources, fates, impacts and microbial degradation. Toxics 9(2), 41. https://doi.org/10.3390/toxics9020041

Zhang, X., Chen., X. and Zhang, X. (2018). The impact of exposure to air pollution on cognitive performance. Proceedings of the National Academy of Sciences (115 (37). https://doi.org/10.1073/pnas.1809474115

Zhang, Y., Xi, B. and Tan, W. (2021). Release, transformation, and risk factors of polybrominated diphenyl ethers from landfills to the surrounding environments: A review. Environ Int 157, 106780. https://doi.org/10.1016/j.envint.2021.106780

Zhang, Z., Li, M., Wu, Q., Wang, X., Jin, H., Chen, H. et al. (2024). Degradation and local growth of "Xing'an-Baikal" permafrost responding to climate warming and the consequences. Earth-Science Reviews, 104865. https://doi.org/10.1016/j.earscirev.2024.104865

Zhu, L., Bossi, R., Carvalho, P.N., Rigét, F.F., Christensen, J.H., Weihe, P. et al. (2024). Suspect and non-target screening of chemicals of emerging Arctic concern in biota, air and human serum. Environmental Pollution 360, 124605. https://doi.org/10.1016/j.envpol.2024.124605

Zhu, Y.G. and Penuelas, J. (2020). Changes in the environmental microbiome in the Anthropocene. Global Change Biology 26(6), 3175-3177. https://doi.org/10.1111/gcb.15086

Ziska, L. H., & Bunce, J. A. (2007). "Predicting the Impact of Changing Co2 on Crop Yields: Some Thoughts on Food." New Phytologist, no. 175(4): 607-18.https://doi.org/10.1111/j.1469-8137.2007.02180.

08 Interlinkages Across Environmental Changes, Scales and Geographic Regions and Subregions

Overall Coordinating Lead Authors: Keisha Garcia (ANSA Merchant Bank Limited), Jeff Seadon (Seadon Consulting)

Overall Fellows: Tarik Alkharusi (University of Technology and Applied Sciences, Oman), Henry Häkkinen (Zoological Society of London)

AFRICA AND SUBREGIONS

Coordinating Lead Authors: Clever Mafatu (GRID-Arendal), S. Nadia Ouedraogo (UNECA)

Lead Authors: Adenike Akinsemolu (Afe Babalola University), Efitre Jackson (Makerere University), Modupe O. Jimoh (University of Warwick), Didacus Namanya (Government of Uganda)

Contributing Authors: Tatenda Dalu (Centre for Invasion Biology, Stellenbonsch University)

Fellow: Francis Asamoah (International Forestry Students' Association; University of Energy and Natural Resources)

ASIA AND THE PACIFIC AND SUBREGIONS

Coordinating Lead Authors: Mizan R. Khan (LDC Universities Consortium on Climate Change (LUCCC), LDC Group), Kyung Ah Koo (Korea Environment Institute)

Lead Authors: Maryam Alkharusi (independent), Ekhtekharul Islam (Independent University Bangladesh), Jianguo Liu (Michigan State University), Indu K Murthy (Center for Study of Science, Technology and Policy), Kamal Kumar Rai (Indigenous Knowledge and Peoples Networks, IPs Society for Wetland Biodiversity Conservation Nepal; ITT-Nepal)

Contributing Authors: Suruchi Bhadwal (The Energy and Resources Institute)
Fellows: Tarik Alkharusi (Imperial College London, UTAS-Oman), Qian Jia (Tongji University)

EASTERN EUROPE AND SUBREGIONS

Coordinating Lead Authors: Joanna Kulczycka (Mineral and Energy Economy Research Institute, Polish Academy of Sciences, AGH University of Krakow), Ruben Mnatsakanian (Central European University, Vienna)

Lead Authors: Beata Houšková (National Agricultural and Food Centre), Vojtěch Kotecký (Charles University Environment Centre), Melisa Ljusa (University of Sarajevo)

Fellow: Marianna Baslandze (SOGAZ)

LATIN AMERICA AND THE CARIBBEAN AND SUBREGIONS

Coordinating Lead Authors: Andres Guhl (Universidad de los Andes), Karina Miglioranza (Universidad Nacional de Mar del Plata, IIMyC-CONICET)

Lead Authors: Eduardo Erazo Acosta (Independent researcher on Indigenous communities), Leisa Perch (SAEDI Consulting (Barbados) Inc.), Ramon Pichs-Madruga (Centre for World Economy Studies)

Contributing Authors: Kenel Delusca (Institute of Technology, Science and Advanced Studies of Haiti), Danielle Denny (Center for Carbon Research in Tropical Agriculture, University of Sao Paolo)

Fellows: Acasia Broomes (Santa Rosa First Peoples Community), Gabriela Kreutzberger (World Economic Forum), Jimena Reyeros Sanchez (Fundación Avina)

WESTERN EUROPE AND OTHERS GROUP (WEOG) AND SUBREGIONS

Coordinating Lead Authors: Gillian Bowser (Colorado State University) Sarah A. Green (Michigan Technological University), Susie SY Ho (Monash University)

Lead Authors: Kofi Akamani (Southern Illinois University Carbondale), Janelle Baker (Athabasca University), Jan Cools (University of Antwerp), Joanne Clarke (Durham University), Lorenzo Benini (European Environment Agency),

Contributing Authors: Henry Häkkinen (Zoological Society of London), Elisabeth Gilmore (Carleton University), Steven Fletcher (University of Portsmouth), Mengxing Li (Monash University), Troy McGee (Monash University)

Fellows: Henry Häkkinen (Zoological Society of London), Laura Fanciulli (Italian Ministry of Environment and Energy Security)

TELECOUPLING

Coordinating Lead Authors: Keisha Garcia (ANSA Merchant Bank Limited) , Jianguo Liu (Michigan State University)

Contributing Authors: Min Gon Chung (University of Colorado Boulder)

Fellows: Tarik Alkharusi (Imperial College London, UTAS-Oman)

Credit: Light-and-Vision/Envato

Chapter summary

Credit: ImageSourceCur/Envato

Overall, the state of the environment in each of the five United Nations (UN) Regions is deteriorating (*well established*). Except for a few success stories, deteriorating environmental trends at the regional and subregional levels have persisted or intensified. The worsening trends are driven by the global environmental crises – climate change, biodiversity loss and land degradation, and pollution and waste – which often work in combination and have differentiated causes and effects, depending on scale and location {8.1}.

All global environmental crises are significant, but their impacts differ across the UN regions. As such, regional and subregional analysis is required to identify how to combat issues effectively (*well established*). This chapter has adopted a priority-based assessment where three of the most pressing environmental issues within each of the five UN regions were assessed, as selected by expert opinion and literature review. This approach is designed to streamline and strengthen environmental science-policy support at the subglobal levels and is expanded upon in Chapter 20 {8.1; Table 8.1}.

Although the specific issues faced by the UN regions are diverse, climate change is a common and compounding challenge across all regions, exacerbating local-level impacts of the environmental crises (*well established)*. These impacts are most pronounced in sensitive biomes and those that have been significantly degraded by human activities. For example, coral reefs in most regions are vulnerable to ocean acidification and bleaching, which affects economies, livelihoods and well-being. Warmer temperatures are driving the expansion of boreal forests and subarctic shrubs northward by up to 100 metres per year. Climate adaptation plays a key role in providing urgent, region-specific and multi-crisis solutions {8.2.3; 8.3.3; 8.5.2; 8.6.3}.

Socioeconomic impacts due to the global environmental crises are present across all UN regions (*well established*). The global environmental crises interact with each other and with regional environmental priority issues, resulting in socioeconomic issues such as climate-induced migration, poor health – for example, due to air pollution, food and water security, and increased inequalities. All communities are impacted, but vulnerable communities are disproportionately impacted {8.2; 8.3; 8.4; 8.5; 8.6; 8.7}.

Lands and territories managed by Indigenous Peoples are among the most bioculturally diverse due to their lengthy stewardship, but they are under increasing threat from the global environmental crises (*well established*). Climate change induces environmental and seasonal unpredictability, threatening human health, livelihoods and land-based spiritual relationships critical for ecosystem health. Land degradation, biodiversity loss and pollution also increase the vulnerability of Indigenous populations in all regions. Indigenous Knowledge systems are an important dimension in local adaptation strategies {8.2; 8.3; 8.4; 8.5; 8.6; IK & LK Chapeau Part B}.

Africa

Across Africa, resource exploitation – including the exploitation of land, forests and fisheries – is unsustainable (*established but incomplete*). This is impacting ecosystems and leading to food and water security. For example, countries such as Chad, Liberia and Sudan are water insecure, while South Africa is affected by high levels of freshwater pollution {8.2.3}.

Africa's terrestrial, marine and freshwater ecosystems are threatened by environmental degradation from the impacts of deforestation, soil erosion, and salinization of rivers (*established but incomplete*). Approximately 14 million km² of Africa's land is degraded, affecting people and costing US$9.3 billion annually. Africa loses 39,000 km² of forests per year. In 2018, East and West Africa were responsible for 13.9 per cent of global disaster-related displacements {8.2.1; 8.2.2; 8.2.4; 8.2.5}.

Climate change impacts Africa's subregions differently but significantly (*well established*), and it has undermined the region's ability to fulfil commitments under the African Union's Agenda 2063 and the SDGs. Floods are becoming more frequent in some parts of Africa. As many as 27.4 million people in East Africa were affected in 2022, while a further 4.5 million were affected in West Africa. Temperatures across the continent are rising faster than the global average, causing droughts in the Sahel, North Africa and Southern Africa. Hydropower generation is significantly reduced in Southern Africa, directly affecting Zambia, where 80 per cent of the electricity capacity is generated from hydropower {8.2.4; 8.2.5}.

Asia and the Pacific (AP)

Over 220 million people in the AP region were displaced between 2010 and 2021 due to climate-related events (*well established*). About 43 per cent of AP countries are among the most vulnerable to climate-related disasters globally. Climate change is threatening the Indigenous cultural heritage and land-use changes of AP countries faster than the global average {8.3.2}.

One-sixth of the AP's forested area was converted to agriculture and pastureland between 1990 and 2020 (*well established*). This land transformation has had a significant effect on ecosystems and biodiversity. Forty-five per cent of the region's vertebrate populations have been lost in the last 45 years. Between 1700 and 2020, over 40 per cent of global inland wetlands in China, India and Indonesia were lost. Conversely, recent land and species restoration projects in AP, such as the SAFE project in Bhutan, Cambodia, Lao People's Democratic Republic and Viet Nam, demonstrate the progress of the AP's ecosystem and biodiversity recovery {8.3.2; 8.3.4}.

Globally, six out of the top ten countries with the worst air pollution levels are from AP, leading to respiratory diseases, poor health and lower agricultural productivity (*well established*). Although PM_{10} particulate matter concentrations have decreased in several Northeast Asian countries over the past few decades, including China, Japan and the Republic of Korea, air pollution remains significant {8.3.4; 8.3.5}.

The average pollution-induced productivity loss is eight times higher in the region's developing countries than in its developed counterparts *(established but incomplete)*. Impacts are most pronounced in low-income and marginalized communities, including Indigenous Peoples and local communities {8.3.4; 8.3.5}.

Eastern Europe (EE)

Ecosystem services, especially on agricultural lands, are being degraded across the EE region *(well established)*. This is driven by two polarizing trends: intensive farming, leading to soil degradation, and abandonment of extensive farmland, through rural depopulation and biodiversity loss. Climate change is exacerbating these losses with EE now considered a global hotspot for increasing soil drought {8.4.3}.

EE relies heavily on fossil fuels and energy-inefficient technologies *(well established)*. Fossil fuels account for over 50 per cent of the total energy supply and consumption. Many EE countries are consequently facing significant challenges with air quality in cities and industrial regions. As many as 19 per cent of deaths in the Western Balkans are attributed to air pollution. The energy transition across EE remains slow, resulting in long-lasting environmental and socioeconomic impacts {8.4.4}.

EE has rich biodiversity and a strong network of protected areas, but climate change, land degradation and pollution remain a threat *(well established)*. Return or stabilization of some rare species indicates local successes of conservation. However, land-use change is driving biodiversity loss outside of protected areas. The planned construction of 3,000 small-scale hydroelectric dams in the Balkans to support the energy transition will significantly affect biodiverse riverine ecosystems. In the Arctic, climate change is leading to the thawing of permafrost, which in turn increases methane emissions {8.4.5}.

Armed conflicts are a crucial environmental threat in the EE region, often compounding other negative trends *(established but incomplete)*. Conflicts result in the depopulation of vast areas and the destruction of agricultural lands, hydropower dams, and irrigation systems. They also lead to landmine fields and military equipment debris in war zones and beyond {8.4.1; 8.4.5; Box 8.4}.

Latin America and the Caribbean (LAC)

Land degradation in LAC has both regional and global implications *(established but incomplete)*. An area roughly the size of Central America was deforested in LAC between 1992 and 2022, while between 2000 and 2019, agricultural land expanded by 49 per cent in South America, affecting forests and other tropical ecosystems. Deforestation has significantly impeded biodiversity, leading to a 95 per cent decline in the World Wildlife Fund's Living Planet Index – the worst regional score from 1970 to 2020. Economies, livelihoods and the health of populations, including those of Indigenous Peoples, have been affected. Continued loss of the Amazon forest could undermine global climate goals {8.5.3; 8.5.4}.

The region of LAC holds 30 per cent of global water resources, while 75 per cent of the region's population lacks safe access to water *(well established)*. Agriculture accounts for the largest demand for fresh water at 70 per cent. Pollution, ecosystem degradation and climate change are driving deteriorating conditions, with less than half the region's waterbodies considered to be of good quality. Increased flooding frequency and more intense droughts further threaten the region's water security. An 83 per cent retreat in the Andean glaciers contributes to the release of pollutants, global sea level rise, and impacts economic activities such as hydroelectric power generation, food production – that is, irrigation and transportation – notably through the Panama Canal {8.5.4; 8.5.5}.

Coastal and marine ecosystems are degrading in LAC, affecting the well-being of at least 27 per cent of its inhabitants *(well established)*. Widespread coral degradation occurs in Central America and northern South America. Ocean acidification contributed to a 37 per cent net erosion of the Mesoamerican Barrier Reef System. However, mangroves increased in extent by 12.9 per cent in the Caribbean and by 3.6 per cent in South America between 2010 and 2020. The region has experienced a rise in the frequency and intensity of extreme events that increase coastal degradation, erosion, flooding and disease. The sustainability of wild caught fisheries is low in the region, although some exclusive economic zones show an improving trend from 2012 to 2023 {8.5.5}.

Western Europe and Others Group (WEOG)

Ecological transformations – driven by alien organisms, habitat loss and land degradation – disrupt ecological processes, spread disease, and harm livelihoods and cultural heritage *(well established)*. Invasive species impose economic and ecological damage.

Protected areas are insufficient to prevent habitat loss. Species loss is especially acute in Australia and New Zealand. Arctic ecosystems are under stress from permafrost melting, threatening livelihoods and culturally significant species. Diseases spread by invertebrate vectors are expanding, exacerbated by existing health inequities {Figure 8.32; 8.6.2; 8.6.3}.

Extreme heatwaves, wildfires and storms are increasing in frequency, severity and impact *(well established)*. Heatwaves are extremely deadly, especially for vulnerable groups such as outdoor workers. Marine heatwaves damage coral reefs and promote toxic algal blooms. Expanding fire weather is driving forest and urban wildfires, destroying cultural resources and degrading air quality far from their source. Extreme storms cause coastal and river flooding, with loss of life, damage to infrastructure and cultural heritage, and long-lasting excess mortality. Europe suffered catastrophic flooding in 2021, 2023 and 2024. Climate adaptation and emission mitigation can alleviate the damages from extreme events {8.6.4}.

The WEOG region actively addresses waste and pollution issues, yet current lifestyles continue to produce excessive waste *(well established)*. The region continues to suffer from a long legacy of fossil fuel extraction and use. Material footprints are 1.5 to 3 times the global average, generating excessive waste. Inefficient nitrogen use in agriculture degrades aquatic systems and groundwater. Air pollution from fossil fuel combustion is decreasing. While $PM_{2.5}$ has fallen by 34 per cent since 2000 across WEOG, over 50 per cent of Europeans are still exposed to levels above 10 µg/m^3. Emerging contaminants, such as per- and polyfluoroalkyl substances, are ubiquitous {8.6.2; 8.6.5}.

Telecoupling

Telecoupling, that is, socioeconomic-environmental interactions over distances that are prompted by processes such as trade, investment, tourism, migration, species invasion, flows of ecosystem services, and armed conflict, can drive environmental deterioration *(established but incomplete)*. The environmental effects of telecoupling are varied but are often associated with greenhouse gas emissions and land use {8.7}.

Telecoupling adds a further layer of complexity as the authority to make decisions often lies outside the geographical areas with environmental impacts *(established but incomplete)*. Regions in the Global South are often harmed more than those in the Global North, though this is not always the case – as seen with the impact of wildfires {8.6; 8.7}.

Credit: bilanol/Envato

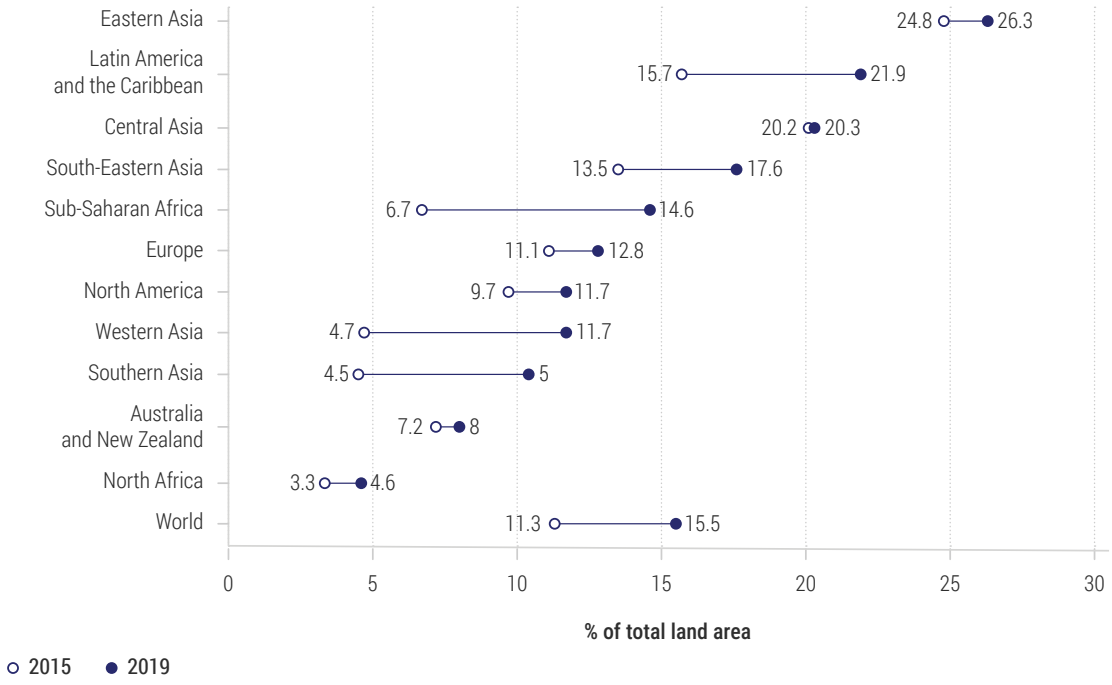
8.1 Introduction

The global environmental crises – the crisis of climate change, the crisis of biodiversity loss, land degradation and desertification, and the crisis of pollution and waste – although established as common challenges at the international level, have different root causes and consequences depending on scale and location (Chapter 2; Global Environmental Crises Chapeau). For example, statistics on land degradation (**Figure 8.1**) illustrate the significant variation in regional and subregional trends, as well as their differences when compared to a global average. The 2024 Living Planet Index also emphasizes regional variations in biodiversity loss (World Wide Fund for Nature [WWF] 2024). This variability underscores the need for special attention to be paid to regional and subregional specificities in environmental decision-making, recognizing that one-size-fits-all policies and actions will not be effective in enabling the type of transformative change required to address the global environmental crises (Bennett, Peterson and Gordon 2021).

Since the publication of the sixth Global Environment Outlook (GEO-6) Regional Assessments in 2016, there has been a persistence, in many cases an acceleration, and proliferation of negative environmental trends in every region of the world associated with the global environmental crises, save a few pockets of noteworthy improvement (Food and Agriculture Organization 2020; United Nations Convention to Combat Desertification 2020; European Commission 2023; United Nations Economic and Social Commission for Asia and the Pacific et al. 2023; Fassinou et al. 2024; FiBL 2024; Vicente-Serrano et al. 2024). These deteriorating trends are clear signs that policy and action to address these challenges have been inadequate. As such, in positioning the GEO-7 report to respond to the increasing urgency associated with the mounting, complex and differentiated environmental challenges faced by regions and their subregions, this chapter has pivoted away from a traditional analysis of states and trends.

To more effectively inform solution pathways and policy options, as elaborated in Chapter 20, this

Figure 8.1: Proportion of degraded land in 2015 and 2019



Note: The risk score is calculated as combined ratios of predicted environmental concentration and ecotoxicity of the 92 most used active ingredients in soil, surface water, groundwater and atmosphere.

Source: UNDESA (2023)

chapter highlights three environmental issues in each of the five United Nations regions, as grouped by the United Nations Department for General Assembly and Conference Management, that have been identified as high priorities in the context of the global environmental crises. These priorities (**Table 8.1**) were selected based on the criteria outlined in **Figure 8.2**. The regional experts involved in GEO-7 conducted both an in-depth analysis of the scientific literature and an examination of regional environmental issues highlighted or prioritized in the most recent policy documentation. As in other major global assessments, refinement of these issues occurred during the GEO-7 process through feedback from advisory bodies and stakeholders during formal reviews.

Within the context of each priority issue, the regional assessments examine trends in the environmental crises at the regional and subregional levels. They further analyse the implications of these trends for natural and human systems, noting in certain cases where there are adverse effects on populations, especially vulnerable populations, within the regions.

Where data is available, the relationships between and the combined effects of the global environmental crises are also analysed, for instance, where biodiversity loss exacerbates climate change and vice versa (Global Environmental Crises Chapeau). Through this lens, there is an opportunity to provide regional decision makers with a more focused analysis of areas for strategic environmental intervention that can potentially reduce the growing financial burden associated with global environmental crises at subglobal scales.

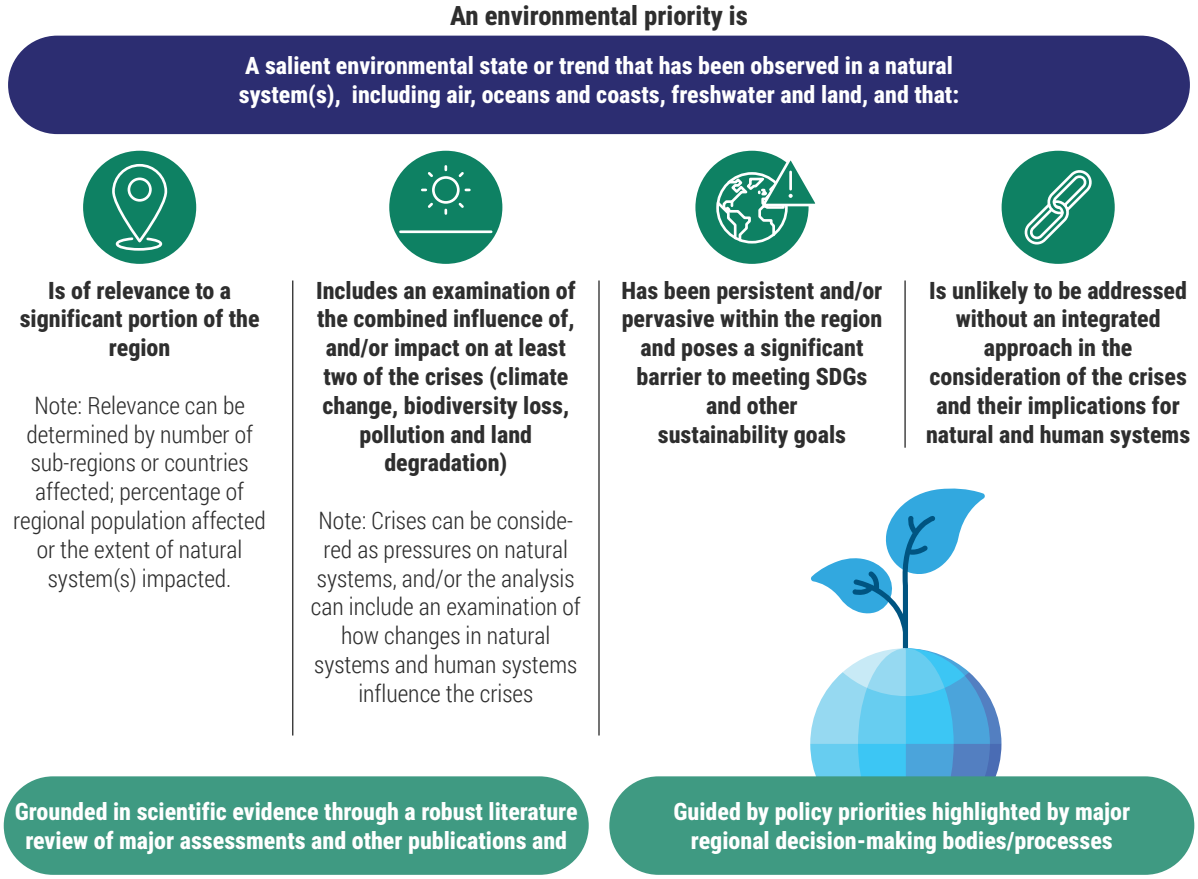
As part of this regional chapter, the implications of telecoupling arrangements are also considered. Telecoupling refers to socioeconomic and environmental interlinkages that span distances, driven largely by trade, tourism, migration, and investments (Liu 2020). These interconnections have environmental implications for all regions, but in differentiated ways. Additionally, the power to make decisions related to telecoupling arrangements often lies outside or goes beyond the country, subregion or region where environmental impacts are most felt. As such, it is important to understand the flows involved in telecoupling so that they can be effectively incorporated into policies and decisions at various scales (Chapter 20).

Finally, although the specific issues faced by the regions are diverse, climate change is a common and compounding challenge across all regions, exacerbating local-level impacts of the environmental crises. As such, there is a growing need to identify appropriate opportunities for adaptation (Chapter 20).

Table 8.1: The three environmental priorities identified for each region in GEO-7

Region	Priorities
Africa	Unsustainable resource exploitation and use Ecosystem degradation Climate change and climate extremes
Asia and the Pacific (AP)	Climate change impacts on development and cultural heritage Land-use change impacts on ecosystems Pollution and waste impacts on ecosystems and human health
Eastern Europe (EE)	Loss of ecosystem services due to unsustainable agriculture Unsustainable energy system effects on climate and health Biodiversity loss due to weak management frameworks
Latin America and Caribbean (LAC)	Changes in land-cover dynamics Changes in freshwater quality and availability Degradation of coastal and marine resources
Western Europe and Others Group (WEOG)	Biodiversity loss and ecosystem change Climate extreme events Pollution and waste

Figure 8.2: Criteria for selecting regional environmental priorities



8.2 Africa and subregions

8.2.1 Introduction

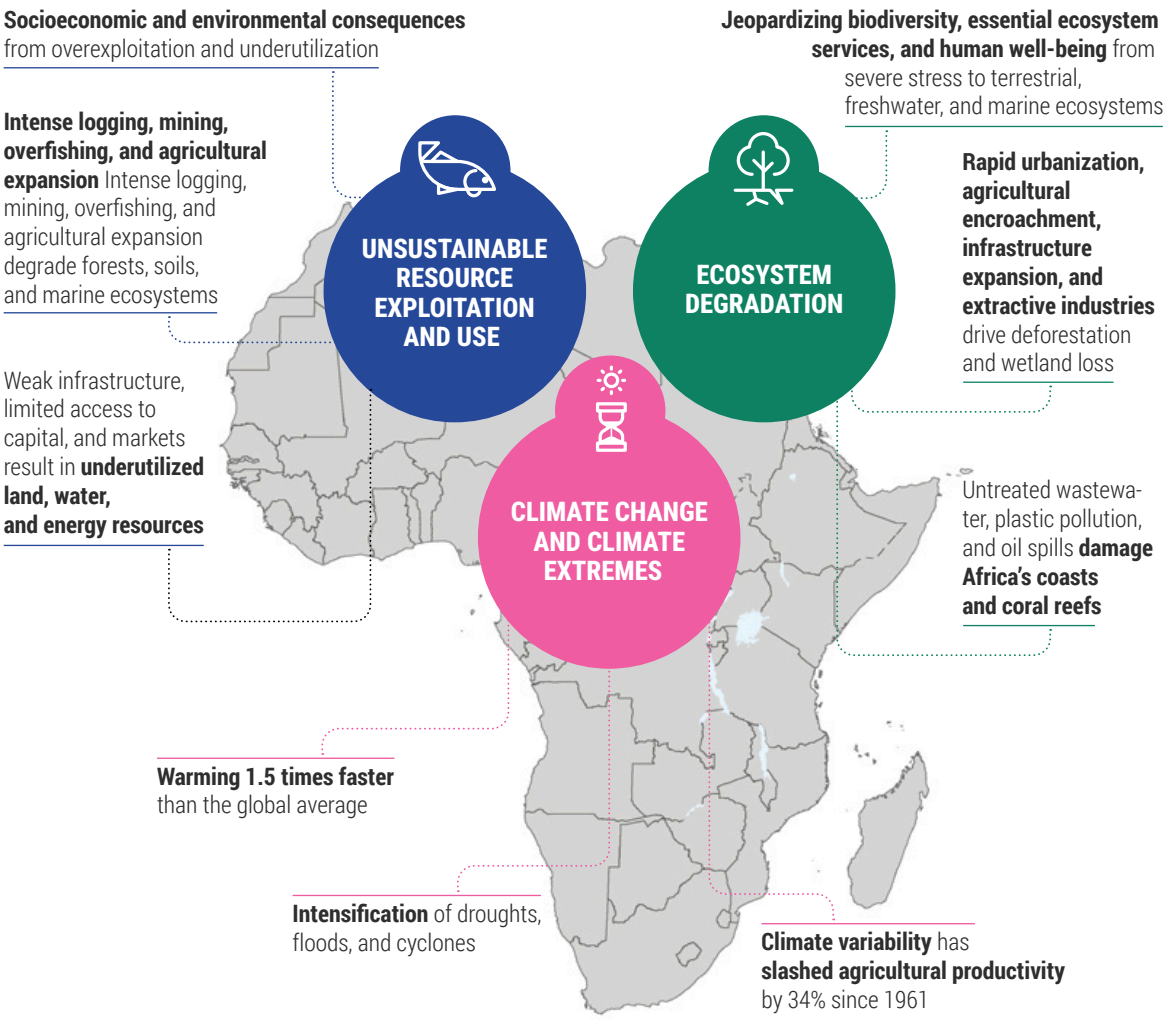
With a population of 1.5 billion (United Nations Department of Economic and Social Affairs [UNDESA] 2024) and a landmass of 30,143 million km^2 (United Nations Environment Programme [UNEP] 2016), Africa is a diverse region that includes deserts, rainforests and savannahs. The 54 countries on the African continent include 16 landlocked ones (United Nations Conference on Trade and Development [UNCTAD] 2023), which are divided into five subregions as shown in. As a sign of the extent to which Africa values its environment, the Great Green Wall initiative is on target to restore 1 million km^2 of land and to sequester 300 million tons of carbon by 2030, having already restored 200 thousand km^2 as of 2020 (United Nations Convention to Combat Desertification [UNCCD] 2020; Fassinou et al. 2024).

Despite these efforts, Africa has been deeply affected by the global environmental crises: the crisis of climate change, the crisis of biodiversity loss, land degradation and desertification, and the crisis of pollution and waste (**Figure 8.3**). The crises reinforce each other and interact with regional environmental priorities, resulting in environmental and socioeconomic impacts. In Africa and its subregions, climate change is a main driver of the impacts of the crises (Intergovernmental Panel on Climate Change [IPCC] 2019; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES] 2019; Nguyen et al. 2023).

As well as being adversely affected by the crises, Africa plays an increasing role in their exacerbation. For example, although Africa has relatively low emissions when compared with other regions, Africa's total CO_2 emissions more than doubled between 1990 and 2018, with an increase of 34 per cent from 1990–1999 and 2000–2009, and a further 31 per cent from 2010–2018 (Mostefaoui et al. 2024). This rise is compounded by an increasing carbon intensity of production, particularly as the region's top 20 emitters shift towards more carbon-intensive industrial systems (de Melo and Solleder 2023).

Climate change has reduced Africa's ability to achieve targets under the Sustainable Development Goals

Figure 8.3: The interplay of the global environmental crises and regional priority issues: effects on Africa's resource use, ecosystem degradation and climate extremes



Source: Africa Center for Strategic Studies [ACfSS] (2016); WMO (2023)

(SDGs) and the African Union's Agenda 2063, within the context of displaced people and worsening food insecurity. In Africa, more people are at risk of malaria due to warming temperatures (de Coning and Krampe 2020). Between 2019 and 2022, there were substantial increases in estimated case numbers in Nigeria with 5.3 million, Ethiopia with 2.4 million, Madagascar with 1.5 million, Uganda with 1.3 million, the United Republic of Tanzania with 1.3 million, Mali with 1.1 million and Mozambique with 1 million (World Health Organization [WHO] 2023a). Additionally, interacting with factors such as water scarcity and water pollution, climate change is exacerbating problems with the region's water availability, threatening food production and hydropower generation (Obahoundje and Diedhiou 2022). This has socioeconomic implications.

Africa's livelihood support systems – including food, energy and finance, already inadequate and stretched – are further compromised by the global environmental crises. The region, which is not on track to meet the food security and nutrition targets under SDGs 2 and 3, had 281.6 million undernourished people in 2020 (Food and Agriculture Organization of the United Nations [FAO], United Nations Economic Commission for Africa [ECA] and African Union Commission [AUC] 2021). With an electricity access rate of 49.2 per cent in sub-Saharan Africa in 2021, Africa's electricity deficit is the largest in the world (International Energy Agency [IEA] 2022).

The cost of borrowing from international markets is higher in Africa compared to other regions due to perceived high risk. In 2021, 40 per cent of African

bonds yielded 8 per cent compared to around 1 per cent in advanced loans for developed economies (Gbohoui, Ouedraogo and Some 2023). As such, investments in infrastructure, including those for clean water supply and sanitation services, are lagging and resulting in the resurgence of diseases such as typhoid and cholera. Between 1 January 2022 and 16 July 2023, fourteen African countries reported 213,443 cholera cases resulting in 3,951 deaths (WHO Africa 2023b).

Building on the preceding chapters on states and trends of the physical environment, this chapter explores, in an integrated assessment approach, key issues affecting Africa and the extent to which these issues are affected by the global environmental crises (**Figure 8.3**). The assessment further explores the influence of the key issues on human issues, including energy, food, waste, health and economics. Through literature review and expert opinion (Section 8.1), the following issues emerged as priorities for Africa:

- unsustainable resource exploitation and use;
- ecosystem degradation; and
- climate change and climate extremes.

8.2.2 Interlinkages between the global environmental crises and regional priorities

Climate change is causing weather patterns across Africa to change, leading to increased climate variability and extreme events. Droughts have become more frequent in the Sahel and Southern Africa, with events occurring nearly every second year since 2000 (de Coning and Krampe 2020). The Sahel, East Africa and Southern Africa are particularly affected by droughts, while Central and West Africa are primarily threatened by floods. For example, in 2021, South Sudan experienced a third consecutive year of flooding, while heavy rainfall in Niger affected 100,000 people (Elagib et al. 2021; Zeufack et al. 2021; Centre for Research on the Epidemiology of Disasters [CRED] 2022). Cyclones are also becoming more frequent, with 9–12 occurring every year in the southern Indian Ocean, affecting countries such as Madagascar, Mozambique, and their neighbours (Kossin et al. 2020; Otto et al. 2022).

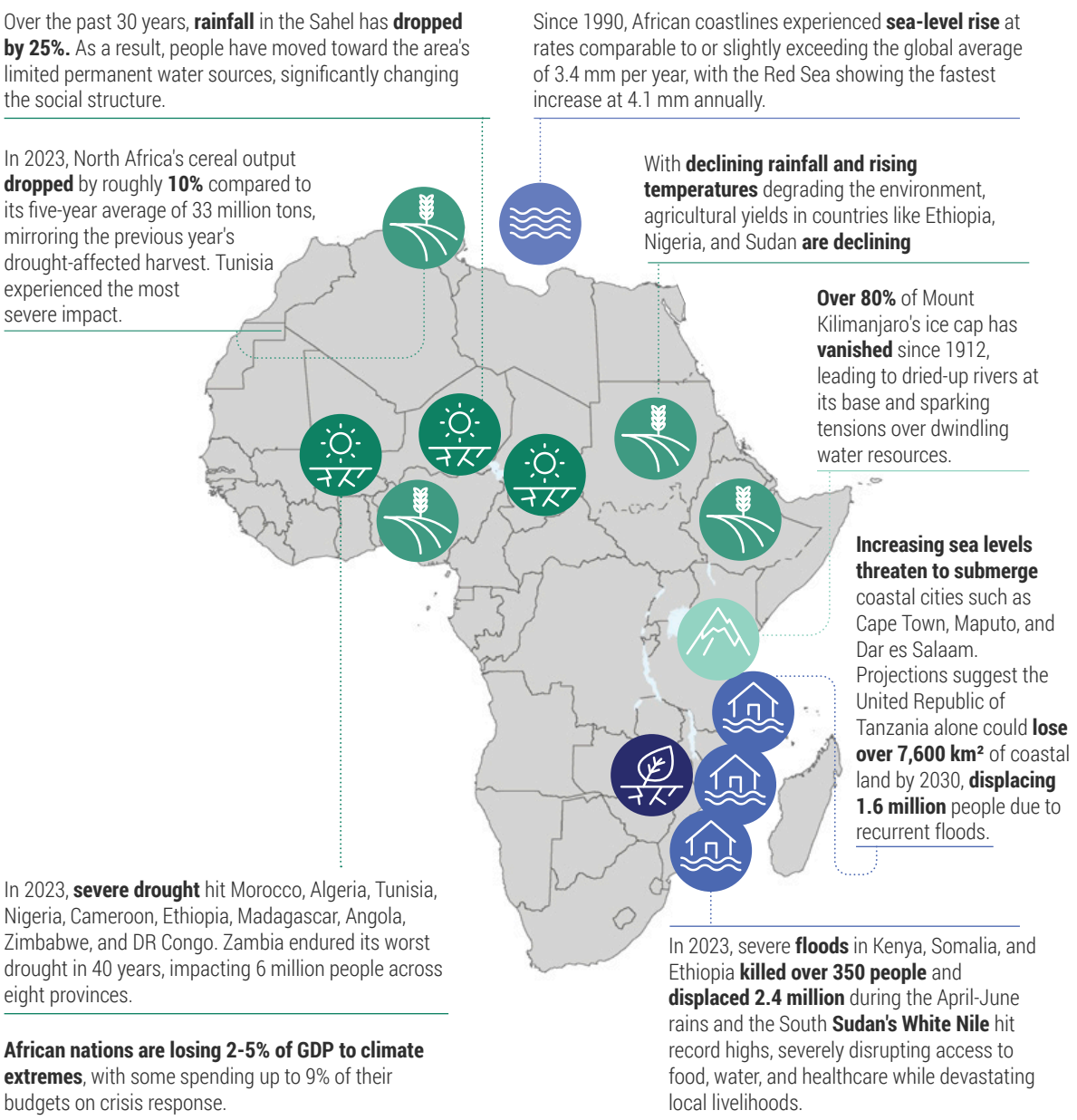
Sub-Saharan Africa experiences a heightened risk of extreme heat events. During the months of June through August, across the Sahel and the western Sahara Desert – approximately 15 per cent of West Africa – most of the population is at risk (Sylla et al. 2018). Exposure to heatwaves has increased in 88 per cent of urban settlements in Nigeria (Tuholske et al. 2021). Consequently, a significant proportion of the population in these subregions is susceptible to heat-related illnesses, including heat exhaustion, heat stroke, and heat cramps (Kunda, Gosling and Foody 2024). The high heat risk in the region is partly related to rapid urbanization, characterized by rapid population growth in high-density urban centres and informal settlements. In cities, large masses of people, industry and transportation are concentrated in compact areas, leading to pollution of the atmosphere, water bodies and soils, as well as the formation of large volumes of municipal and industrial waste.

Rising temperatures, sea levels, and ocean acidity are wreaking havoc on the continent's biodiversity. Consequences include coral bleaching, mollusc-shell decalcification, and a 20 per cent reduction in phytoplankton biomass in the western Indian Ocean since the 1960s (IPBES 2018; World Meteorological Organization [WMO] 2022). These changes devastate fisheries, aquaculture and marine life, with Africa potentially facing the loss of over half of its bird and mammal species, as well as a 20–30 per cent decrease in lake productivity (Chapman et al. 2022).

Climate change intensifies threats by altering weather patterns, leading to more frequent and severe droughts, heatwaves and floods (**Figure 8.4**). These conditions push species beyond their tolerance limits, disrupting ecosystems and food chains. For instance, droughts in the Sahel and extreme heat in Algeria threaten both flora and fauna, while erratic rainfall patterns further destabilize ecosystems (Pecl et al. 2017; Sintayehu 2018).

Africa's ecosystems are deeply affected by the global environmental crises. Unsustainable practices, such as logging, hunting and resource extraction, are major drivers of biodiversity loss (Leisher et al. 2022). This is felt in areas such as the Congo Basin, home to 10 per cent of the world's biodiversity, which is under severe threat from logging. This endangers species and the livelihoods of local communities (Tyukavina 2018; Rocha-Santos et al. 2019). Despite efforts in some countries, such as Nigeria, to curb deforestation, enforcement remains a challenge,

Figure 8.4: Selected effects of climate change on Africa



Source: Africa Center for Strategic Studies [ACfSS] 2016; WMO 2023

leading to further biodiversity loss. Vulnerable species, including amphibians and montane species, struggle to adapt, weakening ecosystems on which millions of Africans depend (Manes et al. 2021).

Africa has seen a dramatic decline in wildlife populations. Overexploitation is rife, with an inability to enforce protective regulations and entrenched unsustainable practices, such as trophy hunting. The region has experienced a decline of 76 per cent in the size of monitored vertebrate wildlife populations between 1970 and 2020, driven primarily by habitat loss, overexploitation, pollution, and the effects of climate change (WWF 2024).

Climate change exacerbates existing land degradation processes and introduces new challenges, such as increasingly severe floods and coastal erosion (Olsson et al. 2019). Coastal degradation is of particular concern. In 2020, it affected 1.4 million people in Benin, Côte d'Ivoire, Senegal and Togo, with 56 per cent of their coastlines eroding at an average rate of 1.8 m per year (Global Centre on Adaptation [GCA] 2022). Overall, 46 per cent, or 14 million km^2, of Africa's land area is degraded, affecting 485 million people and resulting

in an annual economic loss of US$9.3 billion (Olsson et al. 2019). Up to 80 per cent of Africa's cultivated land is degraded, losing 3,000–6,000 kg of nutrients per km^2 per year (Olsson et al. 2019).

Pollution, primarily driven by human activities, is another critical factor contributing to biodiversity loss in Africa. The continent is becoming a hotspot for water pollution, threatening aquatic life through rising water temperatures and sea surface temperature anomalies from 1991 to 2020, ranging from +0.3 to +1.5°C surrounding Africa, with 11 per cent of arable land affected by salinization, and contamination by organic and pathogen pollutants (Jones et al. 2023). In East Africa, rapid urbanization exacerbates the pollution crisis, with rivers contaminated by agricultural run-off, coffee processing waste, and inadequate sewage disposal (Chen et al. 2022). South Africa faces significant groundwater contamination issues, with chemicals and pathogens posing serious health risks (Masindi and Foteinis 2021). Soil pollution from pesticides, industrial solvents and heavy metals is also a significant concern, leading to health problems such as fertility issues, cognitive impairment, and diseases like cancer (Naidu et al. 2021). Improper incineration of pollutants contributes to air pollution, which is the second leading cause of death on the continent, resulting in approximately 1.1 million deaths in Africa in 2019 (Fisher et al. 2021).

Pollution alters the distribution of species and ecosystems. For instance, increasing CO_2 levels are driving bush encroachment because shrub and tree species are better adapted to higher CO_2 levels than grasses, threatening savannah habitats. This shift significantly affects ecosystem services, particularly cattle grazing, in areas such as Namibia's 260,000 km² savannahs (Archer et al. 2017; Belayneh and Tessema 2017; Scheiter et al. 2020).

Rapid urbanization across much of Africa significantly increases waste generation, with implications for water pollution and the spread of human diseases. Africa generates 180 million tons of waste, of which 70 per cent is openly dumped and 9 per cent is plastic waste (Ayeleru et al. 2020), which is reported mainly in the estuarine and marine environments (Akindele and Alimba 2021).

Africa's 121,545 km coastline (Liu et al. 2019) is particularly vulnerable to sea level rise, which has increased the frequency and severity of coastal flooding and erosion (Udinmade Ighedosa 2019). Rising ocean temperatures of +0.3 to +1.5°C around Africa over the last 30 years (Huang et al. 2020) have also led to a doubling in the number of cyclones making landfall since the 1970s (Africa Centre for Strategic Studies [ACSS] 2022). Category 5 cyclones in the southwestern Indian Ocean have not increased in frequency (Fitchett et al. 2016; Ranasinghe et al. 2021; Seneviratne et al. 2021), although tropical cyclones making landfall over central to northern Mozambique are increasing in frequency (Malherbe, Engelbrecht and Landman 2013; Muthige et al. 2018).

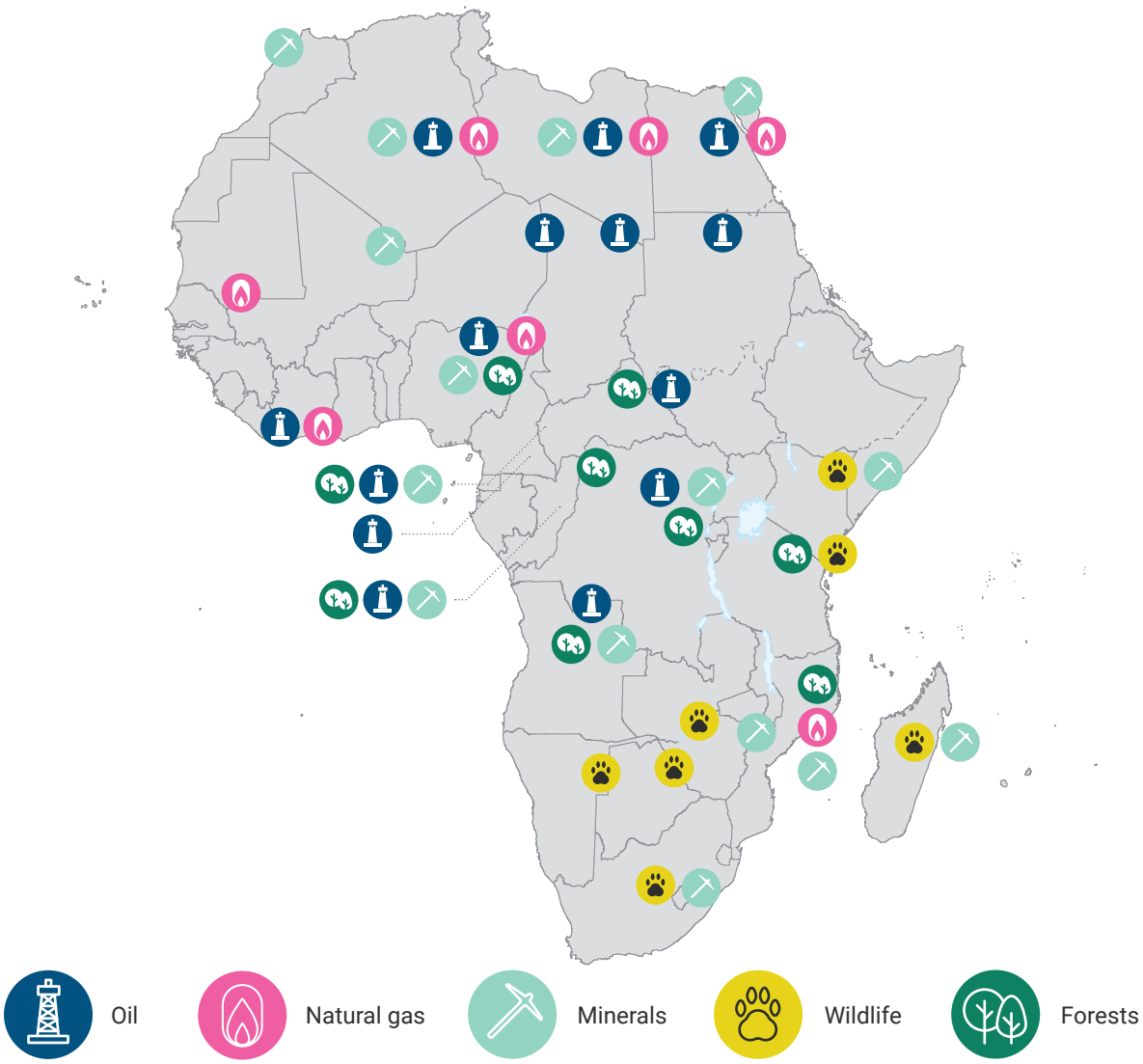
The deteriorating air quality in Africa threatens human health and has been linked to one in every five infant deaths and 16 per cent of all deaths in the region (Mlambo et al. 2023). Over the past five decades, air quality in Africa has deteriorated rapidly, making its cities among the most polluted globally, with particulate matter concentration levels between five and ten times the recommended levels (Mead et al. 2023). Air pollution in Nairobi, for instance, is five times higher than the limit recommended by the World Health Organization (Nakweya 2022). Comparatively, Kampala has poorer air quality, while Lagos, Nigeria, has the worst air quality in Africa (Kirenga et al. 2015; Abulude et al. 2020).

Food security, malnourishment and associated factors such as health, access to energy and access to or ownership of resources affect Africans inequitably based on their social class, gender, national rate of economic growth, and political stability (Wudil et al. 2022). The resulting crisis, fuelled by unsustainable rates of urbanization, has sparked insecurity crises in countries such as South Africa, where limited resources and the proliferation of informal settlements have exacerbated xenophobia (Mamabolo 2015; Hiropoulos 2020).

8.2.3 Priority issue: unsustainable resource exploitation and use

Africa's vast natural resources face a dual threat from both overexploitation and underutilization, resulting in environmental degradation and missed economic opportunities. Africa is rich in natural resources (**Figure 8.5**). The exploitation of these resources has significant environmental implications. This section explores how the continent's resources are currently

Figure 8.5: Africa's resources map



being used, focusing on the dual issues of overuse and underuse and the consequences for the environment and human systems.

Resource extraction drives economic growth but also causes significant environmental damage, threatening sustainable development. Southern Africa presents a contrasting scenario where Botswana and South Africa, rich in diamonds and gold, respectively, show how mineral wealth can contribute to economic growth but also lead to environmental challenges like water and soil acidification, such as pH ranges of 1.9–5.3 in soil (Mokwakwa 2021; Tibane and Mamba 2022; Laker 2023). Similarly, in West Africa, the oil sector contributes about 9 per cent to Nigeria's gross domestic product (GDP) but has led to significant environmental degradation in the Niger Delta (Ite et al. 2013; Sam and Zibima 2023; Sami and Taiwo 2023).

Economic activities, such as logging, further degrade the terrestrial environment in West African countries. In countries such as Burkina Faso, the growing population is driving agricultural expansion into forests, with the country experiencing a deforestation rate of approximately 1 per cent annually, translating to an estimated loss of 900 km^2 of forest per year over the past five years (FAO 2021). This expansion is driven mainly by subsistence agriculture and the increasing demand for arable land to support the growing population.

Illegal logging has become a major issue, particularly in protected areas where valuable timber species such as Pterocarpus erinaceus are targeted. The removal of these trees not only depletes forest resources but also disrupts local ecosystems, leading to soil erosion, loss of biodiversity, and reduced capacity

for carbon sequestration (Dimobe et al. 2015). This trend is replicated across Africa – notably in Zambia, Ghana and the United Republic of Tanzania – where medium-scale farms are established in, or expanded into, areas that were previously forested, exerting more pressure on finite forest resources to feed the growing population (Wineman, Jayne and Stevens 2022). Currently, an estimated 65 per cent of Africa's productive land is degraded, while 45 per cent of the continent's land area is affected by desertification (Mansourian and Berrahmouni 2021).

Africa faces rapid deforestation and soil degradation, which reduces land productivity and pressures forests for agricultural use. Africa is losing its forests and productive lands, with annual deforestation estimated at 390,000 km^2, particularly in countries such as Nigeria, the Democratic Republic of Congo, and Ethiopia (FAO 2021). The Democratic Republic of the Congo is driven by factors including damaged soil structure and quality from chemical pollution in agriculture, which has led to soil contamination and a subsequent reduction in soil fertility. The excessive use of agricultural chemicals, such as nitrogen-based fertilizers, also contributes to soil acidification and nutrient imbalances, further degrading soil quality (Vanlauwe et al. 2015; Acheampong and Opoku 2023). These issues reduce the productivity of agricultural land, necessitating further conversion of more forests into land for food production.

Overexploitation of aquatic resources threatens marine biodiversity and the economic viability of coastal communities. The unsustainable exploitation of aquatic resources through overfishing, sand harvesting, and dredging threatens coastal and marine ecosystems, eroding their ability to produce food or contribute to economic development. Illegal fishing and overfishing are particularly rampant along the West African coast, affecting vulnerable and endangered marine species, including dolphins, monk seals, sea turtles and some shark species, together with Palearctic seabirds that rely on the West African coast for breeding and shelter during winter (Lemrabott et al. 2024; Merceron et al. 2024).

Unsustainable water use and pollution are depleting and contaminating Africa's freshwater sources, exacerbating water scarcity. The most water insecure African countries are Chad (with a national water security score of 39 per cent), Comoros (40 per cent), Djibouti (32 per cent), Ethiopia (31 per cent), Eritrea (29 per cent), Liberia (36 per cent), Libya (37 per cent), Madagascar (37 per cent), Niger (38 per cent), Sierra Leone (38 per cent), South Sudan (37 per cent) and Sudan (30 per cent) (MacAlister et al. 2023).

The degradation of wetlands in Africa, driven by industrial pollution, oil spills, aquaculture expansion and unsustainable mangrove harvesting, has had devastating effects on biodiversity and ecological stability. In the Niger Delta region, for instance, wetlands have lost much of their capacity for carbon sequestration and water filtration, exacerbating freshwater scarcity and increasing vulnerability to flooding and coastal erosion. This degradation not only threatens local species but also jeopardizes the livelihoods of communities that depend on these ecosystems for sustenance (Zamboni et al. 2021; Sam et al. 2023; Wekesa et al. 2023; Turner and Ohimain 2024). In the African mainland, sources of fresh water are being depleted and polluted by agricultural activities and waste from industries and households. For example, DDT levels of 81.2 µg/L were found in South African fresh water (Makgoba et al. 2024). This pollution and unsustainable use of scarce water resources worsen the prevailing freshwater crisis on the continent while threatening human life and overall water security.

Climate change and land degradation are undermining Africa's ability to meet its growing food needs, thereby increasing the risks of malnutrition. The current output is already insufficient to feed the continent's population (Beltran-Pena and D'Odorico 2022), and Africa is facing a rising rate of malnutrition and declining food security (Adesete, Olanubi and Dauda 2023). Kenya's reliance on agriculture, which accounts for 33 per cent of its GDP, is threatened by recurrent droughts and land degradation (Kalele et al. 2021; Yilmaz and Njora 2021).

8.2.4 Priority issue: ecosystem degradation

Africa's ecosystems are facing severe degradation due to the global environmental crises (Olsson et al. 2019; Chomba et al. 2020; FAO 2020; Mansourian and Berrahmouni 2021). While Africa has food supply issues, the wider biodiversity loss is both a driver and a consequence of ecosystem degradation, creating a feedback loop that threatens ecological

integrity and the well-being of human health, water, food, nutrition, energy security and socioeconomic development across Africa. The continent hosts 17 per cent and 31 per cent of the world's forests and other wooded lands, respectively (IPBES 2018). Major drivers of degradation of Africa's ecosystems include increased consumption due to rapid population growth, land-use change due to the conversion of forests, rangelands and wetlands to agriculture, mining, unplanned urbanization, pollution and wastes, and other infrastructure development (Bradshaw and Di Minin 2019; IPCC 2022a).

Africa has lost an estimated 64 per cent of its wetlands since 1900, with a 20 per cent reduction between 1990 and 2020 (UNEP 2021). Wetlands are home to approximately 20 per cent of the continent's biodiversity, including numerous species of fish, birds, amphibians, and plants (Convention on Wetlands [Ramsar] 2022). Approximately 50 million people in Africa face water shortages due to wetland loss (Chelea et al. 2020), which jeopardizes food security and economic stability. However, an estimated 35 per cent of wetlands have been degraded due to land degradation, urbanization, and agricultural expansion (Ramsar 2022). In the Niger River Basin, 25 per cent of wetlands have been converted to farmland (UNEP 2020). Meanwhile, urbanization has led to over 50 per cent degradation of coastal wetlands in Lagos and Accra in West Africa (Ekumah et al. 2020; Adeleke 2022), while pollution from untreated sewage in the Nile Delta in North Africa has resulted in a 30 per cent decline in water quality (Morsy, Mishra and Galal 2020). Similarly, Southern Africa has lost 40 per cent of its wetlands due to land conversion for agriculture and urban development, particularly in the Limpopo Basin and the Okavango Delta (Gxokwe, Dube and Mazvimavi 2024). In East Africa, the area of wetlands around Lake Victoria has decreased by about 30 per cent due to urban and agricultural expansion (Cooperation for International Waters in Africa [CIWA] 2022).

Climate change exacerbates wetland loss, with average temperatures in Africa increasing at a rate 1.5 times faster than the global average (IPCC 2023). Droughts have led to a 30 per cent reduction in wetland areas around Lake Victoria and a 40 per cent reduction in water availability in the Sahel (UNEP 2022). Wetlands in the Lake Chad basin have shrunk by 90 per cent since the 1960s (Zhao, Cook and Vizy 2023), affecting biodiversity, food security and ecosystem services, with 28 per cent of wetland species at risk of extinction and about 40 per cent classified as threatened (IUCN 2023). Wetland degradation threatens livelihoods, with a 20 per cent decline in fish catches around Lake Victoria (Owonikoko and Momodu 2020) and decreased agricultural yields in the Niger Delta (Ramsar 2022).

Degradation of Africa's marine ecosystems and coastal areas is accelerating due to unsustainable human activities. Africa's coastal marine and coastal systems harbour 36 global biodiversity spots, 439 marine key biodiversity areas, and 148 marine and coastal Ramsar sites (World Bank 2022). The continent's marine and coastal ecosystems are experiencing a wide range of degradation, including overexploitation, habitat degradation and loss, unsustainable infrastructure development, pollution, coastal erosion, biodiversity loss, invasive species, and climate change (World Bank 2022). Pollution from untreated wastewater, oil spills and plastics poses a threat to marine ecosystems, tourism, shipping, fisheries, and human health (World Bank 2022). The effects manifest through the impairment of the oceans' carbon-storing function, which is damaged by the destruction of ecosystems such as mangroves, salt marshes and seagrasses. For example, pollution resulting from untreated domestic wastewater is estimated to cost US$31 million in Senegal and US$35 million in Côte d'Ivoire (World Bank 2022). Oil spills in the coastal delta of Nigeria were estimated to cost US$66 million, equivalent to 0.5 per cent of its GDP in 2018 (World Bank 2022) and plastic pollution led to a minimum lifecycle cost of about US$61 million in South Africa in 2019 (Sadan and De Kock 2021).

Climate change threatens biodiversity through a reduction in primary production and fish abundance. Increases in water acidification cause coral reef bleaching, leading to the destruction of fish and other marine life habitats (IPCC 2022b; IPCC 2022c; World Bank 2022). By 2016, in the western Indian Ocean, coral cover had decreased by 30–40 per cent of its 1998 levels (Moustahfid, Marsac, and Gangopadhyay 2018), due to mass coral bleaching that occurred during this time. These effects have negative consequences for the economies and livelihoods of coastal communities (World Bank 2022). For example, in Togo, coastal erosion led to a decrease in fish catch due to rocky shorelines that prevent the local population from landing their boats.

Mountainous regions are experiencing increased degradation due to human activities and climate change, with approximately 70 per cent of these key ecosystems affected (Adler et al. 2023). African mountains, which cover approximately 22 per cent of the continent, are vital ecosystems that support biodiversity, regulate the climate and sustain human livelihoods. However, deforestation and unsustainable agricultural practices have led to significant soil erosion and diminished water quality, with the East African Highlands experiencing a 20 per cent decline in vegetation cover (IPCC 2022d). Pollution from urban run-off exacerbates biodiversity loss, placing 30 per cent of mountain species at risk of extinction (IUCN 2023). Burundi and Rwanda face severe degradation, with a significant percentage of their land affected (Tall et al. 2022). As mountains are essential for agriculture, water supply and traditional knowledge, their decline jeopardizes food security and increases vulnerability to climate shocks for millions across Africa.

Glaciers have lost over 80 per cent of their volume since the early 1900s in East Africa, threatening local communities' water supply (Mastrorillo et al. 2016; Hinzmann et al. 2024). A critical concern is the receding glaciers in regions such as the Rwenzori Mountains of Uganda and the Democratic Republic of the Congo and Mount Kilimanjaro of the United Republic of Tanzania, vital water sources for about 5 million inhabitants (Garelick et al. 2022; Jackson et al. 2020; Hinzmann et al. 2024).

Savannah ecosystems cover about 65 per cent of Africa's land area but are increasingly threatened by human activities such as large-scale mining and oil extraction, leading to the degradation of these ecosystems (Hahn and Leßmeister 2021). Anthropogenic activities, including agricultural expansion, plantation forestry, overgrazing, human settlements, large-scale mining operations and climate change are accelerating the degradation of savannah ecosystems, leading to pollution and loss of biodiversity and endangering the livelihoods of pastoral communities (Dudley et al. 2021; Williams et al. 2022; IPCC 2022a; IPCC 2022b). For example, in East and Southern Africa, extractive industries, including oil and gas drilling and mining of gold, copper and coal, are increasingly encroaching on savannah regions. Agricultural activities, including the clearance of vast tracts of land for crops such as sugarcane, maize and soybeans, in the United Republic of Tanzania and Mozambique, contribute to the loss of native vegetation and biodiversity (Ahmed, Bryant and Edwards 2021; Benton et al. 2022). Climate change exacerbates these challenges due to rising temperatures and changing rainfall patterns, which increase the frequency of droughts and wildfires and reduce rangeland productivity. In Namibia, uncontrolled bushfires threaten Etosha and Namib Naukluft national parks (UNEP 2020). Droughts driven by climate change have led to significant livestock losses, particularly affecting pastoralist communities that depend on livestock grazing, with up to 30 per cent livestock losses in some regions due to recurrent droughts (IPCC 2022b).

Africa's inhabited dryland regions are under increasing threat from the global environmental crisis, reducing ecosystems' resilience, food security, and people's livelihoods (FAO 2019; Mbow et al. 2019; Samuel and Sylvia 2019). These ecosystems account for 11 per cent of the Earth's surface, 27 per cent of the world's total drylands, and 40 per cent of Africa's land area (Wei et al. 2021), supporting nearly 85 per cent of the population (Kogo, Kumar and Koech 2021).

Over 170 species in sub-Saharan Africa are listed in IUCN's endangered categories, with ecosystem degradation as a key driver of this trend. The largest class of threatened taxa is African primates, constituting 96 of the 172 listed species (Duporge et al. 2020). Illegal poaching and trafficking of wildlife pose a significant threat to Africa's iconic species, such as rhinos and elephants. These activities not only decimate populations but also disrupt ecological balance, having far-reaching consequences for local communities (Duporge et al. 2020; Lunstrum and Givá 2020; World Bank 2021; Mozer and Prost 2023). The introduction of the Nile perch, a voracious predator in Lake Victoria, and the invasive water hyacinth led to the decline and near extinction of native haplochromine cichlid fish, changes in the habitat and trophic dynamics, loss of species diversity among cichlids, and water clarity (Aloo et al. 2017; Nyamweya et al. 2018).

Conversely, the degradation of ecosystems has profound socioeconomic consequences. Rural communities, particularly in arid and semi-arid regions, depend heavily on ecosystem services for subsistence agriculture, pastoralism, energy and medicine. Biodiversity loss and land degradation reduce food and water security, increase exposure to climate-related hazards, and heighten the risk of conflict

Credit: osbmxhouse/Envato

over shrinking resources (Barbier and Hochard 2018; IPCC 2022d). Moreover, marginalized populations – especially women and Indigenous Peoples – are disproportionately affected due to their reliance on natural resources and limited adaptive capacity.

8.2.5 Priority issue: climate change and climate extremes

Rising temperatures are causing floods and coastal erosion in some parts of Africa and reducing precipitation in others (WMO 2021). Extreme sea level events are occurring more frequently, particularly in tropical regions. Countries where large proportions of the population live on the coast – such as Senegal at 41 per cent, Benin at 35 per cent, and Liberia at 29 per cent – are particularly vulnerable to sea level rise (ACSS 2022). In addition, since the 1980s, climate change has led to the doubling of marine heatwaves in Africa, destroying marine ecosystems, leading to the extinction of many marine species, and causing migration of marine life from their original habitats (Trisos et al. 2022; Nhantumbo, Dada and Ghomsi 2023).

Climatic changes are straining water systems (WMO 2021; IPCC 2022b). Due to decreased precipitation and increased evaporation, several major African water systems, including Lakes Kariba, Kivu, Tanganyika, Victoria and Malawi, experience regular low water storage levels. Climate change is causing more frequent and intense fluctuations in El Niño and La Niña years, which in turn affect Lake Victoria, 80 per cent of which is dependent on precipitation (Ransom 2021).

Rising temperatures, precipitation changes and the increased occurrence of disasters such as cyclones, severe storms and droughts contribute to the spread of diseases, food security problems, limited or no access to clean water and sanitation facilities, a high risk of waterborne disease, heat stroke, and mental health problems (integrated African Health Observatory [iAHO] 2024). Additionally, there has been an increasing number of waterborne disease outbreaks in Africa due to inadequate sanitation and unsafe water supplies. There is robust evidence in the region that the health impacts of climate change disproportionately affect the poorest individuals and children, and in some cases, can vary by gender and age (Nyahunda et al. 2020; Ragavan et al. 2020).

Persistent declines in food production are distressing Africa. Disruptions in agriculture led to increased hunger in Africa in 2020. Although the continent saw promising agricultural progress – with productivity rising by an average of 13 per cent annually from 2015 to 2020 and the agricultural trade deficit declining by 26 per cent – most African agriculture remains small-scale, rain-fed, and reliant on low

technology (African Development Bank [AfDB] 2021). These circumstances leave farmers particularly vulnerable to biological, economic and climate-related shocks, such as droughts, cyclones, floods and pest invasions like desert locusts, fall armyworm, and animal diseases like peste des petits ruminants. Consequently, disruptions from COVID-19 severely affected agricultural markets and farmer incomes. For instance, a survey conducted in mid-2020 in Malawi showed that 73 per cent of agricultural households reported reduced agricultural earnings due to the pandemic (Nolte, Sipangule and Wendt 2022).

Extreme weather conditions have resulted in a decline in agricultural production. While North Africa's cereal production in 2023 was 33 million tons, similar to the previous year's drought-stricken harvest, this is 10 per cent lower than the five-year average. Tunisia's cereal production decreased by over 80 per cent compared to the annual average, due to drought conditions (FAO 2023). Erratic rainfall and insecurity kept cereal production below average in northern parts of the Greater Horn of Africa. In Sudan, seasonal rains were below average and erratic, with long dry spells. Sorghum and millet production were expected to fall by about 25 per cent and 50 per cent, respectively, from 2022 levels (WMO 2023).

Renewable energy targets are at risk from the effects of climate change. Climate change will affect hydropower generation in Africa by reducing plant generation output (IEA 2020). For example, Zambia depends on hydropower for over 80 per cent of its electricity generation (IEA 2019). The output from major Zambezi hydropower plants could decrease by 10–20 per cent under drier climate conditions, leading to a rise in electricity costs by 20–30 per cent in the short term in the hydro-dependent countries of Mozambique and Zambia (Spalding-Fecher, Joyce and Winkler 2017). The reduction in the duration of the rainy season, coupled with frequent droughts, results in a decrease in water inflows into the Kariba reservoir (Ahmed et al. 2020; Arias et al. 2022;), which led to reduced output and the implementation of daily blackouts in August 2019 (Hill and Ndlovu 2019).

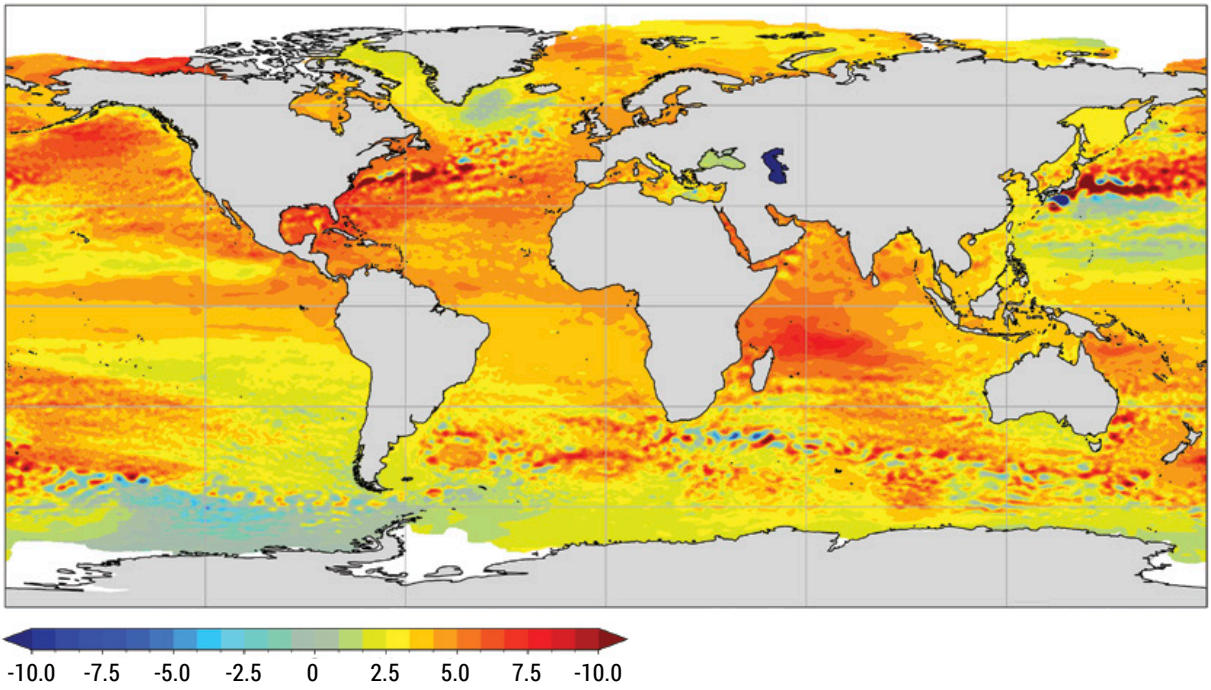
Climate hazards do not only impact the environment – they threaten socioeconomic development in Africa, which has been losing between 5 and 15 per cent of its GDP per capita growth due to climate change and its related impacts (AfDB 2022). Estimated losses in resource-rich countries, such as Botswana, Equatorial Guinea and Gabon, and services or manufacturing-based economies such as Mauritius and South Africa are lower than in other African countries that are heavily dependent on agriculture. Many of the countries most affected by climate change are already impoverished (AfDB 2022). Most of the effects are evident in the form of setbacks in agriculture, tourism, infrastructure and manufacturing.

Climate change is threatening Africa's infrastructure and settlements. This undermines SDGs such as SDG 11. Intense storm surges are worsening sea level rise, endangering coastal communities and infrastructure (Richardson et al. 2022). Coastal nations in West and Southern Africa, including Senegal, Nigeria and Angola, face erosion and sea level rise due to their low-lying lagoonal coasts. The situation is of concern because many of these countries have rapidly expanding coastal cities (**Figure 8.6**). The East Coast of Africa is also at risk, as sea level rise and climate variation may lead to coral and patch reef attenuation, which could increase the potential for erosion (Mafaranga 2020; Vousdoukas et al. 2022; Nhantumbo, Dada and Ghomsi 2023).

Climate change's slow-onset events, including droughts, desertification, deforestation, water scarcity, rising sea levels and coastal erosion, have led to increased migration in Africa over recent decades. This affects SDG progress related to SDG 6, 7, 13 and 15. In 2018 in sub-Saharan Africa, East and West Africa were hotspots for disaster-related displacements, with 1,437,7000 and 798,000 displaced people respectively, accounting for 13.9 per cent of the global total and one of the highest numbers on record (Internal Displacement Monitoring Centre [IDMC] 2019; IPCC 2022b; Trisos et al. 2022).

Climate change is straining health systems by increasing mortality and morbidity, threatening the realization of SDG 3. Climate change and land-management practices have led to an increase in dust storms, particularly in North Africa, which contributes to the spread of respiratory diseases such as asthma and bronchitis (D'Amato et al. 2016; Awadh 2023). Large numbers of people have been affected by climate-related hazards (**Figure 8.7**). In the Saharan regions and in addition to the respiratory and ophthalmic health risks linked to mobile sands and heatwaves, the population is also subject to cross-border diseases, such as malaria

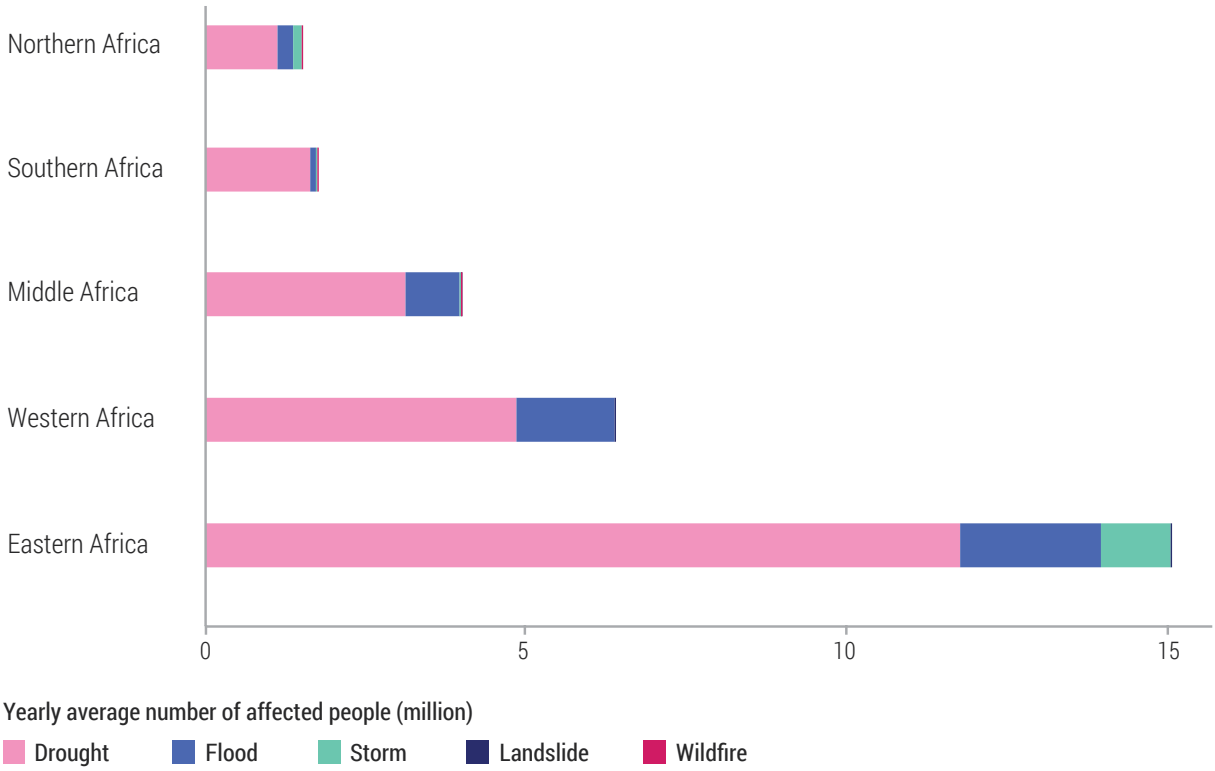
Figure 8.6: Sea level trends from 1999 to 2024



Note: Global ocean sea level trends from satellite altimeter observations (in mm/yr) over the period 1999/02/20 to 2024/11/19. The ocean monitoring indicator is derived from the DUACS delayed-time reprocessed dataset for climate applications (DT-2024)

Source: EU Copernicus Marine Service Information/Copernicus Climate Service

Figure 8.7: Climate-related hazards and number of affected people per sub-region of Africa



Note: Affected people refer to those requiring immediate assistance during a period of emergency or requiring basic survival needs, such as food, water, shelter, sanitation and medical attention. The figure presents the yearly average numbers from January 2011 to December 2024.

Source: EMDAT (2025)

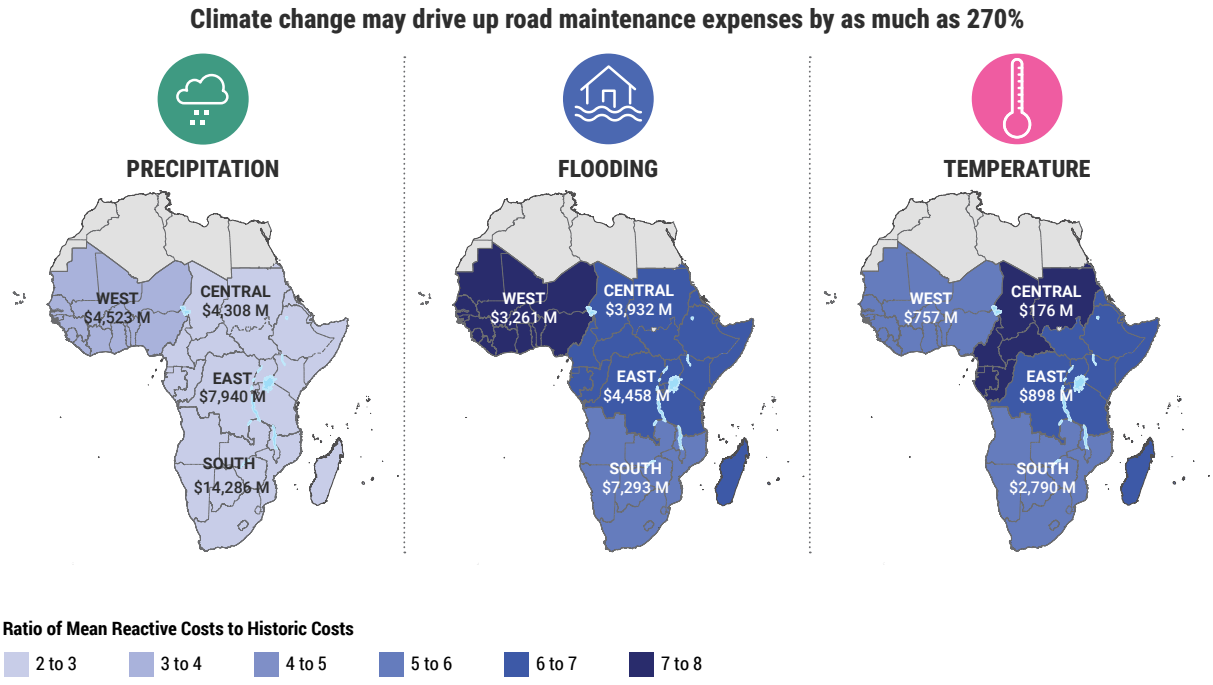
and HIV, that risk spreading through the mobility of citizens or directly via exogenous migratory flows.

Extreme climate situations are directly related to the increased frequency and severity of emerging and re-emerging infectious diseases in Africa, including dengue, cholera and malaria, with more than 166 outbreaks registered in 2023. Malaria outbreaks have spread to areas that were previously unaffected and have become more common in East African highlands, where temperatures now support breeding of the vectors (Caminade et al. 2014; Caminade et al. 2019). A ninefold increase in dengue infections in Africa was reported in 2023, compared with 2019 (WHO 2023c).

Agriculture, which employs 55 to 62 per cent of Africans and accounts for almost a quarter of the continent's GDP, is almost entirely rain-fed (Bari and Dessus 2022). Lower agricultural productivity and sectoral growth due to weather extremes reduce revenue and worsen current account deficits, resulting in economic growth declining from 4 per cent to 3.6 per cent in 2022 and to 2.5 per cent in 2023.

Flood-induced damage in Africa was estimated at over US$4.4 billion between 2005 and 2020. Droughts and floods have reduced African GDP by 0.7 per cent and 0.4 per cent, respectively, since 1990 (Trisos et al. 2022). Climate damage to infrastructure puts massive African government investments at risk, mainly because most of these have been financed by public debt (International Monetary Fund [IMF] 2020). Eight of the 20 countries with the highest expected annual road and rail asset damage due to climate change, relative to their GDP, are in Africa (Trisos et al. 2022) (See also **Figure 8.8**). In addition, weather damage to transport infrastructure raises transport costs, affecting monetary policy. These costs are passed on to consumers, raising inflation. As climate change reduces domestic food production, the region imports more, which increases the current account deficit, erodes foreign reserves, reduces the foreign exchange available to service external debt, and influences exchange rates, thereby exposing African governments to weather-induced inflation (IMF 2020). **Table 8.2** shows anticipated climate change-induced GDP losses by 2030.

Figure 8.8: Estimated increase to road maintenance costs due to climate change



Note: The figures represent the overall impact of climate change on road maintenance expenses (in 2015 dollars, discounted at 6%) caused by precipitation, flooding, and temperature stress in Central, East, South, and West Africa. The color coding shows the proportion of reactive maintenance costs relative to past costs for each stressor in these regions. Flooding and temperature-related stresses are projected to lead to substantial rises in reactive costs compared to historical levels. The subregional grouping from this source differs from the UN regional groupings.

Source: Adapted from Cervigni et al. (2017)

Table 8.2: Anticipated climate change-induced GDP losses by 2030 for temperature increases between 1°C and 4°C

African subregion	GDP (% change/year) at temperature increases between 1°C and 4°C
Northern (7 countries)	-0.76 ± 0.16
Western (15 countries)	-4.46 ± 0.63
Central (9 countries)	-1.17 ± 0.45
Eastern (14 countries)	-2.01 ± 0.20
Southern (10 countries)	-1.18 ± 0.64
Africa	-2.25 ± 1.52

Note: The subregional grouping used here follows the classification adopted by the African Union Commission, which differs from the five United Nations regional groupings.

Source: UNECA (2021)

Climate change increasingly threatens Africa's tangible and intangible cultural heritage, particularly along coastlines. Currently, 56 heritage sites, or 20 per cent of total sites identified, face immediate risk from severe coastal events such as storm surges, high waves and erosion – events expected to grow more frequent and intense. North Africa has the highest exposure with 23 sites, followed by West Africa with 18, Southern Africa with 7, and East Africa and Small Island Developing States with 4 each. Tunisia, Morocco and Senegal have the most at-risk sites, with 7 sites each (Vousdoukas et al. 2022).

8.3 Asia and the Pacific and subregions

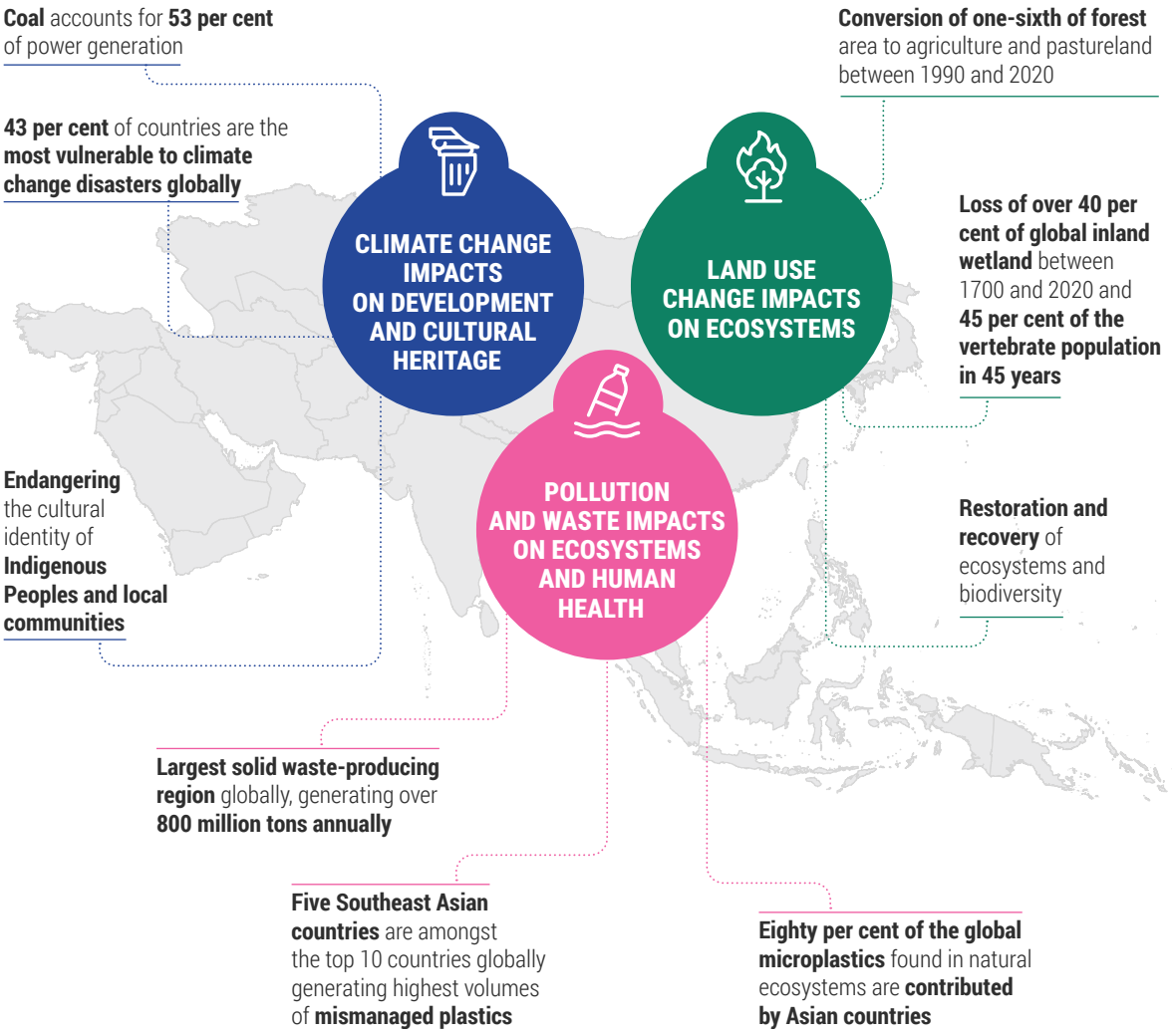
8.3.1 Introduction

The Asia and the Pacific region (AP) covers approximately 22 per cent of the total global land area with high social, cultural, biological and topographical diversity, which provides home to almost two-thirds of the world's population (Karki et al. 2018). The AP's human and other resource bases have enabled it to experience rapid economic growth (Ahmed, Ali and Kousar 2022). However, drivers and pressures (Chapter 2), especially economic development, have contributed to the global environmental crises and caused three related priority issues in AP. (**Figure 8.9**).

Climate change and associated disasters have caused significant economic and social damage in the AP, where approximately 40 per cent of countries are most vulnerable to climate change and related disasters. This vulnerability has resulted in about 2 million deaths from climate change-related disasters since 1970 (World Bank 2022; ESCAP 2023). The losses from such disasters – including floods, droughts, forest fires, sea level rise and marine acidification – are accelerated by poor adaptive capacities (UNEP 2022; World Bank 2022).

Land-use changes, as well as climate change and pollution and waste, have critically affected natural resources, leading to a decline in human well-being, particularly among poor and

Figure 8.9: The inter-play of the global environmental crises as they affect Eurasia's resource use, ecosystem degradation and climate extremes



vulnerable communities in AP (Sibt et al. 2023). The increased demand for both ground and surface water for intensified agricultural output and industrial needs has put the quantity and quality of regional water resources under stress. This stress results in the degradation of wetlands and marine aquatic resources. Building dams accelerates damaging effects on natural floodplain regulation, fish-spawning habitats and rice production, putting the livelihoods of natural resources-dependent Indigenous communities at risk (Ullah et al. 2021).

Environmental pollutants and waste in AP have led to serious health issues and risks to economic growth. Anthropogenic sources, including industrial activities, mining, agriculture, livestock, and consumer lifestyles, significantly pollute the soil, damage agricultural crop yields and endanger human health (FAO and UNEP 2021). For example, very high levels of air pollution with fine particulate matter ($PM_{2.5}$) are responsible for staple crop losses of 5–20 per cent in maize, rice, soy, and wheat in the region (CCAC and UNEP 2019).

Pollutants are closely associated with environmental inequality and injustice in the AP (ESCAP 2018) due to unevenly distributed impacts and effects. Pollution has a greater impact on vulnerable groups, such as women, youth, low-income people, and Indigenous Peoples and local communities and their traditional ways of life. For example, more frequent heatwaves that exceed dangerous levels, especially in South Asia and the Arabian Peninsula, pose a serious threat to poor, vulnerable people working outdoors (IFRC and OCHA 2022). Low-income people living in compact urban settlements face a greater risk of health problems due to their

inability to manage resources to cope with heat (Berger et al. 2022).

8.3.2 Interlinkages between the global environmental crises and regional priorities

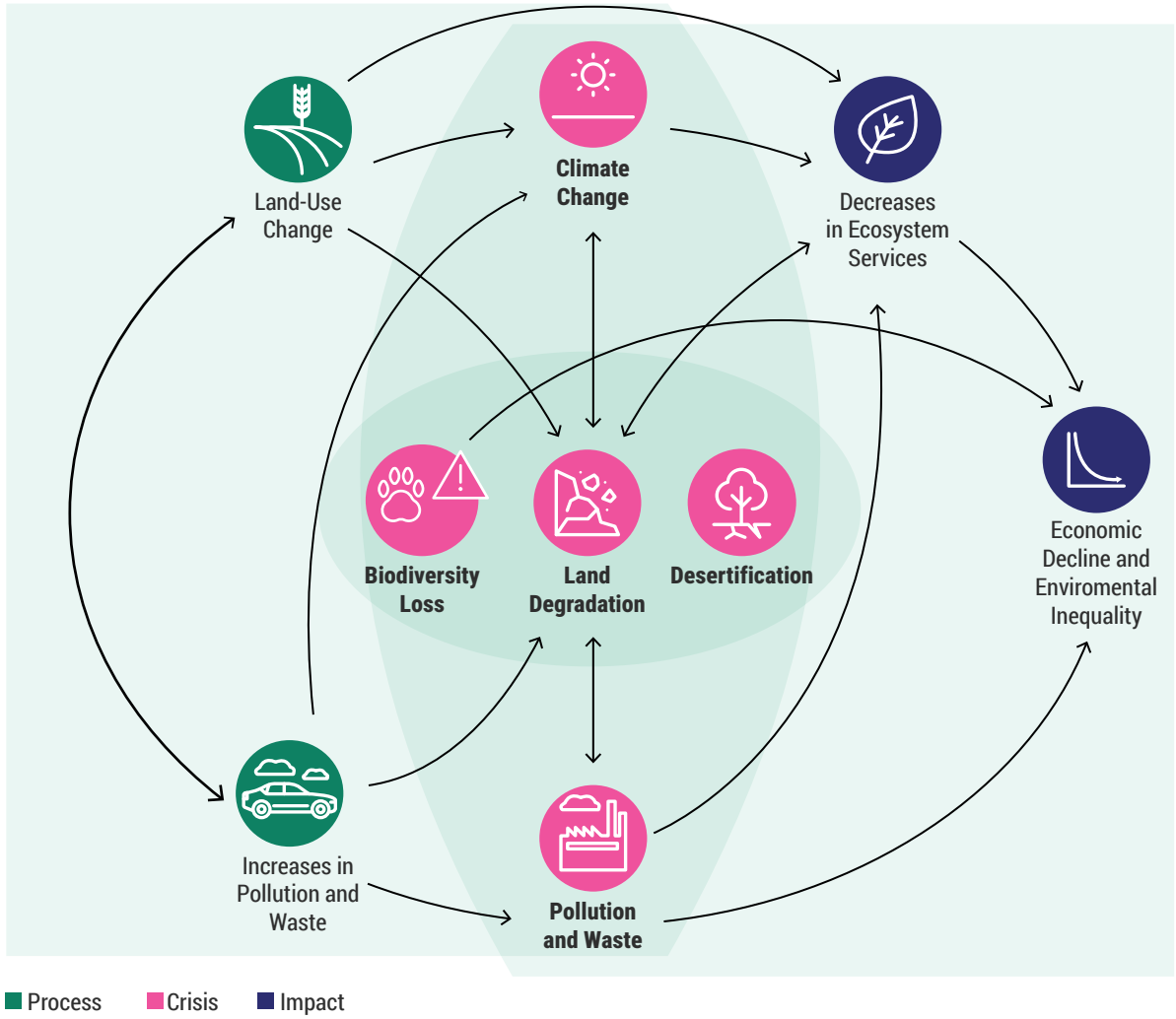
As described in the Global Environmental Crises Chapeau, the global environmental crises – the crisis of climate change, the crisis of biodiversity loss, land degradation and desertification, and the crisis of pollution and waste – are intrinsically linked.

In AP, intensive land-use changes and rising pollution and waste – from high in the Himalayas to the coasts – have created a complex web of drivers and pressures that exacerbate the global environmental crises. The result is a critical decline in ecosystem services in the region and, ultimately, economic decline, and environmental inequality and injustice (**Figure 8.10**).

The AP has undergone extensive land-use transformation to agriculture and pastureland since the 1960s. This land-use change has produced large quantities of air pollutants, pesticides, plastics and other solid wastes, leading to enhanced climate change, a rapid loss of biodiversity and ecosystems, and increased pollution (Alavaisha et al. 2021; Takeuchi et al. 2021; Kondo et al. 2022; Ng et al. 2023). These changes weaken greenhouse gases (GHG) mitigation efforts and adaptation capacity to climate change, increase pollution and waste, and accelerate land further degradation in AP (Ullah et al. 2021; Sibt et al. 2023).

Climate change exacerbates biodiversity loss through altered weather patterns, intensified extreme events, and accelerated habitat destruction (Ajilogba and Walker 2021). Pollution and waste have caused significant biodiversity loss through the excessive use of pesticides, and the pervasiveness and accumulation

Figure 8.10: Selected interlinkages assessed within the Asia and Pacific region



of plastic debris and microplastics in benthic sediments and marine biota (Curren and Leong 2019). Biodiversity loss amplifies vulnerabilities to climate impacts, exacerbating pollution challenges, adversely affecting ecosystem functionality and threatening species survival. The AP region lost 45 per cent of its vertebrate population in 45 years, with India losing 12 per cent of its wild mammals, 19 per cent of its amphibians and 3 per cent of its birds (WWF 2023).

These drivers and pressures heighten socioeconomic vulnerabilities, especially among marginalized groups. Individuals living in poverty are more inclined to downplay the risks associated with toxic exposure and future health concerns in favour of immediate economic gratification (Citaristi 2022). Poverty and economic disparities are closely linked to the generation of waste and other human-induced environmental hazards (Kaÿmierczak 2018; Mihai et al. 2021). However, there are significant gaps in the region's ability to address these challenges, particularly in terms of ensuring full and effective participation of Indigenous Peoples and local communities, as well as their knowledge systems. These circumstances stem from issues including inadequate policies, limited finances, technological disparities and varying levels of readiness and monitoring among nations.

8.3.3 Priority issue: climate change impacts on development and cultural heritage

Climate change is threatening both tangible and intangible cultural heritage in the AP region, contributing to the losses and damages that are increasing faster in this region than the global average. The degradation of heritage sites exacerbates inequality, endangers cultural identity and imposes economic pressures on Indigenous Peoples and local communities. For example, the cultural values and environmental knowledge of Kazakh herders in Mongolia are at risk due to climate change (Simpson et al. 2022), as are the Batad Rice Terraces in the Philippines (Ducusin et al. 2019), a globally significant agricultural heritage system. These impacts threaten not only biodiversity and sustainable productivity but also the preservation of traditions and cultural practices of Indigenous Peoples in Indigenous and traditional territories.

Thirteen Asian countries are among the most vulnerable to the consequences of climate change, with significant economic and financial implications (World Bank 2023). For example, Bangladesh incurs annual losses of US$1 billion from tropical cyclones (World Bank 2022). South Asia is particularly threatened by wildfires, floods and storms, which could affect 10–18 per cent of the region's GDP, higher than in North America or Europe (World Economic Forum 2022).

Climate change presents a multifaceted challenge in the AP due to its diverse landscapes and growing populations, resulting in escalating climate risks (Ajilogba and Walker 2021). Rising temperatures in Asia have increased the frequency of heatwaves, with a 10 per cent chance of one annually in West Asia (Japan International Research Center for Agricultural Sciences 2024). Thawed permafrost has increased subsidence rates by 2–5 fold in the Tibetan Northern Plateau between 2003 and 2019 (Daout et al. 2020).

Altered weather patterns have shifted the Asian monsoon, with the East Asian Summer Monsoon's rainfall intensity increasing, leading to more extreme weather events such as cyclones, floods, and droughts (ESCAP 2022). Climate change is exacerbating air pollution and the urban heat island effect, particularly in rapidly growing East Asian cities, where temperatures are on average 1.6–2.0 °C warmer than their immediate rural surroundings.

The region also faces significant land degradation, particularly in South Asia, where a conservative estimate suggests that economic losses amount to US$10 billion annually, thereby heightening vulnerability to natural disasters (Ahmed et al. 2022; UNCCD 2022; Lal 2023). Ocean acidification and coral bleaching are disrupting marine ecosystems, threatening the livelihoods of approximately 200 million people who depend on fisheries and endangering food security (World Bank 2019).

Additionally, rising sea levels pose a severe risk to coastal megacities and low-lying islands in the AP region (ESCAP 2022; UNDP 2024). Some cities at risk include Tokyo, Manila, Jakarta and Ho Chi Minh (Cao et al. 2021), while low-lying Small Island Developing States (SIDS) include the Maldives, Tuvalu, and Kiribati (Oppenheimer et al. 2019). Freshwater scarcity is worsening due to changing hydrological patterns, threatening agriculture in critical South Asian river basins and affecting 347 million children under 18 who suffer from high or extremely high

water scarcity (Ahmad et al. 2023; UNICEF 2023; Vakulchuk et al. 2023).

Between 1990 and 2020, the loss of 4.3 per cent of the region's mangrove forests resulted in a 70 per cent reduction in global carbon stock (Stankovic et al. 2023) (UNESCAP 2023). However, the region's vast mangrove forests, particularly in Southeast Asia, offer significant potential for nature-based solutions for both mitigation and adaptation.

Environmental inequalities and climate change contribute to migration and exacerbate existing inequalities. Climate change is intensifying inequality and injustice across AP. In 2022, Asia experienced 81 climate-induced disasters, with over 83 per cent being floods and storms (United Nations 2023).

In 2022, the whole region experienced 140 disasters, resulting in 7,500 deaths and affecting over 64 million people. Climate change significantly influences migration patterns in the region, particularly in the Indian subcontinent, where heatwaves and droughts have driven people from rural areas to cities as a coping strategy (WMO 2023).

Between 2010 and 2021, over 220 million people in AP were displaced due to climate-related events, accounting for more than three-quarters of the global total (Internal Displacement Monitoring Centre 2022). East and Southeast Asia saw the highest displacement numbers, while the Pacific SIDS faced the greatest risks. In 2022, floods accounted for 90 per cent of displacements in South Asia, while in East Asia and the Pacific, 2.7 million people were displaced by floods (International Displacement Monitoring Centre 2022).

Climate action in the AP is ongoing, but more is needed. AP is responsible for about half of global GHG emissions (Ahmed et al. 2022). Between 2019 and 2021, three of the 14 Pacific SIDS nations, five of the 11 G20 countries, three of the 14 least developed countries, and seven of the 10 emerging and developing economies in the AP successfully reduced their GHG emissions (UNESCAP 2023). Although some countries in the AP, such as the Philippines, the Republic of Korea, Indonesia, Nepal and Thailand, have begun implementing policy frameworks for net-zero transitions, overall progress is uneven due to factors such as insufficient technical and financial support.

8.3.4 Priority issue: land-use change impacts on ecosystems

The AP region has undergone extensive land-use transformation to agriculture and pastureland since the 1960s, leading to severe land degradation and a rapid loss of biodiversity and natural ecosystems (Alavaisha et al. 2021; Takeuchi et al. 2021; Kondo et al. 2022). About 40 per cent of the world's agricultural land is in the AP region, of which almost 31 per cent is arable, 4 per cent is used for permanent crops, and 65 per cent consists of permanent meadows and pastures (UNEP 2019). Large areas of islands, inland wetlands, coral reefs, and various forest types in AP have been converted to agriculture and pastureland, and the development has caused a rapid biodiversity loss (Takeuchi et al. 2021). The Southeast Asian countries lost about one-sixth of their forest area between 1990 and 2020 due to global demand for palm oil, timber and rubber (Organisation for Economic Cooperation and Development [OECD] and FAO 2017; Chopra et al. 2022). Agriculture is the major driver for the loss of primary vegetation, followed by urban, infrastructural and industrial developments (Scheyvens et al. 2019). Pastoral and Indigenous agricultural and agroforestry systems are the traditional occupations of Indigenous Peoples, and cultural identities play a vital role in biodiversity conservation and land degradation recovery.

Southeast Asia experiences an annual forest loss of 1.2 per cent – the highest rate of deforestation among major tropical regions (Nanyang Technological University 2023). Agriculture and illegal logging are the leading causes of deforestation and forest degradation. South and Southeast Asia have experienced the largest partial canopy cover loss globally, comprising timber logging at 80 per cent, fuelwood collection at 12 per cent, and uncontrolled fires at 5 per cent. Land degradation, affecting about 8.5 million km^2 or 28 per cent of the AP's land area, poses a significant threat to biodiversity (ESCAP 2022).

Deforestation and forest degradation destroy key ocean and coastal habitats of ecologically important species, weakening biodiversity resilience to climate change due to decreased space for species to shift (Díaz 2019). Deforestation of 32,200 km^2 per year from 2001 to 2019 in Southeast Asia, along with forest degradation, led to increases in GHG emissions, disruption of water cycles, soil erosion, and disrupted

livelihoods (Feng et al. 2021; WWF 2023). Converting mangroves to aquaculture and other land-use types reduces the buffer between sea and land, which increases vulnerability to natural disasters (Scheyvens et al. 2019). The decline of natural wetlands has resulted in a substantial decrease in waterbirds (Xu et al. 2019; Mao et al. 2022), which threatens bird migration across East Asia (Xu et al. 2019). Growing anthropogenic and climate-related factors, including coastal erosion, storm surges, tropical cyclones and rising sea levels, threaten the most productive and biologically diverse coastal habitats, such as mangroves (Kadaverugu et al. 2022).

Asia accounts for three-quarters of the net global tidal wetland decrease between 1999 and 2019 due to climate change, wetland transformation to agricultural and aquacultural lands, and infrastructure developments, of which almost 70 per cent occurred in Indonesia, China and Myanmar (The Nature Conservancy 2022). Coastal and marine ecosystems, including coral reefs, seagrass and mangroves, are important to island nations in AP, but destructive fishing methods and environmental change threaten them (Ross et al. 2019). More than 10,000 km^2 of coastal areas in China have been affected by seawater intrusion due to overexploitation of groundwater for domestic, agricultural and industrial uses (King et al. 2022).

Inland wetlands are disappearing three times faster than forests in Asia (Convention on Wetlands 2021). Between 1700 and 2020, approximately 3.4 million km^2 of inland wetlands worldwide were lost, primarily for conversion to croplands (Fluet-Chouinard et al. 2023). China, India, and Indonesia are among the top five countries that account for more than 40 per cent of global wetland losses (Fluet-Chouinard et al. 2023).

One initiative addressing this is the Sustaining an Abundance of Forest Ecosystems (SAFE) Project: a collaborative initiative between the Korea Forest Service and the United Nations Environment Programme (UNEP) (AFoCo 2023). Since 2023, the initiative has launched multiple projects aimed at conserving and restoring vulnerable forest ecosystems across selected Asian countries, including Bhutan, Cambodia, Lao PDR, and Viet Nam, by prioritizing areas of high biodiversity value (AFoCo n.d.). These ongoing projects aim to address climate change and biodiversity loss by empowering local communities, developing community-based forest management plans, restoring degraded forests, conserving habitats of endangered species, and advancing sustainable forest management practices.

Conversions to agricultural lands mainly cause soil pollution, leading to land degradation. In China, 22.1 per cent of farmland soil had a mixture of contaminants. Chemical industries, agriculture and afforestation-deforestation are significant activities in ASEAN countries affecting soil quality. High levels of lead, copper, zinc, iron and mercury have been detected in the sediments of Pacific SIDS such as Fiji's Suva Harbour. Papua New Guinea, the Solomon Islands and Vanuatu also continue to experience high levels of these trace elements in harbour sediments (FAO 2023). In the Bengal Delta, extracting groundwater for rice irrigation moves arsenic from groundwater to surface soils (Ivy 2023). Approximately 45 per cent of net sown agricultural land was severely degraded, and urbanization increases trace elements, including cadmium, chromium, lead and mercury in urbanized soils of South Asia (Pereira et al. 2023). In Pacific SIDS, land degradation is a major concern. Currently, population pressure, large-scale agriculture using poor agricultural practices, deforestation through commercial logging, mining, dredging, land tenure issues and changing climate have been identified as major factors behind increasing rates of land degradation across the islands in the region (Wairiu 2017; Duncan et al. 2020).

Conversions to agricultural lands led to a loss of natural freshwater resources. AP's rapid economic growth has led to the depletion of natural resources, primarily due to the overuse of groundwater for irrigation (Ahmed et al. 2022). Groundwater loss, commonly greater than 0.5 m per year this century, has rapidly depleted aquifers in major food-producing regions in Asia (Dangar et al. 2021; Wu et al. 2022; Jasechko et al. 2024). As the world's largest consumer of groundwater, India's groundwater has provided 60 per cent of the nation's irrigation supply since 2010. Groundwater loss in northwest India is higher than 20 m and declines at a rate beyond 1 m per year, which is exacerbated by climate change (Dangar et al. 2021; Bhattarai et al. 2023). If current depletion trends continue, there may be a 20 per cent decrease in cropping intensity nationwide and a 68 per cent decrease in groundwater-depleted regions (Jain et al. 2021). The groundwater-depletion rate of China

Credit: © UNEP

was 20.4 km^3 per year on average from 1965–2016, especially in the arid and semi-arid areas of northern China (Huang et al. 2023), where overexploiting groundwater for domestic, agricultural and industrial uses, aggravated by climate change, has caused land subsidence of about 920,000 km^2 (Zheng and Guo 2022). Some parts of northern Jakarta have sunk by four metres over the past two decades, primarily due to illegal groundwater extraction (UNFCCC 2022).

8.3.5 Priority issue: pollution and waste impacts on ecosystems and human health

Cities in AP have experienced combinations of harmful effects from industrial and transportation emissions and the burning of agricultural waste. Globally, six out of the ten countries with the worst air pollution levels are from AP (Rahmayani et al. 2023). South Asia, with the highest population, has the lowest GHG emissions per capita, while East Asia, the second highest population, has very high emissions per capita (IPCC 2022). Although PM_{10} concentrations have decreased in several Northeast Asian countries over the past few decades, including China, Japan and the Republic of Korea, air pollution remains significant (Lee, Song and Choi 2024).

Plastic production in AP countries contributes to emissions and damages human health. Many regions in Asia are hotspots for plastic pollution, with microplastics contributing 80 per cent of global totals, from various sources, that end up in ecosystems (Phuong et al. 2022; Aung et al. 2021). Carbon dioxide emissions from plastic production in China's transportation sector, India's construction sector and Indonesia's electronic sector have increased over fiftyfold since 1995 (Cabernard et al. 2022). Five Southeast Asian countries – Viet Nam, the Philippines, Thailand, Indonesia and Malaysia – are among the world's 10 countries generating the highest volumes of mismanaged plastics, at 1.5 million metric tons per year for these Asian countries (Ng et al. 2023). Plastic pollution harms Indigenous Peoples in coastal and marine ecosystems, wetlands, rivers and forests by contaminating food sources, such as fish and shellfish. It further threatens traditional Indigenous Knowledge and Local Knowledge, innovations, practices, food, health, biocultural systems and traditional ways of life throughout the AP region.

Excessive use of pesticides on agricultural lands is causing water pollution. Countries from South and Southeast Asia are the largest consumers of pesticides (Kumar et al. 2023). Unregulated and excessive use of chemical fertilizers has led to low nitrogen use efficiency, more environmental pollution and enhanced GHG emissions (Kishore, Alvi and Krupnik 2021; Fan et al. 2023). India and China consume more than 42 per

cent of global nitrogen fertilizer (Sapkota and Takele 2023). Agricultural activities have taken a heavy toll on environmental quality in Central Asia (Cheema et al. 2024). Major rivers in Asia, including the Ganges, Irrawaddy, Mekong, Pearl, Yangtze, Yellow, Liao and Amur, are among the largest conduits of pesticides to the world's oceans (Maggi, Tang and Tubiello 2023). Rivers in Central Asia, including Amu Darya, Syr Darya and Chu Talas, are also polluted by industrial waste and agricultural run-off (Liu 2021).

High concentrations of antibiotics from aquaculture expansion were identified in water bodies in many Asian countries, resulting in ecosystem degradation (Tang et al. 2021). There are high levels of aquaculture-related antibiotics in the surface waters of some South Asian countries (Hannah et al. 2023). Aquaculture expansion has resulted in drug resistance in freshwater ecosystems in many Northeast and South Asian countries (Sahar et al. 2021).

Unsustainable industrial practices have threatened the marine and freshwater ecosystems in the AP region. Pollution and environmental degradation threaten nearly 37 per cent of species in freshwater ecosystems in AP (IPBES 2022). Some South Asian countries are among the world's top wastewater-producing countries with the lowest reuse rates, at less than 5 per cent (UNEP 2023). Due to ecosystem degradation, there has been a 50–70 per cent decline in dolphin habitat in Asia (WWF 2019).

Landfill sites in many Asian countries are significant sources of pollution, particularly in terms of water and air. Asia is the largest solid-waste-producing region globally, generating over 800 million tons per year (Agamuthu and Babel 2023). More than half the waste ends up in dumps (Kaza et al. 2018). Open dumping and unsanitary landfill sites in Southeast and South Asian countries are causing unprecedented water and air pollution. Methane emissions from landfills across South Asia and Central Asia are widely reported (UNEP 2021).

Exposure to air pollution in the AP is a significant contributor to premature deaths and economic losses. Air pollution exposure reduces the overall average life expectancy by 1.6 years in Southeast Asia (Greenstone and Hasenkopf 2023). Three-quarters of air pollution's adverse effects on global life expectancy occur in just six Asian countries: Bangladesh experiences an 8.3-year reduction in life expectancy, India a 5.3-year reduction, Nepal a 4.6-year reduction, Pakistan a 3.9-year reduction, China a 3.1-year reduction, and Indonesia a 1.2-year reduction (Greenstone 2023). Together, these six countries account for 75 per cent of the years of life lost due to air pollution.

Of the total population of AP, 99 per cent of those in the South and 95 per cent of those in the East are exposed to unsafe $PM_{2.5}$ conditions (**Figure 8.11**). $PM_{2.5}$ in the air of populous cities is mostly anthropogenic in South and East Asia (IPCC 2022).

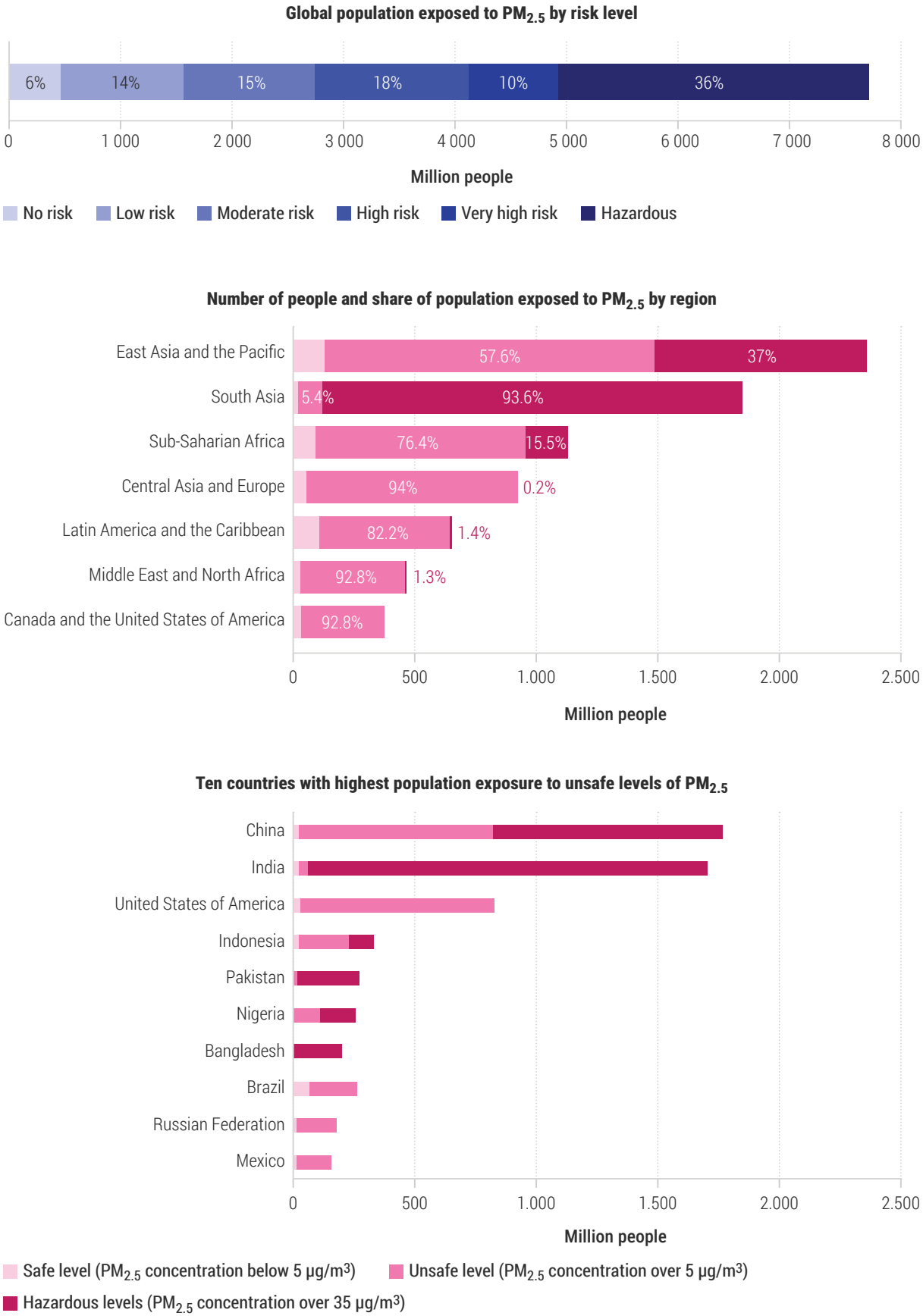
Air pollution causes a 9.3 per cent loss of GDP in regions of East Asia and the Pacific, and a 10.3 per cent loss in South Asia (The World Bank 2022). The average loss of productivity among workers due to pollution is eight times higher in developing countries than in developed countries within the AP (World Economic Forum 2022).

In 25 Asian countries, the total economic loss due to premature deaths attributed to $PM_{2.5}$ exposure amounts to US$45 billion, of which 65 per cent of the affected were male. In China alone, pollution caused 879,000 premature deaths in 2017 (Nansai et al. 2020). In some Northeast Asian countries, household fuel consumption for cooking and heating contributed to more than 1.4 million premature deaths in 2019, particularly in rural low-income families (Zhao et al. 2019). Mortality rates increased by 0.36 per cent in China for every 10 μg/m^3 rise in PM_{10} concentration (Xie and Gao 2024). Losses of welfare in South and Southeast Asia due to air pollution are estimated at 7.5 per cent of regional GDP (Jabbar et al. 2022).

The pollution burden in many Asian countries disproportionately falls on the rural population (Shupler et al. 2020). For instance, while urban governance to mitigate pollution in China is getting more stringent, polluters set up factories in rural industrial parks where they enjoy greater freedom to dump toxins into the environment (Zhang 2023). Since 2000, the increase in the number of "cancer villages" – small communities in China located near pollution sources where cancer rates are substantially higher than the national average, currently 462 villages – especially near river basins, indicates how inequality and injustice stemming from pollution create burdens in rural areas (Cui 2020).

The increased cost of healthcare associated with pollution is rising in many countries in Asia, accounting

Figure 8.11: Exposure to air pollution



Source: Rentschler and Leonova (2023)

for 92 per cent of the lives lost worldwide due to air pollution. However, only 6.5 per cent of governments in Asia provide accessible data on air quality (IIASA 2023). At 3.3 per cent of global GDP in 2019, older people and low-income groups in South and Southeast Asia incur disproportionately higher healthcare costs related to air pollution (Ma et al. 2023). Twelve million babies in South Asia and 4.3 million in East Asia live in areas where outdoor air quality surpasses six times the WHO thresholds (Jabbar et al. 2022). In addition, economic damages from IQ loss due to lead poisoning accounted for a 2 per cent loss in Asia's GDP (UNICEF 2020).

Health impacts of pollution are unevenly distributed among various sociodemographic groups. South Asia is the hotspot for stillbirths related to $PM_{2.5}$ (Xue et al. 2022). The highest number of annual stillbirths attributable to $PM_{2.5}$ exposure was recorded in India at 217,000, China at 64,000, Bangladesh at 49,000, and Pakistan at 110,000. Incidents of paediatric asthma attributable to nitrous oxide in the air are rising in South Asia and the Middle East (Paciência et al. 2022). Exposure to air pollution contributes to a significantly higher rate of stunting among South Asians, by 38 per cent, compared to the global average (Saif and Anwar 2023). South Asians have a 2–3 times higher risk of cardiovascular diseases and diabetes due to early and lifelong exposure to pollution (Wilder et al. 2024). In addition, women in some Asian countries are at far greater risk of cancer compared to men, being 45 per cent more likely due to indoor air pollution (Chu, Wang and Su 2023).

Five South Asian countries account for approximately 188 million people who are exposed to arsenic-contaminated groundwater (Aryan et al. 2024). Infants and children are more exposed to arsenic-contaminated water due to their smaller body mass. Prolonged exposure can cause impaired cognitive development and DNA damage. Girls are at high risk of cancer due to arsenic exposure (Rana et al. 2022). Dangerous exposures are not limited to arsenic. Research in the Ganges River basin area in India has revealed that the presence of faecal coliforms exceeds safety standards. Exposure to such conditions adversely affects the reading and writing scores of children (Islam and Ghorai 2024).

Hazardous waste in the AP poses a threat to public health and safety. Industry owners gain four times more benefits from ships at the end-of-life cycle than workers and local communities, due to weak regulations and the absence of mechanisms to internalize environmental costs (Mathew 2021). The result is that areas near shipbreaking sites in South Asia are contaminated with carcinogens such as asbestos and polychlorinated biphenyls (PCBs) (Dewan and Sibilia 2024). For instance, 35 per cent of workers from shipbreaking yards in Bangladesh have been diagnosed with asbestosis caused by exposure to asbestos dust due to the lack of workplace safety standards (NGO Shipbreaking Platform 2023). In addition, accidents like explosions, fire and suffocation cause deaths of shipbreaking workers (430 deaths since 2009) in South Asian countries (Wan 2021).

8.4 Eastern Europe and subregions

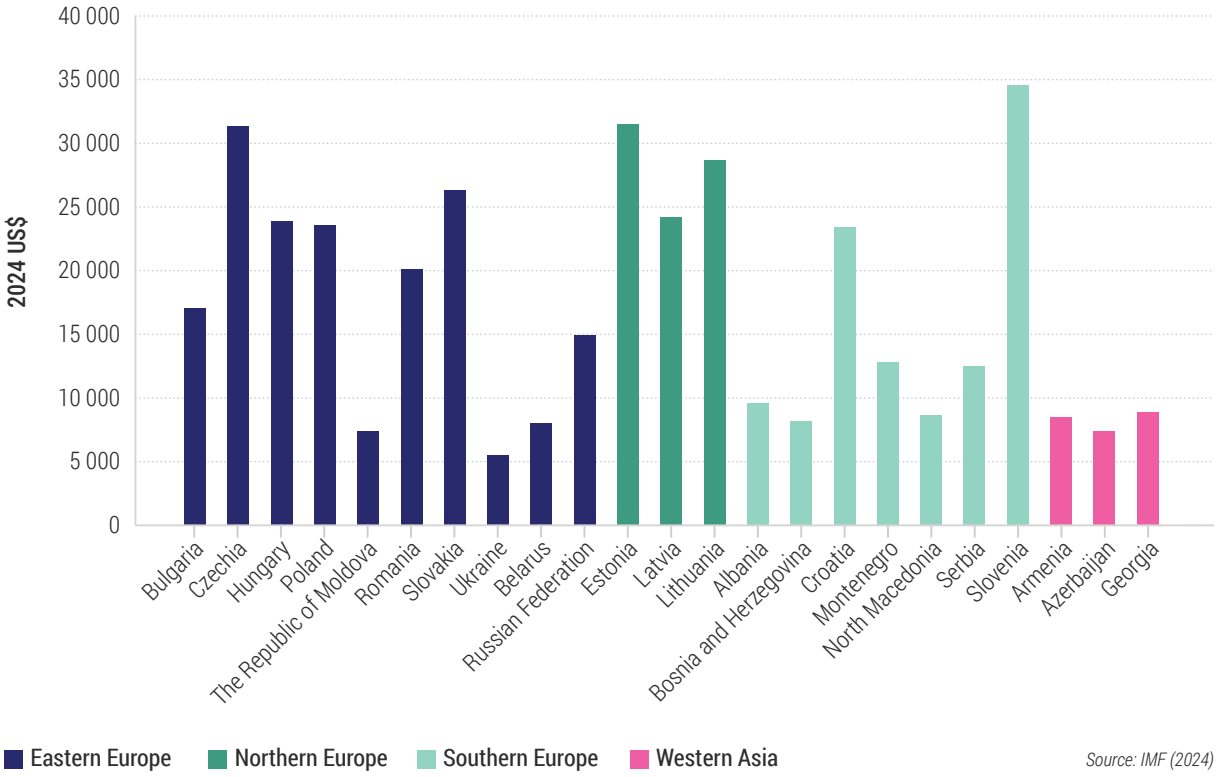
8.4.1 Introduction

The Eastern Europe (EE) region consists of 23 countries that cover a vast and diverse area, spanning from the Baltic Sea in the west to the Pacific Ocean in the east. It encompasses a wide range of ecosystems, from polar deserts and tundra in the Arctic to subtropical regions in the South Caucasus, and broadleaf forests in the west through boreal forests and steppes to temperate rainforests in the Russian Far East. Most of the countries either belong to the European Union (EU) or are EU accession countries, while a smaller proportion cooperate with the Eurasian Economic Union.

The EE's diverse politics and economics (**Figure 8.12**) have produced different socioeconomic development models across the region. As a result, there are different procedures of environmental policy and planning. Many past and present conflicts, along with their implications, further complicate this complex picture. This can undermine avenues for coherent regional policies and cross-boundary solutions.

Large arable monocultures, which prevail in many EE landscapes, are highly vulnerable to climate change. Climate change is projected to cause a significant increase in water erosion, soil degradation and loss of soil organic matter, undermining water retention and increasing irrigation demands that can lead to salinization. The risk of spring droughts is of particular concern. The abandonment of semi-subsistence farming and extensive management practices, loss

Figure 8.12: GDP per capita of Eastern European sub-regions



Source: IMF (2024)

of local knowledge and high-nature-value farmland are leading to the demise of important resilient agricultural landscapes.

Although EE is rich in a variety of resources that could be used for renewable energy, countries still depend heavily on different types of fossil fuels. Over time, many countries have developed their own fossil-fuel-based energy sources, including coal, brown coal and lignite, among others. Additionally, military conflict in the region has driven a need to find additional diverse sources of natural gas.

Historically, countries in the region established numerous protected areas. Some of these areas are among the largest in the world, such as those protected in the Russian Federation. Proper management of this system, the development of ecological networks, and the preservation of biodiversity remain important priorities that will require more robust management strategies.

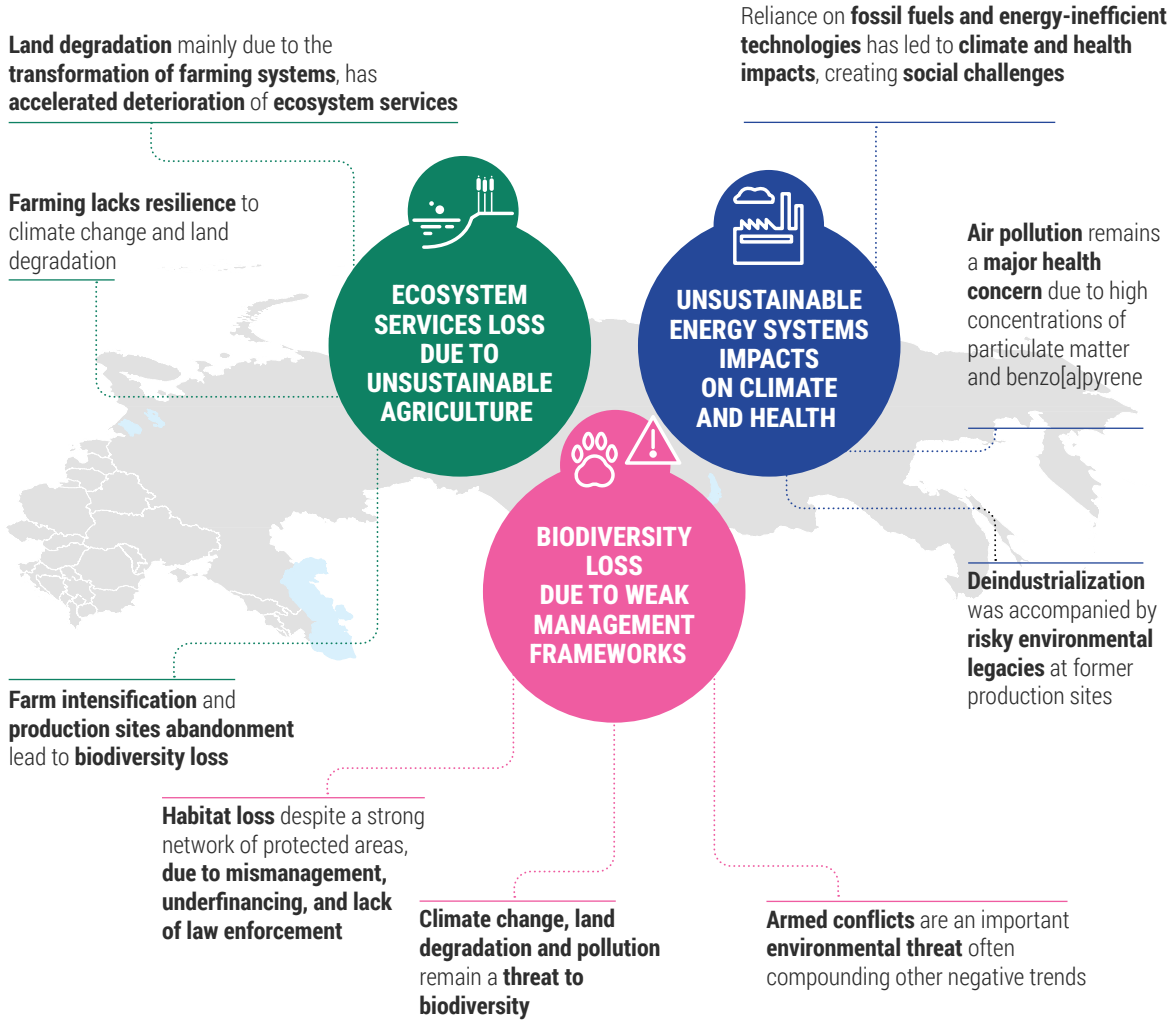
Considering the specific nature of EE, the global environmental crises – the crises of climate change, biodiversity loss, land degradation and desertification, and pollution and waste – manifest in three main circumstances (**Figure 8.13**). Land degradation, primarily due to the transformation of farming systems, has accelerated the deterioration of ecosystem services. As well, a heavy reliance on fossil fuels and energy-inefficient technologies has led to significant climate and health consequences, creating social challenges. At the same time and despite a strong network of protected areas, the threat of habitat loss across the region remains high, mainly due to mismanagement, underfunding and inadequate law enforcement.

8.4.2 Interlinkages between the global environmental crises and regional priorities

As in other regions, EE's environmental challenges cannot be understood in isolation. The global environmental crises – the crisis of climate change, the crisis of biodiversity loss, land degradation and desertification, and the crisis of pollution and waste – are intertwined and mutually reinforcing (Global Environmental Crises Chapeau).

In EE, climate change intensifies land degradation through more frequent droughts, flooding and shifting precipitation patterns, all of which impact agricultural productivity. In parts of EE, large-scale monocultures erode soil health and biodiversity, creating a cycle of

Figure 8.13: The interplay of the global environmental crises and regional priority issues: effects on Eastern Europe's ecosystem services, health and energy, and biodiversity



ecological decline. These impacts are compounded by unsustainable land-use practices (Section 8.4.5) (European Environment Agency [EEA] 2019; EEA 2024).

The EE region's reliance on fossil fuels and energy-intensive heavy industries drives climate change and air pollution. High levels of emissions contribute to climate change and degrade air quality, impacting human health. This is especially true in urban areas where pollution from fossil fuels, especially coal, leads to respiratory illnesses and environmental degradation (EEA 2023a).

Pollution and biodiversity loss are also linked. Eutrophicating pollutants originating from point sources such as cities and industrial activities, and non-point sources such as agriculture, affect freshwater quality and inland seas such as the Baltic and Black Seas (EEA 2015; Breitburg et al. 2018; Modabberi et al. 2020). The loss of biodiversity reduces ecosystem resilience, making landscapes more vulnerable (IPBES 2019; United Nations Economic Commission for Europe 2023).

These global crises interact with regional priorities and issues such as ecosystem loss, unsustainable agriculture, energy transformations, the impact of air pollution on human health, and land degradation. Further understanding of the regional priority issues can help to identify how to address and mitigate the global environmental crises in EE (Chapter 20).

8.4.3 Priority issue: ecosystem loss due to unsustainable agriculture

Land degradation, driven by transformation of farming systems, has accelerated the deterioration of ecosystem services across the region.

Food systems arguably resist sustainability transition more than other economic sectors in EE, largely due to the increasing polarization of agriculture. Two dominant and contrasting contemporary trends contribute to large-scale degradation of ecosystem services: intensive farming, which leads to soil degradation (EEA 2019; Rigal et al. 2023; EEA 2024); and abandonment of extensive farmland, often associated with rural depopulation and biodiversity loss (IPBES 2018; Dengler et al. 2020). Despite variation in these patterns within the region, the overall trends hold across EE. To date, neither governments nor the farming sector have been able to develop and implement sustainable solutions to address either of these two trends. While large-scale farms remain environmentally unsustainable, an economically viable solution is lacking for extensive management.

Large-scale agribusinesses, often spanning several dozen square kilometres, are often owned and operated by former collective farm managers or newly emerged elites (see also **Box 8.1**). Investment companies – notably in the Russian Federation, Ukraine and Romania – invest heavily in agriculture, focusing on export-oriented grain production (Petrescu-Mag et al. 2020; Uzun et al. 2019; Visser et al. 2019; Tleubayev et al. 2021; Graubner et al. 2021; Khodakivska 2023; Liao and Agrawal 2024). This segment has become an integral part of the global food economy. A substantial part of this grain is used as a source of animal feed (FAO 2024).

The smallholder farming model of some countries in the Balkans and Caucasus, as well as in parts of Poland and Romania, struggles to remain viable. Along with economic pressures, rural depopulation and the ageing of smallholder farmers lead to the cessation of centuries-old practices (Živanović et al. 2022). In some rural areas of Bosnia and Herzegovina, for example, the population decreased by 75 per cent between 1991 and 2023 (Agency for Statistics of Bosnia and Herzegovina [BHAS] 1991; Institute for Statistics of the Federation of Bosnia and Herzegovina [FBiH] 2024). Additionally, the decline of mixed farming due to agricultural specializations has led to the abandonment of extensive grassland plots in arable landscapes previously used to graze livestock and produce hay (Dengler et al. 2020). As a result, EE has been a hotspot of farmland abandonment (IPBES 2018).

Notably, organic farming and, more recently, regenerative practices are emerging as major trends in some countries. The total area of organic farms in EE increased by 18 per cent between 2018 and 2021 alone (FiBL 2025) (**Figure 8.14**). Although these practices are only present in a small minority of farms, the importance of these trends is twofold: local improvement in soil health and the restoration of biodiversity in the short term, which increases climate adaptation capacity; and a path to overcome polarized farming methods in the longer term. If scaled, they may offer a new model for EE food systems that will be both environmentally and economically sustainable.

Farming in EE lacks resilience to climate change and land degradation.

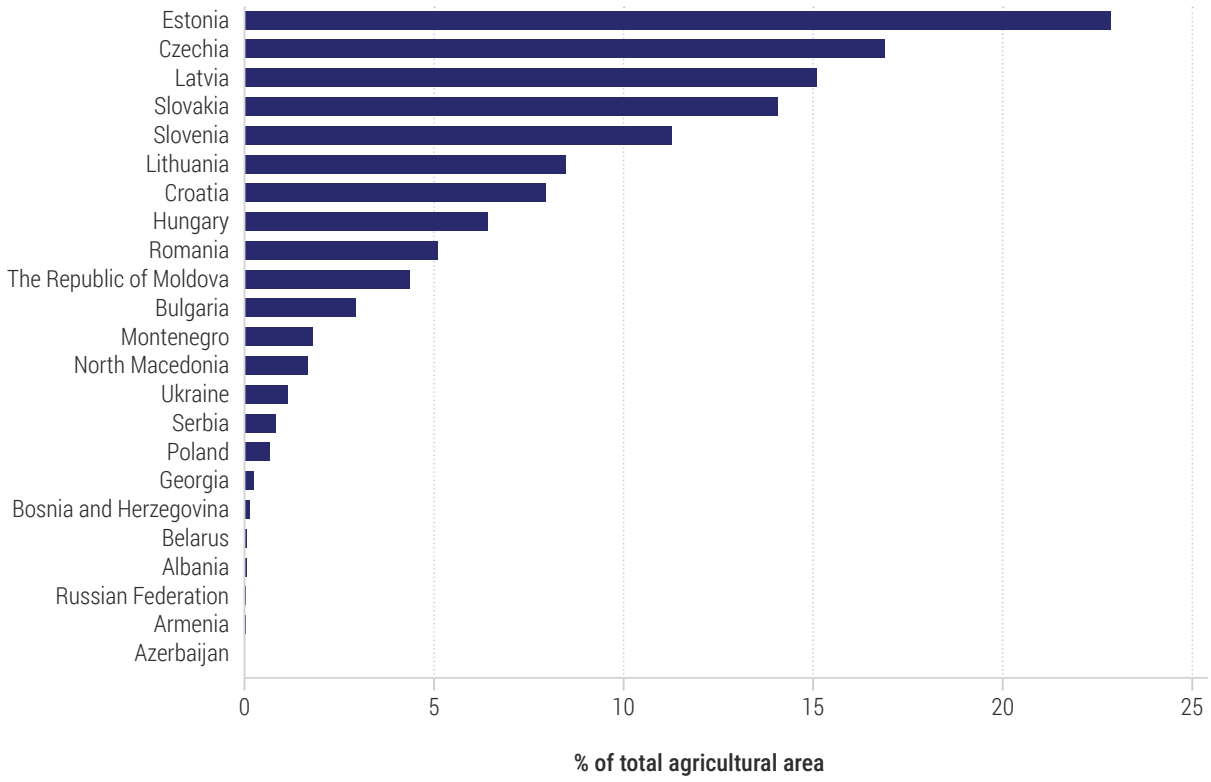
Fields tend to be generally large, reaching dozens of hectares, particularly in the Russian Federation and Ukraine (Lesiv et al. 2019). The region is home to eight of the ten EU countries with the highest average area of arable monocultures (Gális 2020). While the average field size in the EU is 0.04 km^2, the average field size in Slovakia, for example, is 0.12 km^2, and 46 per cent of the fields are larger than 0.3 km^2 (Gális 2020).

Accounting for only 7 per cent of the world's agricultural land but producing 22 per cent of the world's wheat, the EE region is important for global food security. But

Box 8.1: Where has the agriculture in Eastern Europe come from?

The concentration of farms, typical of temperate biomes in the second half of the 20th century, was even more rapid in much of EE than elsewhere due to forced collectivization. However, after the collapse of collective agriculture in the 1990s, paths diverged. While some farms changed hands but retained the pre-1990 highly concentrated structure, land has been returned to smallholders elsewhere (Hartvigsen 2014; Gorgan and Hartvigsen 2022).

Figure 8.14: Share of total agricultural area used for organic farming in the Eastern Europe countries in 2023



Source: FIBL (2025)

large arable monocultures, which prevail in many EE landscapes, are highly vulnerable to climate change. Climate change is projected to cause significant increases in water erosion (Panagos et al. 2021). Soil degradation and loss of organic matter undermine water retention; increased demands on irrigation can lead to salinization; and crop specialization (due to intensive farming models) restrains farmers' choices (EEA 2019; EEA 2024). EE is one of the global hotspots of increasing soil drought (Řehoř et al. 2024). The risk of spring droughts is of particular concern because newly established crops often lack sufficient moisture to support their growth. This lack typically results in reduced yields. Meanwhile, the abandonment of semi-subsistence farming and local knowledge, extensive management practices and high nature-value farmland leads to the demise of important, resilient agricultural landscapes.

Soil monitoring systems have been extensively developed in the EE region, providing large amounts of detailed spatial data (Jones et al. 2005). Despite these resources, intensive farming has led to soil degradation (Ivanov et al. 2020; Golosov et al. 2021; Pozniak et al. 2021; MNRERF 2022; EEA 2023c; Li et al. 2025). Water erosion affects 35–43 per cent of farmland in Caucasus countries, about one-third in the Republic of Moldova and Ukraine, and 26 per cent in the Russian Federation (FAO and ITPS 2015; Bejan et al. 2022). Large-scale farm businesses in the flat landscapes of the Russian Federation, Ukraine and parts of Romania are also prone to wind erosion. In Ukraine alone, the area affected by erosion has increased by 800 to 900 km^2 every year (FAO 2020).

In some countries, most of the land is owned by smallholders but farmed by tenant agribusinesses. In many cases, renting land leads to unsustainable soil use because tenants lack incentives to ensure long-term productivity (Sklenicka et al. 2015). However, soil awareness, a significant movement particularly among the younger generation of farmers, small landowners and the public, is slowly shifting attitudes towards soil as an integral part of the environment, rather than simply a means of production.

Both farm intensification and abandonment lead to biodiversity loss.

The polarized structure of regional agriculture affects biodiversity in two contrasting ways. Large agribusinesses often emphasize intensive farming, a major driver of the rapid decline in biodiversity, as seen in the decrease in common bird species, for instance (Hanzelka et al. 2019; Reif and Hanzelka 2020; Rigal et al. 2023). Globally, EE is the region where very large fields are concentrated more than anywhere else (Lesiv et al. 2019). Landscape homogenization leads to a decline of ecosystem services such as pollination and pest control. In some countries, high inputs of mineral fertilizers and pesticides contribute to biodiversity loss, including the decline of soil biota. Conversion to arable land and intensive management of grasslands – excessive fertilization, re-seeding, overgrazing and high frequency of cutting – decrease species richness in meadows and pastures (Dengler et al. 2020; Török et al. 2020; Karapinar 2021; Pe'er et al. 2022). In EU Member states, Common Agricultural Policy subsidies facilitate increasing agricultural intensity along with stability (Pe'er et al. 2020).

Under certain circumstances, farming abandonment has often had a positive impact on biodiversity. In the steppe region of the Russian Federation alone, the closure in the 1990s of 260,000 km^2 of intensive farms with low productivity led to the restoration of grassland habitats and the prevention of further soil erosion and salinization (Hölzel et al. 2002; Smelansky and Tishkov 2012; Tsymbarovich et al. 2020), while creating a substantial carbon sink (Kudeyarov 2019). The legacy of the Virgin Lands Campaign, a politically driven effort to convert the steppe to arable land in the 1950s and 1960s, has been largely reversed. However, this phase is mostly over.

The current abandonment primarily affects extensive grasslands on dry plains, wetlands, and in mountainous areas. Vacated species-rich farmland that cultivated grasslands, woodland pastures and orchards gradually becomes overgrown with scrub and trees, and landscapes lose their heterogeneity (Török et al. 2018; Dengler et al. 2020; Török et al. 2020; Karapinar 2021). However, traditional farmlands often provide important species-rich habitats (European Commission, Directorate-General for Environment et al. 2016; Török et al. 2020). Ancient, flower-rich hay meadows in the Carpathian Mountains hold global records for small-scale plant diversity, surpassing those of tropical rainforests (Roleček et al. 2025). The ongoing demise of extensive semi-subsistence agriculture and agroforestry is currently the most important cause of biodiversity loss in EE farming landscapes, with devastating consequences for a range of threatened bird, insect and plant species (Tryjanowski et al. 2011; Sutcliffe et al. 2015; European Commission, Directorate-General for Environment et al. 2016; IPBES 2018; Török et al. 2018; Dengler et al. 2020; Török et al. 2020; Prangel et al. 2024).

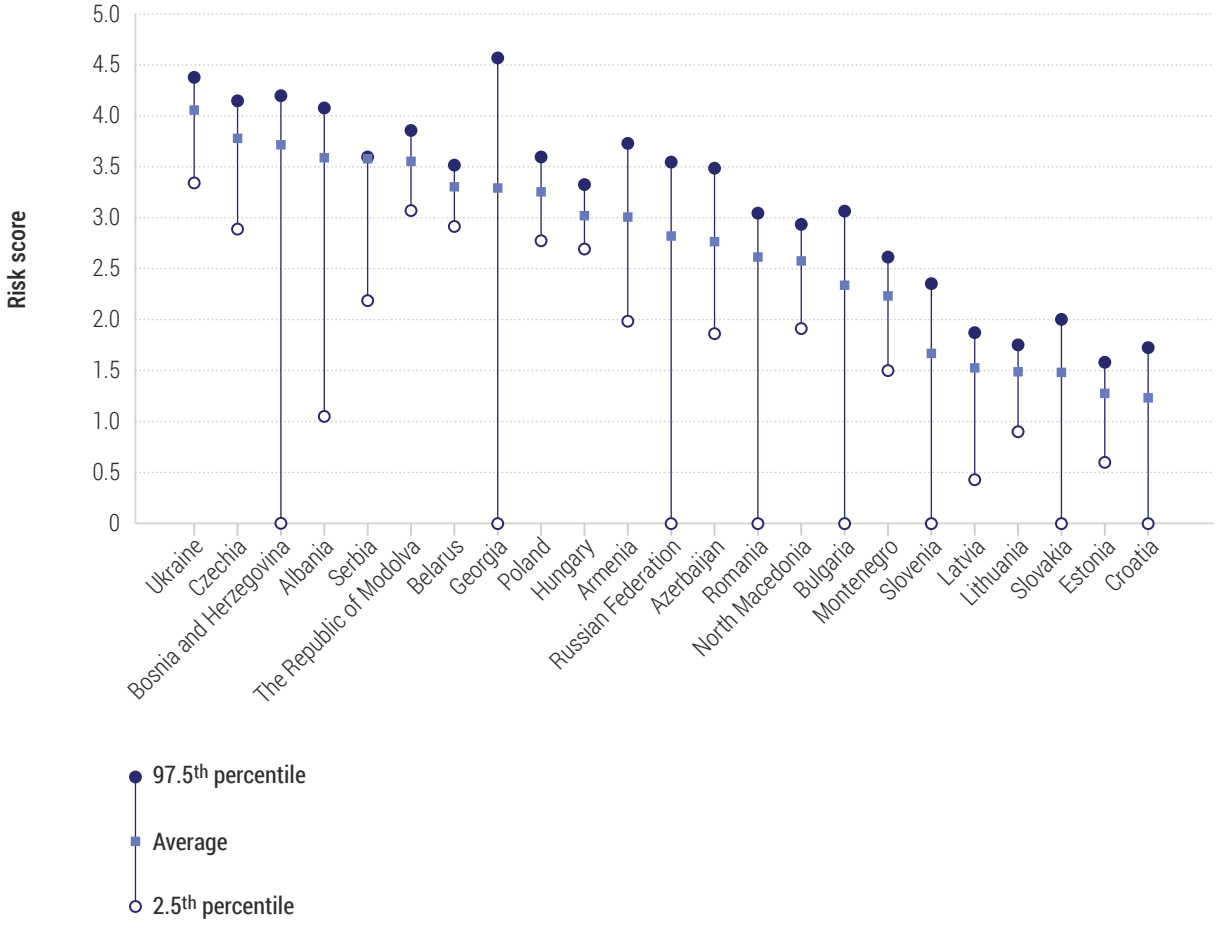
Many EU countries have implemented agri-environmental payments to prevent land abandonment and intensification, both of which lead to biodiversity loss (Batáry et al. 2015; ECA 2020). These payments influence the economic choices of commercial farmers, often enabling the survival of ancient grasslands (Dengler et al. 2020; Török et al. 2020). However, as these measures are designed to operate on commercial farms under the EU's Common Agricultural Policy, they are less effective in preserving the small-scale mosaic of traditionally managed ecosystems. Furthermore, agri-environmental payments focus on specific farming practices and are poorly suited to reshaping the food systems or addressing wider demographic and cultural changes.

Intensive farming is the key source of nutrient pollution.

The intensive production model of large farm businesses often involves high inputs of agrochemicals. Aggregate pesticide risk is also high in some countries, such as Ukraine, due to the use of relatively small amounts of more hazardous pesticides (Tang et al. 2021) (**Figure 8.15**). There has been a substantial effort to reduce soil contamination by obsolete pesticides since around 2000. However, this issue remains significant in several EE countries (FAO and UNEP 2021).

Heavy application of mineral fertilizers and manure contributes to nitrogen and phosphorus pollution. Average nitrogen and phosphate fertilizer use has increased steadily in recent years, following a decline in the 1990s, ranging from relatively low levels of 20 kg per hectare of cropland in the Russian Federation to 179 kg in Armenia between 2018 and 2021 (FAO 2023). Nitrogen surplus is relatively high in EU countries such as Czechia and Hungary, even if it does not reach the extreme levels of some Western European countries (EEA 2020b). Vast areas of the northern and eastern Russian Federation, as well as some

Figure 8.15: Pesticide risk scores of the Eastern European region



Note: The risk score is calculated as combined ratios of predicted environmental concentration and ecotoxicity of the 92 most used active ingredients in soil, surface water, groundwater and atmosphere.

Source: Tang et al. (2021)

mountain ranges, remain largely unaffected by this threat because the currently harsh climate precludes significant agricultural activity.

Nutrient overload leads to toxic algal blooms in the most stressed rivers and lakes, affecting drinking water quality, the recreation industry and fisheries. The region's main farming lands drain into its three semi-enclosed seas and the world's largest lake, each of which is naturally highly sensitive to water eutrophication (EEA 2015; Breitburg et al. 2018; Modabberi et al. 2020). Agriculture is the key cause of nutrient overload in the Baltic, Black, Azov and Caspian Seas, with some areas affected by widespread hypoxia – a lack of oxygen. Almost half of the total waterborne nutrient inputs in the Baltic Sea originate from agriculture (HELCOM 2023). The Volga River basin, which accounts for approximately 45 per cent of the Russian Federation's agriculture, drains into the Caspian Sea (Mozafari et al. 2023).

8.4.4 Priority issue: unsustainable energy system effects on climate and health

Heavy reliance on fossil fuels and energy-inefficient technologies has led to climate, health and social impacts.

While substantially below the global average, air pollution remains a significant health concern in many EE countries. This is mainly due to high concentrations of particulate matter and benzopyrenes, mostly caused by burning coal for heating individual houses and buildings. Millions of households in EE cities and rural areas still use coal and, to a lesser extent, fuelwood, to heat their homes (UNEP 2021; Zgłobicki et al. 2024; Andersen et al. 2025). The Western Balkans and Poland, in particular, are air pollution hotspots (Health Effects Institute [HEI] 2020; EEA 2023a). Air pollution is responsible for 15 to 19 per cent of deaths in Western Balkan cities (UNEP 2019). The economic

costs of health damage caused by coal power plants are estimated to be in the range of EUR6.1 billion to EUR11.5 billion (equivalent to US$6.8 billion to US$12.9 billion in 2019) (Puljic et al. 2019). Caucasus countries have reached similar levels of air pollution (HEI 2020).

Provisioning systems – a set of elements that interact to transform resources to satisfy human needs – require the use of raw materials, particularly for heating (UNEP 2024) (See also **Box 8.2**). Energy systems in EE countries still depend heavily on fossil fuels, often due to obsolete energy-inefficient technologies that require high energy usage. The transition from non-renewable raw materials to clean energy poses a significant energy poverty challenge. In 2024, millions of people in EE struggled to adequately heat their homes (European Commission n.d.). Nearly 7 per cent of the EU population were behind on utility bills, and around 1 per cent lived in homes with issues including leaks, dampness, or rot as of 2020; 11 of the 23 EE countries are in the EU (Eurostat 2025). These problems remain particularly severe in countries where a substantial portion of the population still relies on solid heating fuels, exacerbating fuel poverty (EEA 2023a). This trend has been reinforced by the rise in energy prices over the past two years since the onset of war in Ukraine (Guan et al. 2023), alongside the reorientation of oil and gas export flows from the Russian Federation to Asia due to the embargo. Meanwhile, domestic extraction of raw materials in EE, the Caucasus and Central Asia remains the world's second highest, amounting to 19 tons per person in 2020 (UNEP 2024).

Coal remains the dominant energy source in the Balkans, driving high emissions and energy inefficiency. In 2022, coal accounted for over 60 per cent of gross electricity generation, with 54 per cent of this coal in the form of lignite (Berlin Process Summit 2022). Outdated infrastructure – much of it over 30 years old – contributes to inefficiencies, while site reclamation activities are often delayed or neglected (Energy Community Secretariat 2021). District heating is also fossil-fuel-based: 97 per cent is based on fossil fuels, with only three per cent from renewable energy (Ali et al. 2022). The energy sector is the largest contributor to GHG emissions in the Balkans region at 53–87 per cent, and coal-based energy production accounts for two-thirds of the region's CO_2 emissions (Berishaj 2021). The carbon intensity of electricity production in the Balkans exceeded that of the EU-27 by more than three times in 2020. In 2019, Balkan power plants emitted 10 times more CO_2 per unit of GDP than those in the EU-27, and this ratio unfortunately worsened in 2020 (Energy Community Secretariat 2021). Similarly, regarding pollution, the Norilsk industrial complex in the Russian Federation, the world's most polluted Arctic region, releases 1.86 million tons of sulfur dioxide (SO_2) annually (Raputa et al. 2019; Kirdyanov et al. 2020).

Recent regulatory efforts in parts of EE showcase a tangible improvement in air quality. In 2019, local

Box 8.2: Forest fuel exports in Eastern Europe

Bioenergy is an essential resource in rural communities. While enhancing the resilience of local economies, fuelwood use can provide an economic lifeline to ancient species-rich management such as coppice woodlands (Camia et al. 2021).

The EE region is a major supplier of biomass for heat and electricity in Western Europe and East Asia (Thurner et al. 2022; EEA 2023d). However, the increasing demand for wood chips and wood pellets used for export accelerates industrial-scale logging of native forests in the Baltic countries (Kuresoo, S., Kuresoo, L. and Lilleväli 2020). The Carpathian Mountains are similarly affected. Consequently, the Land Use, Land-Use Change and Forestry (LULUCF) sector has become a net source of emissions in some EE countries (EEA 2023b). The extraction of dead trees and snags for bioenergy further deprives forest ecosystems of an important resource for species, including birds, beetles and fungi (Thorn et al. 2020; Camia et al. 2021). Unfortunately, many of the region's remaining primary forests are still unprotected (Sabatini et al. 2020). The broader adoption of sustainable forest management practices would help reduce pressure on forest ecosystems.

authorities introduced a ban on household use of coal in the historical city of Kraków, Poland, to reduce urban air pollution. Approximately 65,000 solid fuel furnaces were removed, and particulate matter (PM) concentrations decreased to, or below, statutory levels (European Commission 2023). Similarly, in 2023, Slovenia banned the installation of heating boilers for fuel oil and coal, signalling a shift away from household fossil fuel use.

Transformation towards sustainable landscapes

The use of renewable energy as an energy source varies across EE. According to the IEA (2022), Latvia, Albania, Montenegro and Estonia reached the highest share with around 40 per cent, whereas Armenia at 9 per cent, the Russian Federation at 4 per cent and Azerbaijan at 1 per cent have the lowest. The average share of modern renewables across the whole of Europe, for comparison, was 19 per cent (IEA 2022; Vafeas et al. 2024). Many countries in the EE region support the funding of projects focused on transforming energy systems for positive environmental impacts (Dembicka-Niemiec, Szafranek-Stefaniuk and Kalinichenko 2023) (**Box 8.3**).

The energy transformation and clean technologies will rely on raw materials such as critical minerals, including lithium, cobalt, nickel, titanium and tungsten, among others. The dependence on these raw materials may lead to both environmental and economic risks. For example, disruptions to global markets caused by conflict have exposed vulnerabilities in the secure supply of raw materials essential for industrial production and for the green transition (Koyamparambath et al. 2025).

Across EE, heavy industries began to shrink from the early 1990s, following the fall of the Eastern Bloc. The transformation processes of industrial closures were accompanied by the discovery of high-risk environmental legacies at former production sites (Robb 1994; Bridge 2004). Mining industries often leave heavily altered landscapes. In EE, these pollution legacies have often not been remediated because of funding problems or unclear ownership issues (Harfst and Wirth 2011; Wirth et al. 2018) and improper implementation of legislation. Overall, the post-mining futures of these sites are often perceived as entailing decay, disinvestment, and polluted industrial wastelands (Marot and Harfst 2021).

Box 8.3: Geothermal energy in Eastern Europe

The first geothermal station in the Russian Federation was built in 1966, namely Pauzetskaya on the Kamchatka peninsula. Currently, there are four geothermal stations in the Russian Federation – three on Kamchatka and one on Kunashir Island in the Pacific – with a total capacity of about 88 MWt (National Association of Oil and Gas Service [NANGS] 2022).

Geotermia Podhalańska S.A. was the first installation in Poland, which was established in 1993 to utilize geothermal resources, contributing directly to a reduction in SO_2 concentration by approximately 68 per cent over the period 2004–2018, lowering suspended PM_{10} concentrations and reducing CO_2 emissions (Geotermia Podhalańska S.A. n.d), as well as developing energy clusters to increase the use of geothermal resources with a joint initiative in the region (Czaplicka-Kotas, Kulczycka and Iwaszczuk 2020).

Slovakia has significant potential to use geothermal energy and contribute to a decrease in GHG emissions. In 2023, the EU's Just Transition Fund allocated more than EUR 56 million, equivalent to US$60 million in 2023, to support geothermal energy and heat distribution in the Košice region. Ďurkov, with its geothermal wells, has been designated as a national project. It is also one of the largest geothermal projects in the region (Geotermálna Energia 2024).

A significant opportunity lies in utilizing geothermal energy for both heating and spas in the Carpathian Region (Lis and Savchenko 2022).

Credit: MaplesImages/Envato

However, there are now good examples for the proper management of these areas, including both reclamation of coal mines, as demonstrated by good management of the post-mining area in the Upper Silesia region, and metal recovery from waste, as conducted by ZGH Bolesław SA in Poland, as well as reclamation towards tourism facilities. Such success often depends on particularly unique or salient examples of the mining heritage – not least United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage sites, such as the Wieliczka Mine in Poland (Pactwa et al. 2021).

Nowadays, extractive industries continue to generate significant volumes of waste across most EE countries, even though the total share of these activities occupies a relatively small share of countries' land use. Locally, however, they can have severe impacts. As extractive waste constitutes a large proportion of total waste in this region, its management is critical as part of the transformation to a circular economy. Monitoring systems should consider the exploration, extraction, and physical and chemical processing of ores and other minerals, in line with the waste management hierarchy (Kulczycka and Dziobek 2021).

Across the region, many sites still store waste from historical mining activities. However, these legacy sites are increasingly viewed as strategic assets. The EU Green Deal and the New Industrial Strategy for Europe recognize access to raw materials and the security of supply from both primary and secondary sources as essential for the EU's transition to sustainability (Nowaczek et al. 2021). Recovering raw materials from post-mining heaps and dumps, as well as from urban mining, could play a role in this transition. Additionally, in 2025, the European Commission, as part of the Clean Industrial Deal, proposed creating an EU Critical Raw Material Centre to purchase raw materials jointly.

Mining has left a diverse range of environmental concerns across EE. The most severe environmental concerns included the loss of landscapes, aesthetic degradation, surface water and groundwater pollution or depletion, air pollution and loss of biodiversity. Although some of these concerns have already been realized, others pose ongoing potential risks (Kivinen et al. 2020).

8.4.5 Priority issue: biodiversity loss due to weak management frameworks

Despite a strong network of protected areas, the threat of habitat loss across the region remains high, mainly due to mismanagement, underfunding and inadequate law enforcement.

In many EE countries, a system of protected areas started to develop in the 19th century. During the 20th century, it grew significantly, with iconic sites including the Danube and Volga River deltas, Białowieża/Byelavyezhskaya Pushcha, the Tatra Mountains, Kazbegi, Wrangel Island, Baikal, Sikhote-Alin and many others. The EE region gave rise to many early conservation efforts by establishing strict nature protection areas. The idea of ecological networks also originated in EE. The green networks developed within Natura 2000 and Emerald are of critical importance (IPBES 2018).

Protected areas already cover more than 30 per cent of the land area in six countries – Armenia, Slovakia, Slovenia, Bulgaria, Poland and Croatia - achieving the target of the Kunming-Montreal Global Biodiversity Framework (**Figure 8.16**). The Russian Federation has the most protected areas, numbering 11,900, and the greatest expanse at 2,421,000 km^2 in 2021 (MNRERF 2022). Over the last two decades, protected area coverage in EE increased by approximately 150 per cent in the Republic of Moldova, 100 per cent in Azerbaijan, 75 per cent in Ukraine, 37 per cent in Georgia, 29 per cent in the Russian Federation, 26 per cent in Armenia and 17 per cent in Belarus (EEA 2020a). Meanwhile, protected area policies evolved towards sustainability principles that aim to provide economic and social benefits along with biodiversity objectives (Yakusheva 2019).

If properly maintained and developed, the protected area system can partly offset the biodiversity loss that is occurring due to adverse trends in land-use change. The ability of EE states to maintain and expand this network, however, is uncertain in the current economic and political context. Key conservation institutions are often understaffed, underfunded, and lack the systems and resources to ensure efficient management of their countries' vast natural heritage (Novikau 2021). Species protection lacks comprehensive data and is often limited to a few flagship species. Illegal logging, hunting, fishing, overgrazing and unsustainable infrastructure development within protected areas remain as chronic threats (Brochet et al. 2019; Zazanashvilli et al. 2020; Cazzolla Gatti et al. 2021; MNRERF 2022; Shytov and Shytov 2022; Shytov 2023; Ghoddousi et al. 2024). A typical example is the Hutovo Blato Nature Park in Bosnia and Herzegovina, a wetland of international importance, especially for migratory birds and endemic fish species, and recognized by the Ramsar Convention. The park suffers from degradation due to logging, the development of tourist facilities and weekend houses, the exploitation of mineral resources, and agricultural development (Hrelja 2019).

Biodiversity of the region is affected by negative trends outside of protected areas.

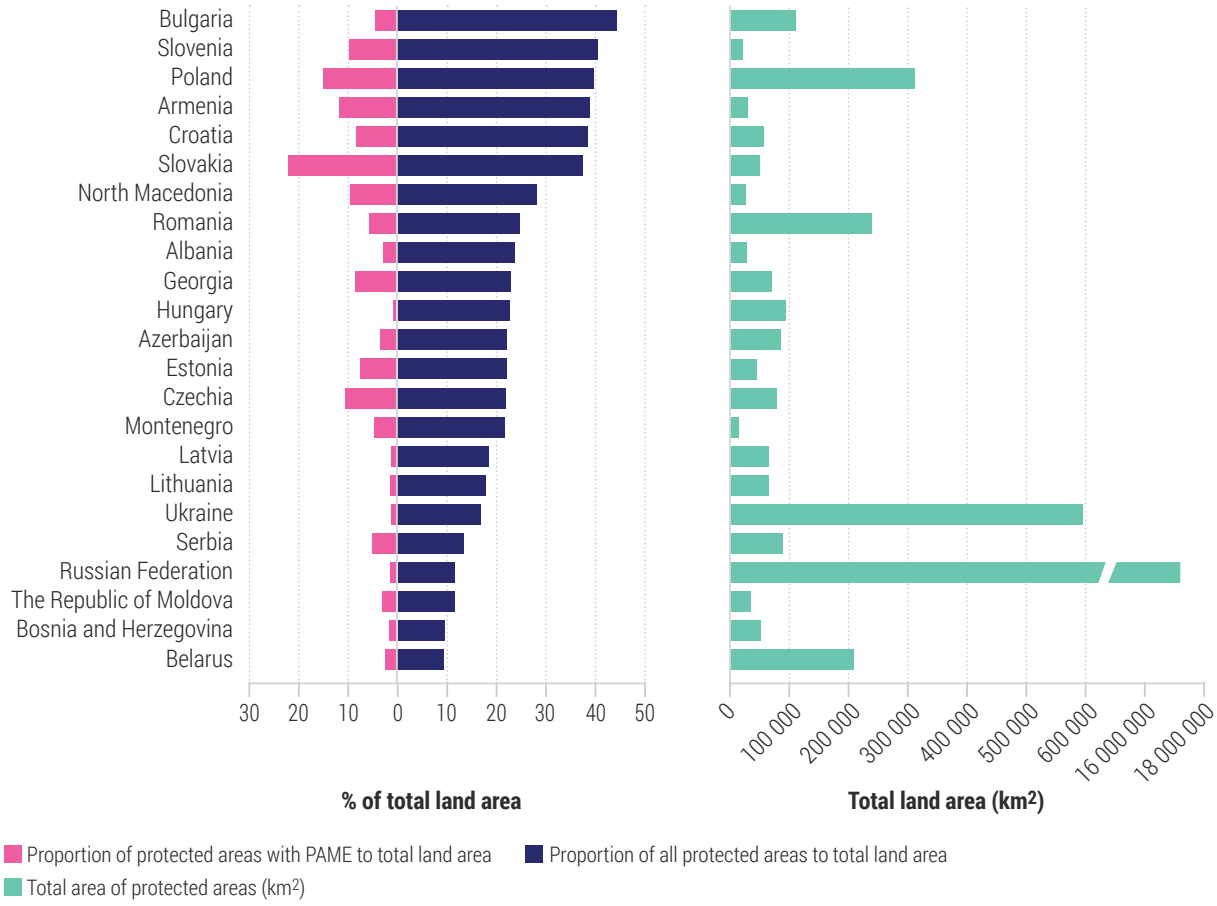
Climate change is mostly affecting biodiversity in the Arctic and mountain regions due to the melting of glaciers and permafrost soils (Álvarez Fernández 2021; Shivanna 2022). There is a threat of growing methane release from melting permafrost in the tundra during summer. Methane concentrations at the Tiksi and Teriberka monitoring stations in the Russian Federation Arctic have grown from 1,900 ppb in 2012 to up to 2,000 ppb in 2021 (MNRERF 2022).

Climate change is partly responsible for the increase in forest fires and pest outbreaks in Siberia and in the Balkans, along with other human-made factors, including forest monocultures and inadequate forest management (Alfthan et al. 2015; Alikadić et al. 2016; Ratknic et al. 2018; Natole et al. 2021; Kharuk et al. 2021; Kharuk et al. 2022; Ponomarev et al. 2023; Luo et al. 2024; Mataković et al. 2024). In turn, forest fires and diebacks also contribute to the release of greenhouse gases (GHGs).

Land-use change is the major direct driver of change in both biodiversity and ecosystem services degradation in EE (IPBES 2018; FAO 2021). Biodiversity is threatened by intensive agriculture and unsustainable forestry (Pe'er et al. 2022; Kjučukov et al. 2022; Rigal et al. 2023). In the past, local knowledge pertaining to soil management and land sustainability was replaced by uniform types of cultivation that do not necessarily respect the local environment, as discussed in Section 8.4.3. Hydropower dams produce renewable electricity but have a significant influence on rivers and impede native freshwater fauna. In the Balkans, a region with exceptionally high levels of fish species richness and endemism, around 3,000 small-scale hydropower dams are planned, although they are often in conflict with the EU Biodiversity Strategy. Some 90 per cent of the projected hydropower dams are small and will contribute little to the total installed capacity but will have a significant impact on river fragmentation (Carolli et al. 2023).

Soil degradation threatens soil biodiversity by compromising or destroying the habitat of the soil biota (Section 8.4.3). Agricultural lands had the highest

Figure 8.16: Proportion of protected area, including terrestrial and inland waters areas, with and without Protected Area Management Effectiveness (PAME) assessment in Eastern Europe



Source: UNEP-WCMC and IUCN (2025)

levels of threats to soil biodiversity. The EE countries have up to 10 per cent of their soils ranked at a high level of threat, while the boreal region has the lowest threat because of the small share of agricultural lands (CEEweb for Biodiversity 2021). Soil biodiversity tends to regenerate in abandoned and fallow arable land as monocultures disappear, and fertilizers and pesticide applications cease (Pulleman et al. 2022).

Microplastic pollution has considerable consequences for biota, the environment and public health (Savuca et al. 2022). Agricultural crop quality, the growth and photosynthesis of plants, and biodiversity are threatened by the presence of microplastics (Dong et al. 2021; Yang et al. 2021). In addition, microplastics can adsorb and transport contaminants, such as heavy metals and other pollutants, in soil and river environments (Castan et al. 2021). Moreover, the health of soil organisms and the enzymatic activities of these organisms are disturbed by microplastic contamination (Boughattas et al. 2022).

More than 80 per cent of marine pollution, with a high proportion of plastic material, comes from land-based activities (Dobrzycka-Krahel and Bogalecka 2022). Pressure at the coast from mismanaged plastic packaging and small non-packaging plastic items is particularly intense in the Mediterranean Sea and the Black Sea. The total amount of mismanaged plastic packaging waste at the coast even increased in these two regions from 2012 to 2018, while in the Baltic Sea, it slightly decreased (Veiga et al. 2022). Plastic waste represents 95 to 100 per cent of marine floating waste and 50 per cent of litter on seabeds in the Mediterranean Sea (UNEP/MAP and Plan Bleu 2020). Plastics make up 83 per cent of the marine litter found in the Black Sea. Plastics are the most common litter category in the Baltic Sea (Veiga et al. 2022). Rivers constitute critical pathways of the transport of litter from land into the sea. An average of 7.5 g of plastic litter per 1,000 m^3 s^{-1} with respect to the mean flow (4.2 tons per day or 1,533 tons per year) is transported via the Danube to the Black Sea (Lechner et al. 2014). Marine plastic

pollution has increased tenfold since 1980 (Veiga et al. 2022; Savuca et al. 2022), while air and soil pollution are also on the rise (FAO and UNEP 2021; HEI 2022; Chen et al. 2024).

The EU Nature Restoration Regulation is the first continent-wide, comprehensive law of its kind, and a key element of the EU Biodiversity Strategy (Hering et al. 2023). Relatively well-preserved habitats and healthy populations of many species in EE countries provide policy opportunities not available in the western parts of the continent. Restoring nature in forests, wetlands and grasslands in EE is often easier and less costly than in northwestern Europe. Rather than restoring ecosystems from scratch, national implementation of the Nature Restoration Regulation in Balkan, Baltic and Central European countries will often entail improved management to realize the biodiversity potential of existing land cover. For example, the region's nearly 2.3 million km^2 of peatlands are a globally significant ecosystem (Karapinar 2021). Many of them are degraded, offering prime opportunities for restoration.

Indigenous Knowledge and Local Knowledge (IK & LK) are widespread within EE, and provide unique insights into environmental challenges in the region.

The Russian Federation Arctic, encompassing vast areas of taiga and tundra, is home to approximately 30 groups of Indigenous Peoples, with a total population of around 180,000 (Russian Association of Indigenous Peoples of the North 2021). Many still work in traditional occupations, such as reindeer herding, as well as hunting and fishing. The continued expansion of extractive industries and infrastructure projects on Indigenous Peoples' lands leads to toxic pollution and environmental damage. Under current legislation, they have rights to their land in principle. However, none of the "territories of traditional nature use" have been implemented at the federal level so far (Sharapova et al. 2022). In 2020, the Russian Federation adopted the Arctic Development Strategy, which envisions the implementation of investment projects, social and economic development, improving the quality of life for the local population, and creating a stable financial basis for traditional lands in the form of a special fund (Novoselov et al. 2021). Often, incoming companies provide local people with compensation in the form of modern technology, such as snowmobiles and radio sets, which enable them to conduct their traditional husbandry more effectively and partly offset the gradual decline in the herder population. On the other hand, there are concerns that the Russian Federation has withdrawn from the Framework Convention for the Protection of National Minorities and is one of the few countries in the world not to have endorsed the UN Declaration on the Rights of Indigenous Peoples. Additionally, due to ongoing geopolitical confrontations, the long-term cooperation in the Arctic region between the Russian Federation and the EU has been suspended.

Traditional knowledge of extensive farming is an important dimension of biodiversity in many EE rural regions (Section 8.4.3). Conservation of agrobiodiversity is closely linked to socioeconomic issues, so globalization and EU rules could affect the use and existence of old, traditional and native genetic material. In today's post-communist countries, traditional knowledge concerning land tenure and cultivation was disrupted by the collectivization of land, which led to the ploughing of biodiversity-rich boundaries between fields and the cultivation of monocultures in large fields. These practices destroyed significant components of ecosystems and their biological diversity. The local knowledge was replaced by unified planning. Currently, it is possible to observe the emergence of farms that practise regenerative agriculture and utilize the local knowledge of the older generation.

Biocultural heritage use, such as wild food and medicinal plants gathered in natural and seminatural habitats, remains common practice in many rural parts of the region (Varga et al. 2019; Łuczaj et al. 2019; Vári et al. 2020; Babai et al. 2020; Pruse et al. 2021; Aziz et al. 2022; Nowak-Olejnik and Mocior 2022). Informal food markets that locally sell home-made products contribute to the sustainability and diversity of food systems (Soukand et al. 2022). Interestingly, these traditions are increasingly popular in modern city markets and create food tourism in some EE countries, providing a new and economically viable value for local knowledge (Soukand et al. 2022; Luković et al. 2024). The increased use of quality labels to highlight traditional regional products, promoted by EU policies, is an example of local knowledge preservation and realization.

Similarly, food production in family allotments and gardens is a local tradition widely practised, with surprisingly large environmental and social benefits. The Russian Federation's dacha gardens produce a significant share of the country's food output, especially

Box 8.4: The influence of conflicts in the EE region on the environment

The war in Ukraine, which escalated on 24 February 2022, has already resulted in environmental repercussions unprecedented since World War II. Some critical natural areas in the war zones are currently being damaged or destroyed (Pereira et al. 2022).

Besides the direct destruction of natural and human-managed ecosystems and the loss of associated ecosystem services, the long-lasting environmental effects of war include widespread contamination of soils, water resources and biota by persistent pollutants, comparable to the consequences of large-scale industrial disasters (Solokha et al. 2023). There is significant destruction of infrastructure in the war zone, of towns and villages, oil refineries, bridges and dams. The destruction of the Kakhovka dam resulted in massive flooding of the downstream area and a change in the hydrological regime of the lower Dnipro River. Nuclear power stations in Zaporizhzhia on the Ukrainian side and in Kursk on the Russian Federation side are located close to the war zone, with all associated risks. The problem of landmines left by war is both profound and long-term. Unprecedented rehabilitation action will be required as soon as the war has ended (UNEP 2023). The war in Ukraine also spurred a massive migration of hundreds of thousands of people out of the conflict areas (United Nations High Commissioner for Refugees 2025).

Environmental damage is also evident in the Russian Federation, as well as in the Black Sea. The damages in the Black Sea and its littoral zone may result in a spillover of environmental consequences to other countries (Pereira et al. 2022).

A peculiar aspect of post-conflict situations is the significant change from pre-war ecosystems. Bosnia-Herzegovina experienced a military conflict three decades ago, and diverse consequences have become evident. The human pressure on ecosystems decreased due to depopulation.The original agricultural landscapes are either non-existent or have undergone considerable transformation. An example of such a change in Bosnia-Herzegovina is the plant succession in the Sarajevo Canton area, as well as the spread of *Pinus mugo* due to reduced grazing by sheep (Ljusa and Custovic 2025). The depopulation of mountain areas has encouraged the spread of species such as *Pinus heldreichii* (Bosnian pine), an endemic and relict Balkan-Apennine pine species (Meštrović 2007). Depopulation has also led to fewer people harvesting medicinal plants, sometimes to the point of overexploitation, which has contributed to the revival of many species.

in fruits and vegetables. Half of Poles and one-third of Hungarians grow food at home, and 18 per cent of the Czech consumption of fruit, vegetables and potatoes comes from garden plots (Jehlička 2021). Research shows that families do not grow their own food out of necessity, to cope with shortages and economic crisis. They view it as a cultural tradition and part of local identity, a hobby and a source of healthy, fresh food, inadvertently creating what researchers call a "quiet sustainability" model (Jehlička 2021; Daněk et al. 2022). Indeed, the practice is common in affluent countries of Central Europe and occurs almost evenly across society, irrespective of education, employment status or income (Jehlička 2021; Daněk et al. 2022).

8.5 Latin America and the Caribbean and subregions

8.5.1 Introduction

Latin America and the Caribbean (LAC) is home to more than 664 million people, of whom 81.86 per cent live in an urban setting (World Bank 2023). The region encompasses 33 countries in three subregions – the Caribbean with 13, Central America with 8 and South America with 12 countries – and covers more than 19 million km^2 of land and 16 million km^2 of maritime territory with over 70,000 km of coastline. LAC constitutes a significant global freshwater

Credit: wirestock/Envato

reservoir, accounting for approximately 30 per cent of the world's water resources. However, the region faces substantial disparities in the distribution of this essential resource, with nearly 25 per cent of the region's population residing in water-scarce areas (Lentini 2022; Rodríguez et al. 2022). Agricultural and livestock activities account for 70 per cent of freshwater demand, while household and industrial use represent 11–15 per cent and 15–19 per cent, respectively (Lentini 2022).

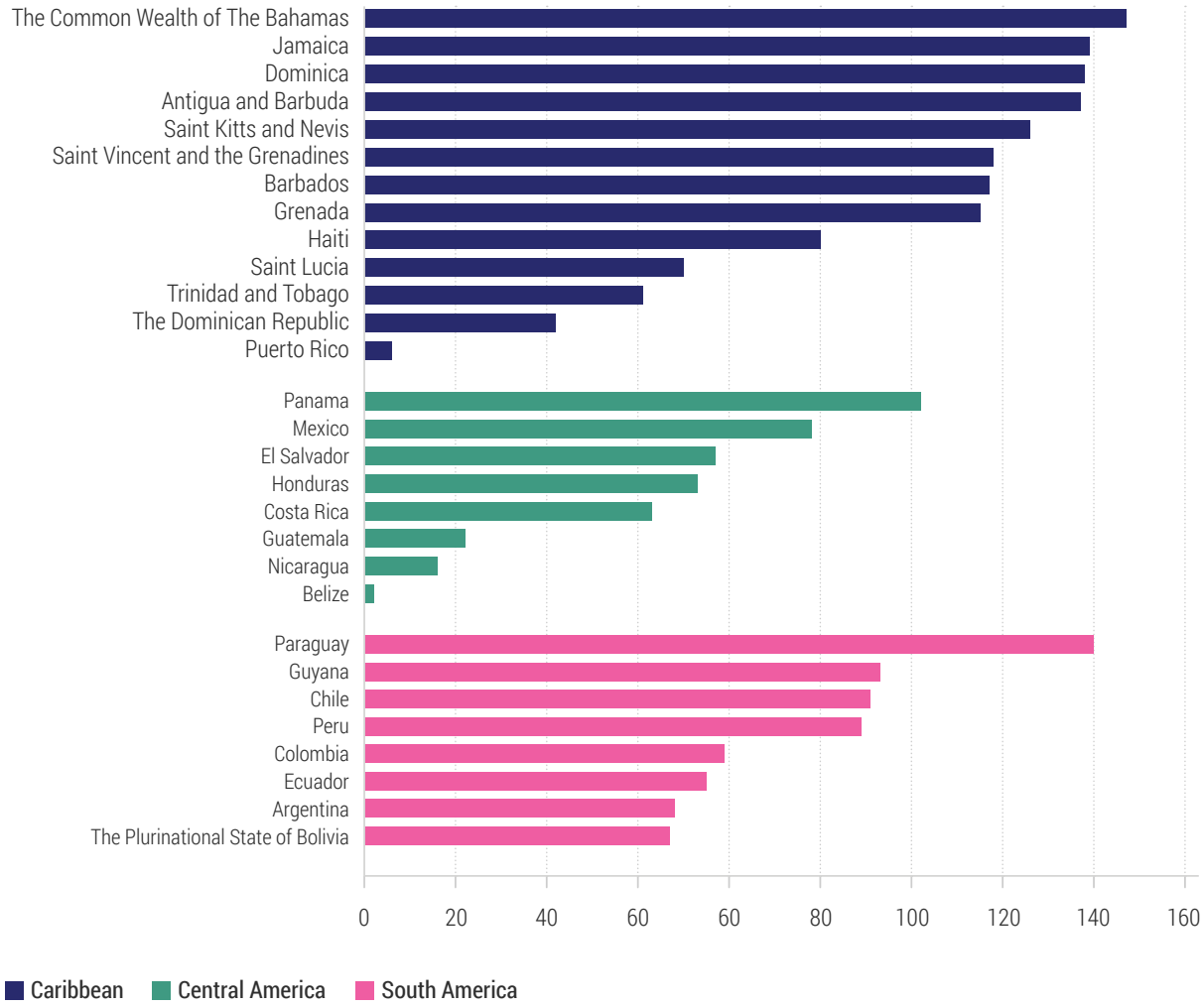
The LAC region is home to a vast array of ecosystems and species. The region includes six megadiverse countries – Brazil, Colombia, Mexico, Peru, Ecuador and Venezuela – providing opportunities for global conservation (UNEP-WCMC 2020). The region's extensive marine territory encompasses 19 Small Island Developing States (SIDS), the Mesoamerican Barrier Reef and other vital marine environments (UNEP 2020), and 47 global marine ecoregions (Tambutti et al. 2020).

The region is also characterized by a diversity of cultures, peoples, languages, traditions and histories. This diversity contributes to vibrant national identities, but it also poses challenges related to social cohesion and equitable development (UNESCO 2020). While there are prosperous countries in the region, at both national and subnational levels, the region also faces significant socioeconomic challenges, including inequality, poverty, and unequal access to and control over basic services such as water and energy (Economic Commission for Latin America and the Caribbean [ECLAC] 2021).

The global environmental crises – climate change, biodiversity loss and land degradation, and pollution and waste – interact and generate effects differently in various parts of the region, necessitating nuanced and localized approaches to address specific challenges (UNDP 2019) (**Figure 8.17** and **Figure 8.18**).

The global environmental crises – encompassing climate change, biodiversity loss, land degradation and desertification, and pollution and waste – threaten the delicate balance of the region's ecosystems, especially with regard to deforestation and soil erosion, leading to consequences for biodiversity and human well-being (IPBES 2019). In this context, most

Figure 8.17: Latin America and the Caribbean Climate Risk Index (CRI) 2022



Note: The CRI indicates how extreme weather events affect countries. It is a backward-looking index (previous 2 years) that ranks countries by their health and human effects (fatalities and affected, injured, and homeless people). Higher numbers mean countries that have been more affected in the past two years by extreme weather events.
*The countries not included in this figure do not have data available

Source: Germanwatch (2025)

countries face significant vulnerabilities and social gaps, including hunger and food insecurity. Many of these issues affect Indigenous and other minority groups in a disproportionate way (UNEP-WCMC 2020).

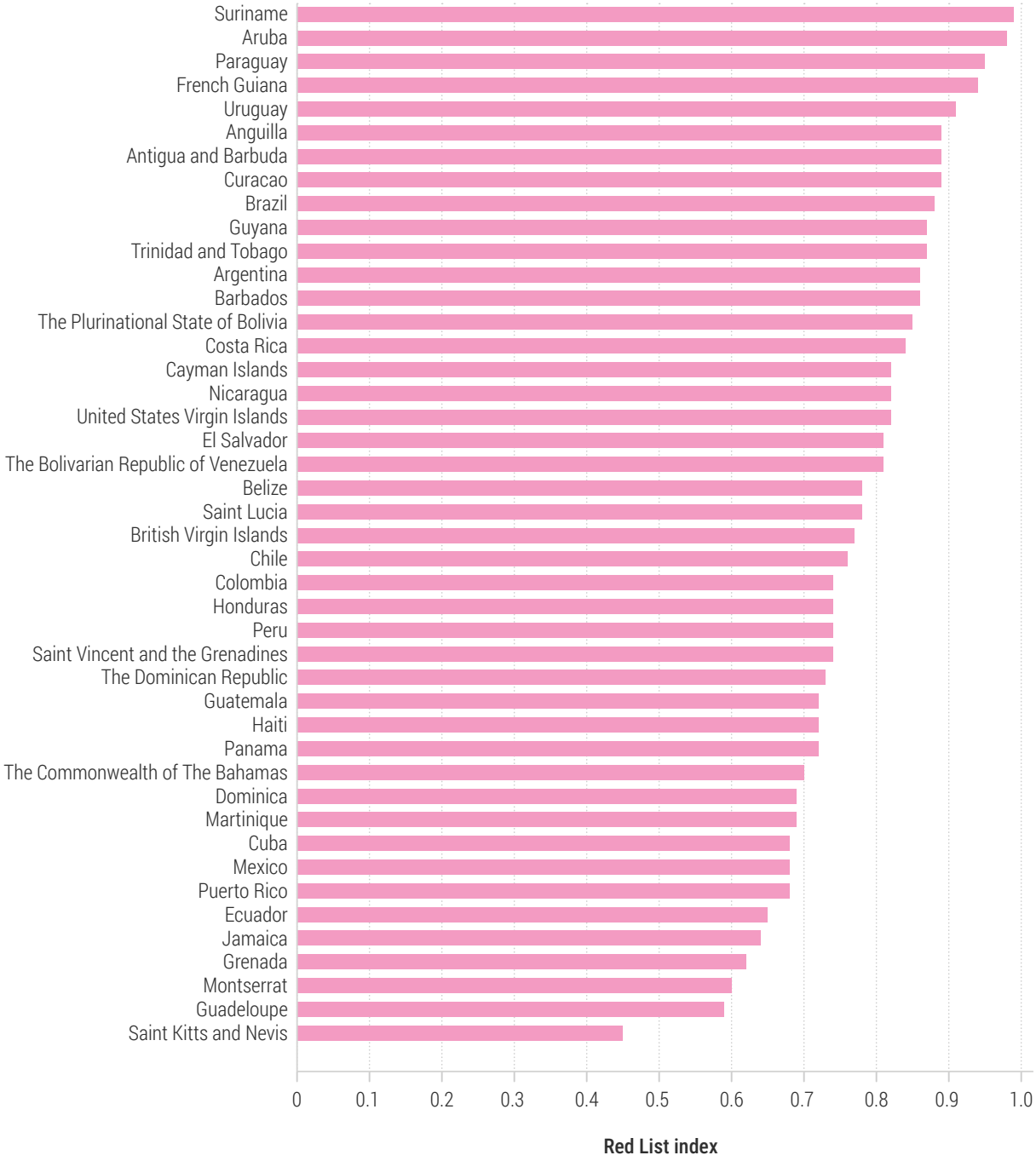
8.5.2 Interlinkages between the global environmental crises and regional priorities

The global environmental crises act in synergistic ways as driving forces of environmental change (Global Environmental Crises Chapeau). For LAC, this report has identified three key priorities (**Figure 8.17**) where the interlinkages among the crises lead to significant consequences for people and ecosystems:

- changes in land-cover dynamics
- changes in freshwater quality and availability
- degradation of coastal and marine resources

Land-cover dynamics refer to how biophysical processes on land interact with each other, and how human activities might affect them. Climate change aggravates desertification (IPCC 2019; Hagen et al. 2022), increases wildfire risks (Hagen et al. 2022; Jones

Figure 8.18: Red List Index 2023 for countries in Latin America and the Caribbean



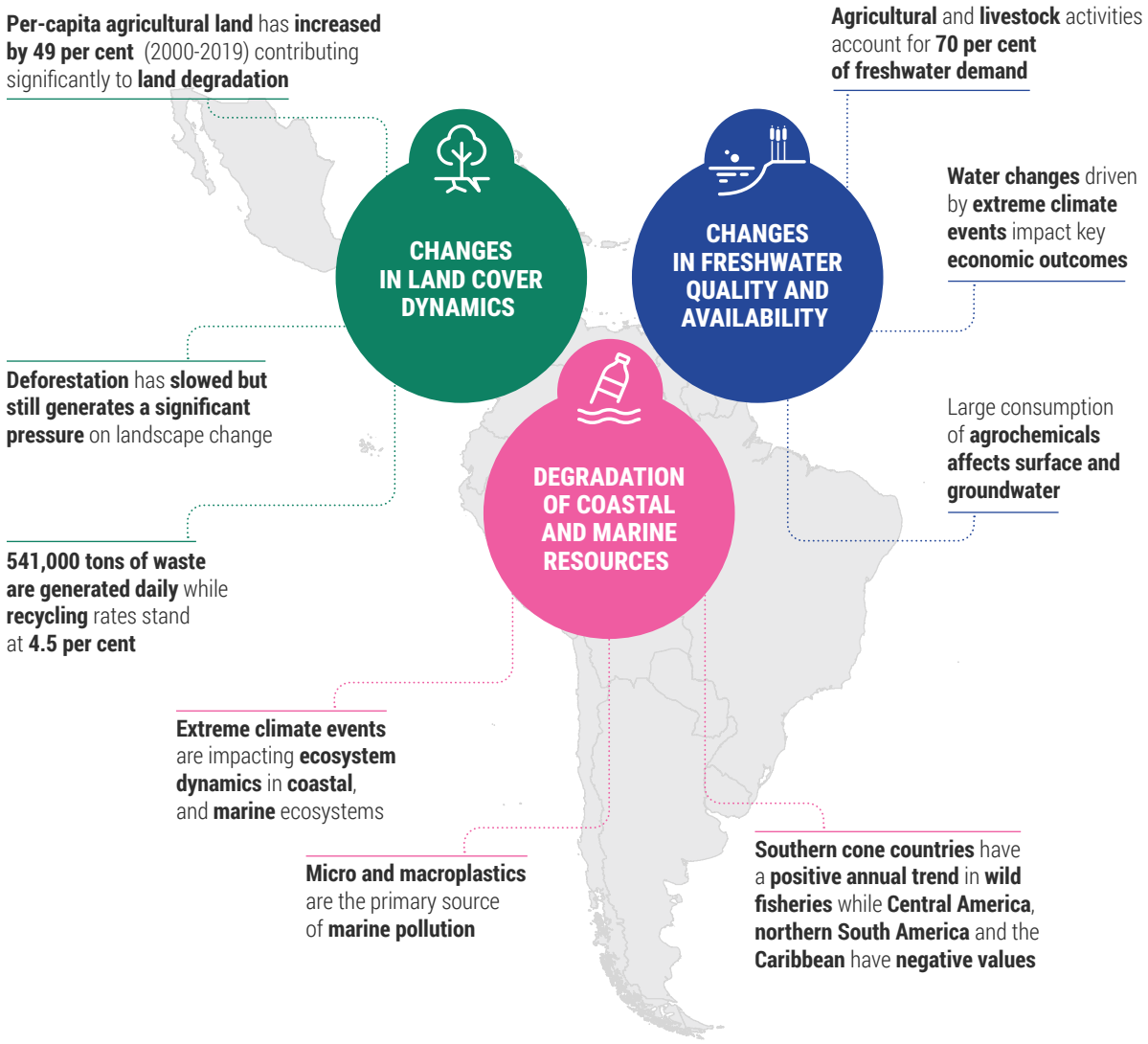
Note: The IUCN Red List Index determines the overall extinction risk of animal, fungus and plant species. A Red List Index value of 0 equates to all species having gone extinct and a value of 1 indicates that there is no current extinction risk to species.

Source: IUCN and BirdLife International, processed by Our World in Data (2024)

et al. 2022), and affects the range of endemic species (Silva et al. 2019; Tovar et al. 2022). Biodiversity loss, primarily due to land-use changes such as urbanization and agricultural expansion, reduces ecosystem services, resulting in a less resilient environment (IPBES 2018). Land degradation, exacerbated by unsustainable farming and deforestation, decreases soil fertility and increases migration (UNCCD 2019; UNCCD 2022). Pollution from land sources contributes to biodiversity loss (Laterra et al. 2019) and climate change.

Changes in freshwater quality and availability have significant effects in the LAC region. Climate change

Figure 8.19: The interplay of the global environmental crises and regional priority issues: effects on Latin America and the Caribbean's land cover dynamics, freshwater quality and availability, and coastal and marine resources



alters hydrometeorological patterns, affecting the intensity and frequency of rainfall (Carvalho et al. 2020), and leading to ecosystem stress (Sheldon 2019) and land degradation (Hermans et al. 2021). Pollution from agrochemicals, microorganisms, industrial compounds and plastics, as well as soil erosion and other forms of land degradation, threaten water quality (Warren-Vega et al. 2023). Biodiversity loss and land degradation significantly impact freshwater regulation ecosystem services (IPBES 2018).

In the LAC region, coastal and marine resources are degrading at an accelerated rate due to anthropogenic activities (Tambutti et al. 2020). Greenhouse gas emission overload causes ocean acidification (Findlay and Turley 2021). Together with climate change's extreme events, such as ocean heating, this leads to coral bleaching (Cortes et al. 2020). Rising sea levels drive onshore land degradation through erosion and the salinization of coastal soils and aquifers (Hagen et al. 2022). Marine pollution results mainly from land-based sources. Microplastics and hypoxic zones are becoming increasingly prevalent in marine and coastal areas (Tambutti et al. 2020). Overall, the loss of coastal ecosystems exacerbates the impacts of other crises.

8.5.3 Priority issue: changes in land-cover dynamics

How we change the land alters, and in most instances degrades, global environmental processes. LAC is home to a diverse range of ecosystems, from tropical rainforests to some of the driest deserts on Earth, which provide the region with a higher-

than-average availability of natural resources per person (IPBES 2018). The regional emphasis on extractive industries and agricultural activities can constrain the capacity of ecosystems to maintain this supply of natural goods and services. Land-use changes – including deforestation, habitat conversion and agricultural expansion – also affect water regulation ecosystem services and can lead to land degradation. Many of these initiatives have generated socioecological conflicts: by 2018, more than 60 per cent of the environmental defenders killed in the world were from Latin America (Picq 2020). Indigenous Peoples and local communities are disproportionately affected by such conflicts (Billon and Lujala 2020).

The interacting global environmental crises affect land-cover dynamics in the region.

Climate change contributes to desertification, particularly in areas adjacent to existing deserts and drylands (IPCC 2019). Some areas of northeastern Brazil are undergoing desertification, due to decreasing rainfall and increasing deforestation (Burrell et al. 2020). Wetlands, too, are drastically transforming as drying trends persist in some areas of Mexico and Central America, which threatens migrating bird species (Xi et al. 2020).

Climate shifts affect species distribution, resulting in disruptions to ecosystem composition and function. Climate change consequences are more substantial on endemic species, as their habitat conditions and ranges are more restricted. The most prominent adverse effects are on terrestrial endemic species in South America, with about 30 per cent of assessed species threatened with extinction (Manes et al. 2021). Climate change in mountainous areas causes whole ecosystems to migrate and fragment as they move upward. Andean grasslands will dry out and be invaded by trees, while the cloud forest will shrink due to the reduction in cloud immersion and frost in the Tropical Andes (Helmer et al. 2019).

Climate change also increases wildfire risks in LAC (IPCC 2023). Record heat and low humidity in 2022 led to more than a 200 per cent increase in hotspots in Brazil, Paraguay and Argentina (WMO 2023). In the case of the Amazon, the lengthening of the dry season may be catastrophic for its rainforest, increasing vulnerability to forest fires (Hagen et al. 2022).

The interaction between climate change and land degradation in the Amazon highlights the interlinkages of global environmental crises. Deforestation in the Amazon generates substantial warming over distances as far as 100 km from the forest-loss location (Butt et al. 2023). Deforestation and forest degradation also generate GHGs, but at the same time contribute to the savannization of the Amazon rainforest, a form of land degradation with profound livelihood impacts both to Indigenous and local rainforest dwellers, and people in the Tropical Andes (Quintanilla et al. 2022).

Deforestation has slowed in the region, but it still generates significant pressure on landscape change (FAO 2020). Between 1992 and 2022, the area deforested in the LAC region reached approximately the size of Guatemala, Belize, Honduras, Nicaragua, Costa Rica and Panama combined (FAO 2025). While forest cover has decreased in South and Central America, it is increasing in the Caribbean. Forest fires are the predominant pressure in the tropics, primarily used for clearing forests to establish cattle ranches or for agriculture (FAO 2022). Although mangroves are regrowing in South America and the Caribbean, their numbers continue to decline in Central America (**Figure 8.28**) (FAO 2020). According to the Living Planet Index, from 1970 to 2020 in LAC, trends in the viability of wild populations of monitored terrestrial, marine and aquatic vertebrates declined by 95 per cent (World Wide Fund for Nature [WWF] 2024).

LAC is the only region where per capita agricultural land has increased, emphasizing its role as a global food producer. Habitat transformation continues throughout South America – particularly in Brazil, Paraguay and the Plurinational State of Bolivia, among others – where tropical ecosystems are being converted into agricultural fields and pastures (UNCCD 2019). Between 2000 and 2019, agricultural land in South America expanded by 49 per cent, with 61 per cent of that expansion occurring on land usually left fallow for long periods or pastures (Potapov et al. 2021). In the Caribbean, agricultural land area remains nearly constant, while it has decreased slightly in Central America (FAO 2023a). The loss of habitats is expected to continue, particularly in South and Central America (Powers and Jetz 2019).

Current management practices in South and Central America have contributed to soil degradation (Prăvălie et al. 2023). As soil productivity declines, more

land needs to be cleared to maintain production. Furthermore, the more land cleared, the more agricultural expansion significantly contributes to land degradation in the Amazon Basin, the fragile Andean grasslands (UNCCD 2019) and the Southern Cone pampas (Song et al. 2021; Foucher et al. 2023). In Uruguay, grasslands were converted into forest plantations in the mid-1990s and, after 2000, into soybean fields, resulting in increased erosion rates.

Land-use competition also contributes to the transformation of ecosystems. In the Caribbean, a land-limited subregion with an abundance of natural assets, particularly beaches, the lack of regulation or enforcement and the marginalization of local communities contribute to unsustainable land-use changes. Tourism has a direct effect on coastal ecosystem loss through urbanization and infrastructure development at the expense of natural vegetation and rural land use. An example from coastal Belize indicates that natural vegetation declined nearly 11 per cent, while urban areas increased by 39 per cent between 2000 and 2017 (Sweetman et al. 2019). The development of tourism infrastructure in the Mexican Riviera Maya, for instance, has intensified resource depletion and disrupted traditional and Indigenous livelihoods, undermining land-management practices in ancestral territories (Fernandez et al. 2020).

Moreover, land degradation contributes to rural–urban migration because land no longer guarantees the subsistence of smallholder families. In Central America, severe soil degradation is associated with drought. Areas in Mexico (Nuevo León, Oaxaca) exemplify how soil degradation has forced the displacement of rural communities (Méndez et al. 2010).

Urban air pollution is recognized as one of the most pressing environmental issues in LAC, especially in the form of particulate matter (PM) (Gómez Peláez et al. 2020). Although data are limited (Gómez Peláez et al. 2020), $PM_{2.5}$ and PM_{10} exceeded the WHO guidelines between 2010 and 2017 in the assessed cities (Gouveia et al. 2021). Furthermore, the region does not show a strong trend in reducing PM pollution.

In LAC, 541,000 tons of waste are generated daily, and this is expected to increase to at least 640,000 tons by 2050 (UNEP 2018). Higher-income countries, such as Chile and Trinidad and Tobago, tend to generate more waste than lower-income nations, such as Haiti and Nicaragua (Margallo et al. 2019). Six SIDS are in the region's top 10 countries in terms of waste generation (Margallo et al. 2019). Although waste management has improved, about 27 per cent of waste is disposed of in open dumpsites (UNEP 2018). Primarily an urban phenomenon, there is limited information on the status of rural areas, where the use of agrochemicals affects both land and freshwater systems.

Urbanization may generate pollution hotspots that degrade local and regional air, land and water conditions. For example, climate change exacerbates urban heat islands in the region (Palme and Carrasco 2022), where more than 80 per cent of the population resides in urban settlements (ECLAC 2023a). The use of biomass as fuel for cooking and heating, mostly in rural households but also present in urban settings, is a critical source of indoor air pollution (Jorquera et al. 2019; Manzano et al. 2022).

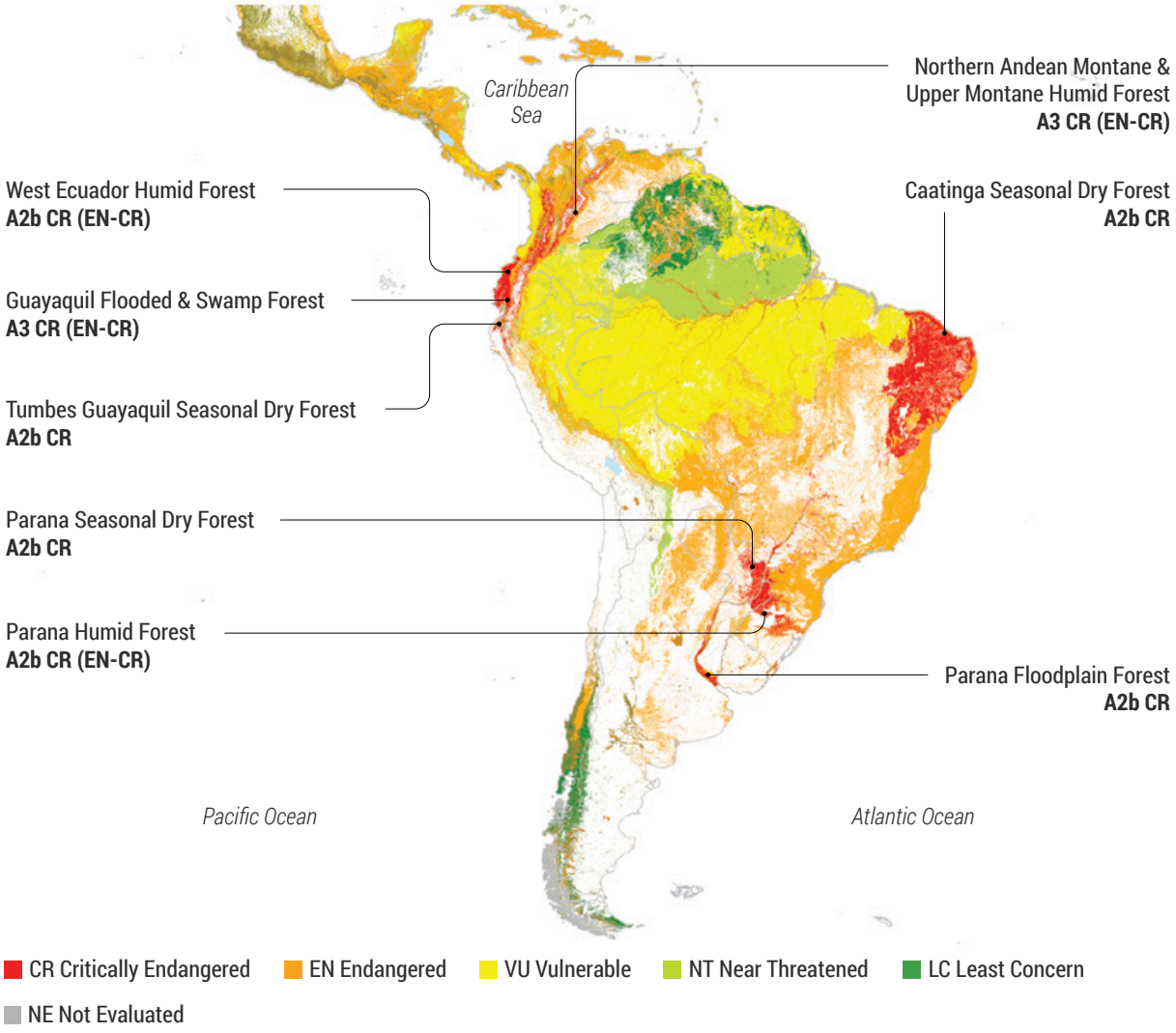
Changes in land-cover dynamics have impacts on natural and human systems.

Current land management in LAC continues to degrade terrestrial ecosystems (IPBES 2018; UNEP 2019). Since the beginning of the 20th century, forest cover in the region has declined from 70 per cent to 50 per cent (UNCCD 2019). Most of the region's remaining forests (**Figure 8.20**) face some level of threat (Ferrer-Paris et al. 2019).

Forest deforestation and regrowth influence water regulation ecosystem services in the Andean subregion (Bonnesoeur et al. 2019), while to the east, in the Chaco, poor land management contributes to a decrease in soil organic carbon, which in turn affects water regulation ecosystem services (Baldassini and Paruelo 2020). Agrofuel production in the region relies heavily on fresh water, particularly when based on sugarcane and palm oil plantations (Zhong et al. 2021).

Land-cover dynamics affect the ability of soils to provide ecosystem services. The capacity of vegetation to protect soils declined between 2001 and 2013 in large areas of Argentina and Brazil (Guerra et al. 2020). Results also suggest that between 2006 and 2013, erosion risk increased in South and Central America. Approximately one-third of this risk is attributed to vegetation dynamics, while the remaining two-thirds is a result of climate change. The erosion rates in South

Figure 8.20: Latin America and the Caribbean forests risk assessment



Source: Ferrer-Paris et al. (2019)

America are expected to increase by 37 per cent under current scenarios of climate change by the end of the 21st century (Riquetti et al. 2023).

Changes in wildlands and poor agricultural management contribute to erosion, leading to sedimentation on floodplains and coastal areas (Fagundes et al. 2021). Sea levels in LAC have increased at a greater rate than those in the South Atlantic and the subtropical North Atlantic (WMO 2023). Sea level rise poses a significant threat to the livelihoods of growing coastal populations (Tambutti et al. 2020).

In the LAC region, fire plays a crucial role in the transformation of forests into agricultural land (Armenteras et al. 2021) and in the management of agricultural land (Mendez-Espinosa et al. 2019). Fires in the Amazon and northern South America have significantly deteriorated air quality across vast portions of the basin, including places far away from the fires (Butt et al. 2020; Ballesteros-González et al. 2020). Research shows that from 2018 to 2021, people's exposure to extreme high fire danger increased in 9 out of 12 South American countries compared to the baseline period of 2001–2004 (Hartinger et al. 2023).

Fuelwood remains a dominant cooking fuel for rural LAC households (Schilmann et al. 2021). Wood collection occurs in forests and agricultural landscapes. Estimates of the number of fuelwood users range from 70 to 160 million as of 2021 (Schilmann et al. 2021). Large-scale deforestation in the remaining forested landscapes may lead to a scarcity of fuelwood for rural populations.

Agricultural production is very heterogeneous in LAC. Agroindustrial operations coexist with small, subsistence farms. The region is a leading exporter

of agricultural products, including soybeans, livestock, maize and coffee, among others. Brazil is the largest agricultural producer and exporter in the region, followed by Argentina, Mexico and Chile (FAO 2023a). Despite LAC being a food basket, malnutrition is persistent, with greater impact on people with lower income, women, Indigenous and Afrodescendant Peoples (PAHO 2023). For example, Indigenous communities in the Amazon depend on nearby resources produced in home gardens or collected in the forest or rivers. The expansion of agro-industry and mining contributes to habitat destruction and biodiversity degradation, compromising Indigenous nutrition and food security (Penafiel et al. 2019; Bergazo-Curie and Vranken 2025). As a result, landscape transformation has affected local and Indigenous communities, disrupting their traditional land management and cultural practices (Aoki et al. 2016). This loss of knowledge is also evident in LAC's Afrodescendant communities. Traditional knowledge, brought from Africa to Latin America, is being eroded by industrial agriculture and natural resource extraction, affecting communities in Colombia, Peru, Ecuador, Brazil and Venezuela. These activities caused the displacement of many Afrodescendant communities (Mosquera-Vallejo 2020).

Agriculture has led to the intensive use of agrochemicals, with consequences for rural populations (Timmerman 2019). However, the effects are not limited to rural areas, as these compounds can also reach urban dwellers through air currents and contaminated food (Hendges et al. 2019).

Sea level rise reduces suitable lands for agriculture in SIDS and other coastal areas, and it leads to increases in food-borne, waterborne, and vector-borne diseases, such as malaria and dengue, as well as to increases in premature deaths.

Recycling rates in LAC are approximately 4.5 per cent (Kaza et al. 2018), with the majority being informal (Ziglio and Ambrizzi 2024). Some of the solid waste associated with agricultural practices in the region requires the intensive use of plastics, making recycling difficult (Cadena et al. 2021). In LAC, estimates indicate that food waste accounts for between 8 and 10 per cent of the food weight entering households (Chen et al. 2020). These amounts of waste can be considered as an additional pressure to transform wildlands into agricultural fields.

8.5.4 Priority issue: changes in freshwater quality and availability

Increasing water scarcity and decreasing quality form a dual threat to nature and people.

Although LAC holds 30 per cent of the world's freshwater resources, 25 per cent of its population lacks access to safe drinking water, and 66 per cent still do not have adequate sanitation services (ECLAC 2023a). Climate change, land degradation, and pollution are exacerbating the freshwater crisis in LAC (IPCC 2022a), with changes being experienced in both water quality and availability.

The interacting crises affect the region.

Climate change affects LAC's freshwater resources by altering the intensity and frequency of rainfall, reducing soil humidity and infiltration capacities, and changing river run-off (Lentini 2022). These changes are exacerbated by alterations in vegetation cover. For example, in the Amazon, deforestation has decreased moisture in the lower atmosphere, leading to increased drought and fire in self-reinforcing feedback loops (IPCC 2022a).

Drought conditions in 2022 across the La Plata Basin in South America were the worst since 1944 (WMO 2023). Parts of Argentina, Paraguay, Uruguay, Chile and southern Brazil recorded below-normal to much-below-normal river discharge in 2022. The effects of drought have been severe in drylands, where a third of the region's population is concentrated. Effects are most pronounced in places like Peru, where 80 per cent of the people live in arid or semi-arid environments. In addition, between 1997 and 2017, the region experienced an 80 per cent increase in the frequency of floods, compared with the previous 20 years.

Glacier melt in South America contributes to sea level rise, increases sediment load and releases trapped contaminants (Santofimia et al. 2017; Magnússon et al. 2020; Vergara et al. 2024). Between 2000 and 2015, the largest contributions came from the Patagonian icefields, where 83 per cent of mass loss occurred, primarily from dynamic adjustments of large glaciers. These changes contribute to global sea level rise (Braun et al. 2019). Colombia's glaciers, such as those in the Sierra Nevada del Cocuy and the Sierra Nevada de Santa Marta, have experienced dramatic reductions

in size, losing over 90 per cent of their total mass in the last century. This loss not only threatens local water supplies but also contributes to downstream water scarcity and reduced river flows (IDEAM 2023). Rising sea levels, intensified by extreme weather, such as hurricanes and storm surges, pose a serious threat to water quality in coastal regions.

The LAC region is one of the world's largest consumers of agrochemicals, deteriorating the quality of surface and groundwater (Sharma et al. 2019). Land degradation results in increased run-off into freshwater and coastal marine systems and promotes pollution by agrochemicals and other contaminants. Intensive livestock production adds to the problem by releasing manure that contaminates both aquatic ecosystems and groundwater.

Watershed degradation from the discharge of untreated effluent in peri-urban and rural areas is significantly damaging the quality of both surface water and groundwater (World Bank 2023). In several countries, inadequate solid waste management results in the prevalence of plastic debris and emerging contaminants, leading to leaching that pollutes both surface and groundwater (Olivatto et al. 2019; Dagwar and Dutta 2024). These solid wastes also constitute an important source of coastal and marine pollution through various pathways, including run-off, wastewater discharge and atmospheric transport.

Changes in freshwater quality and availability impact natural and human systems.

Water changes driven by extreme climate events are adversely affecting the region's key economic sectors (WMO 2022). For example, drought conditions between 2020 and 2022 in the Río de La Plata Basin severely impacted agriculture, inland navigation, energy production and water supply (Rivera 2024), increasing the possibility of conflict between countries (Barbosa and Ribeiro 2024). In 2023, the Panama Canal faced operational challenges due to warm ENSO conditions, resulting in an estimated earnings loss of US$200 million (WMO 2022; Dhal 2024).

Drought-induced water scarcity is a significant concern, particularly in regions heavily dependent on hydroelectric power generation, such as Paraguay, Ecuador and Venezuela (World Bank 2023) (**Figure 8.21**). For example, Ecuador's Coca Codo Sinclair hydroelectric plant has faced interruptions due to reduced river flows from the Coca River, attributed to both climate variability and increased blockages caused by landslides (IDB 2022).

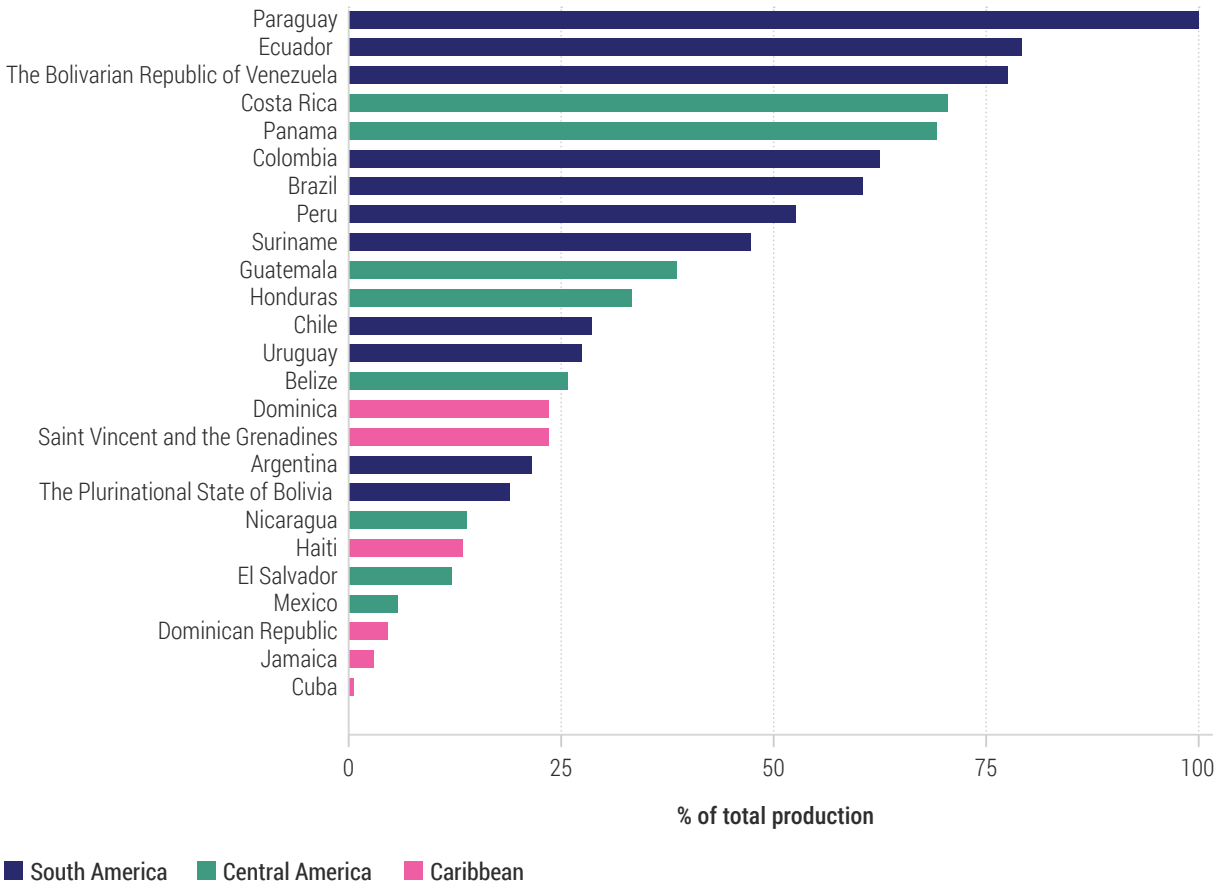
Water scarcity and quality directly threaten food security in the region. Agricultural irrigation accounts for 35–86 per cent of the total available water (Salazar et al. 2022). Droughts in the Southern Cone disrupt agricultural production, particularly for small farmers who depend on rain-fed agriculture (Loukos and Arathoon 2021). The region's SIDS also face threats to food production (World Bank 2022), highlighting the urgent need to improve water-use efficiency in agriculture, where limited water availability is already a major constraint (IPCC 2022a). Effective water management is a key concern because the use of the region's freshwater ecosystems for damming is having an impact on freshwater biodiversity and fisheries. For example, Andean-Amazon tributaries, which play a vital role in sustaining local fisheries, are losing biodiversity due to these hydrological alterations (Caldas et al. 2022; de Oliveira Lima et al. 2024).

According to the UN-Water report (United Nations 2022), indicators on water quality and management in LAC highlight that 48 per cent of monitored water bodies in the region have good ambient water quality (SDG indicator 6.3.2, 2021). Moreover, the degree of implementation of integrated water resources management reaches 37 per cent in LAC (SDG indicator 6.5.1, 2020). Regarding ecosystems, 24 per cent of the water basins in the region are experiencing rapid changes in the area covered by surface waters (SDG 6 indicator 6.6.1, 2020) (United Nations 2022).

Coastal regions in many LAC countries are experiencing land retreat due to a combination of sea level rise, human-induced tidal surges, and subsidence from human activities. These encroachments lead to increased salinity in coastal areas, affecting both ecosystems and freshwater resources, particularly in the Caribbean SIDS (IPCC 2022a; CARICOM 2020). Mangroves are particularly vulnerable due to their limited capacity to migrate inland as sea levels rise (IPBES 2019).

Freshwater pollution, caused by pesticides, emerging contaminants, microplastics and eutrophication, impairs aquatic ecosystems and soil quality. Combined with increasing competition for water resources, this

Figure 8.21: Share of electricity production from hydropower in Latin America and the Caribbean



Source: Energy Institute (2023)

pollution has generated tensions and conflicts among stakeholders, compounding existing inequalities in water access (CARICOM 2020). Vulnerable populations, including rural communities, women and Indigenous groups, are disproportionately affected (Oswald-Spring 2022). In high-altitude Andean grassland areas, these damages are particularly severe, disrupting the ritual and creation-acknowledgement practices of peasant and Indigenous communities, who regard water as a vital part of their worldview. The disruptions heighten social risks and strain rural–urban relations and territorial disputes (Parra 2023).

The increasing exploration for oil, gas and lithium, which often involves specialized techniques, is further compromising water quality and contributing to environmental and social pressures, particularly in subregions where biodiversity and traditional economic activities are already at risk (ECLAC 2023b). The elevated use of pharmaceutical products in aquaculture is also contributing to increased food contamination levels in the region. It is worth noting that water pollution is linked to atmospheric pollution and exacerbates health risks for human populations (Münzel et al. 2023).

Increasing urbanization and population growth are driving demand for water services, requiring greater investments in climate-resilient sanitation infrastructure (UN-Habitat 2023). Nevertheless, around 161 million and 431 million people in LAC cannot access safe drinking water and safe sanitation, respectively, leading to a higher incidence of waterborne diseases and malnutrition, and vector-borne diseases such as dengue and Zika. These are becoming more prevalent due to climate change (Lentini 2022). In 2019, more than 2.7 million cases of dengue were reported in LAC, of which 22,127 were severe, with 1,206 deaths reported (IPCC 2022a; Santos et al. 2023; WHO 2023).

Key indicators on water and health in LAC include access to drinking water, sanitation, and wastewater treatment. In this sense, 75 per cent of the regional population has access to safely managed drinking

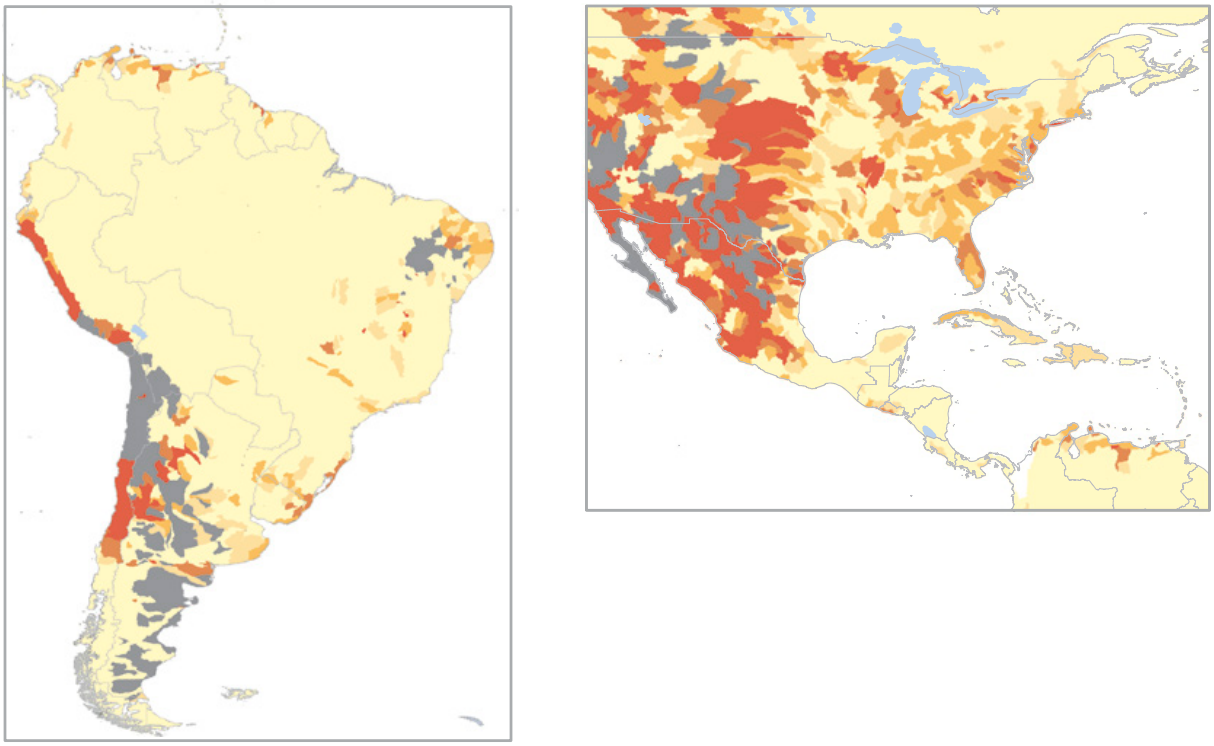
water services (SDG indicator 6.1.1), while 49 per cent use safely managed sanitation services (SDG indicator 6.2.1a). Additionally, 46 per cent of domestic wastewater in the region is safely treated (SDG indicator 6.3.1) (United Nations 2022).

Water is often produced and extracted from lands traditionally inhabited by Indigenous Peoples and local communities (Mena and Hofstede 2006; Mosquera et al. 2023). Indigenous communities are often not consulted on development models affecting natural resources on their lands, disrupting both their traditional socioenvironmental organization and the ecosystem processes those traditions reflect. It is essential to recognize the need to safeguard their territories and to ensure prior consultation under international agreements, as it is both just and crucial to achieving sustainable water governance (CNA 2020; UNDESA 2022).

LAC has many areas with high water stress (**Figure 8.22**) and an average loss rate of 40 per cent before it reaches the end user. Estimates suggest that by 2040, Peru, Chile, Mexico, the Dominican Republic and Argentina will be most at risk from water stress (World Bank 2022). Over-extraction of water from aquifers, obsolete distribution infrastructure and leaks in supply networks exacerbate the problems throughout the region.

Transboundary water cooperation, which includes shared rivers, lakes and aquifers, is critical for ensuring sustainable management of water resources and achieving SDG 6: "Ensure availability and sustainable management of water and sanitation for all". Of the 33 countries that make up the LAC region, 22 share transboundary rivers, lakes and aquifers. Most countries have low coverage of operational arrangements in relation to transboundary water cooperation. It also influences the levels of coverage for transboundary aquifers. Only four countries – Argentina, Brazil, Ecuador and Paraguay – have 90 per cent or more of their transboundary river and lake basin area covered. In Central America, transboundary basins occupy more than 42 per cent of its territory, totalling 221,000 km^2, with approximately 21 million inhabitants (UNESCO 2021).

Figure 8.22: Baseline water stress in LAC



Note: the percentages represent the ratio of total water demand to available renewable and groundwater supplies. Baseline period: 1979-2019

Source: World Resources Institute (2023)

8.5.5 Priority issue: degradation of coastal and marine resources

Coastal and marine resources are degrading at unprecedented rates: our common future is very uncertain without them.

The LAC region covers 16 million km^2 of marine territory and includes 47 of the 258 global marine ecoregions (Tambutti et al. 2020). Twenty-three out of the 33 countries in LAC have more marine than terrestrial territory, and 27 per cent of the region's population lives in coastal areas (Tambutti et al. 2020).

The consequences of hurricanes, droughts, torrential rains and other extreme events are altering ecosystem dynamics in coastal and marine ecosystems across LAC (WMO 2023). Critical areas for human well-being, affected by these events, include energy, food, health and finance (WMO 2023).

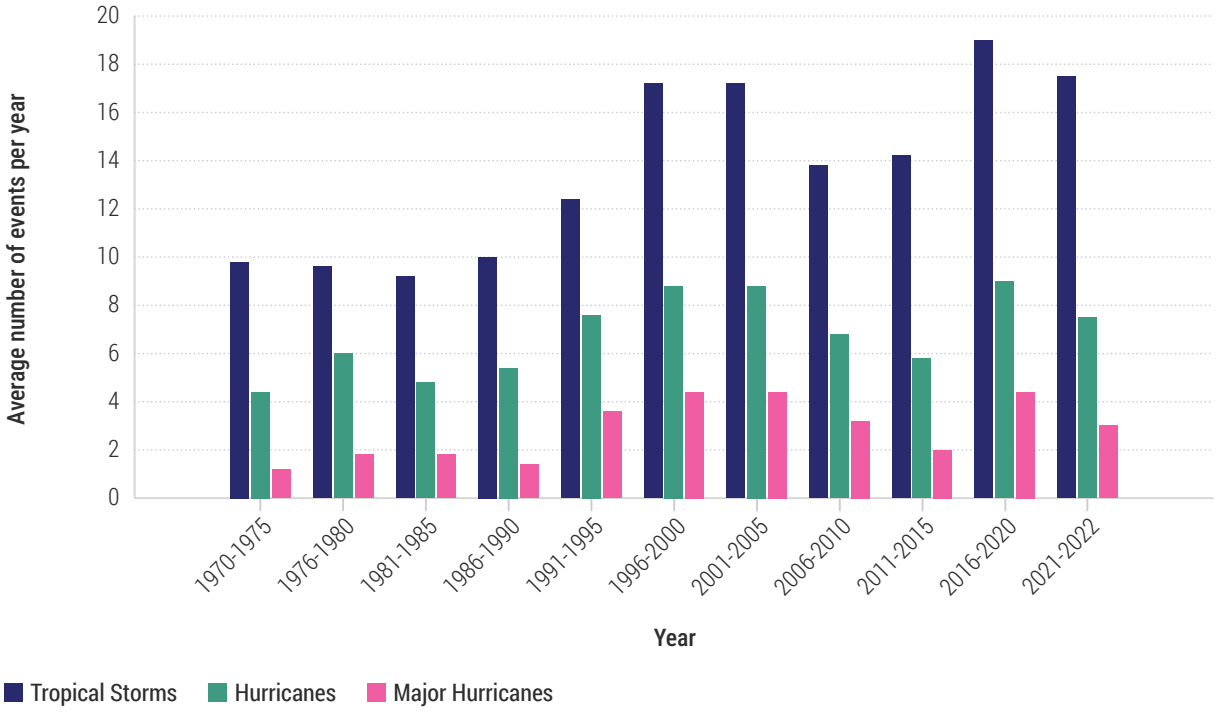
Interacting crises intensify pressures and accelerate the decline of coastal and marine ecosystems.

Climate change drives the degradation of coastal and marine ecosystems (Castellanos et al. 2022). Impacts include the reduction of coral cover in Central America and northern South America, as well as an increasing number of coral-bleaching events. Other marine ecosystems affected in the region include estuaries, salt marshes and mangroves (Castellanos et al. 2022). LAC has experienced an increase in the frequency and intensity of extreme events (**Figure 8.23**), leading to increased coastal inundation and a higher risk of waterborne and other diseases. Warm ENSO events also contribute by causing extreme rainfall, flooding and landslides in the Ecuadorian (Thielen et al. 2023) and Peruvian coastal plains (Son et al. 2020).

Ecosystem changes and degradation are increasing as extreme events become more frequent (Levin et al. 2020). Consequently, the ability of these ecosystems to cope with extreme events has decreased (França et al. 2020; Vincent et al. 2021).

Global estimates indicate that nearly 50 per cent of the region's beaches could be fully underwater by the end of the century (Vousdoukas et al. 2020). In Central and South America, sea level rise is the prevalent process leading to beach loss, while in the Caribbean, geological, anthropogenic and other physical factors are dominant (Vousdoukas et al. 2020).

Figure 8.23: Average number of yearly tropical storms, hurricanes, and major hurricanes in the Atlantic



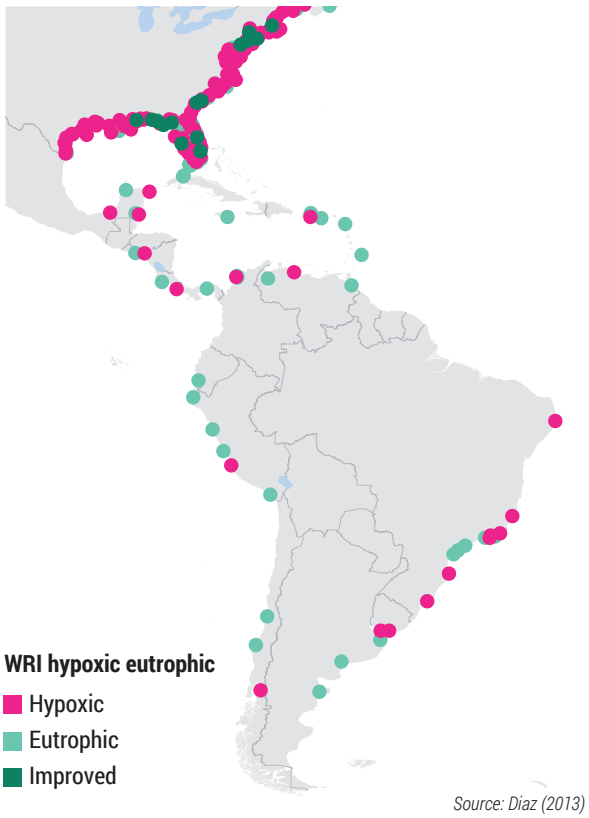
Source: Tropical Cyclone Climatology, NOAA (2022)

Increasing CO_2 concentrations contribute to the acidification of the ocean, which causes coral reef degradation (Tambutti et al. 2020). Some of the more acidic waters are found on the Pacific coast, from Mexico to Ecuador (Ocean Health Index [OHI] 2023). Higher water temperatures result in more frequent coral-bleaching events. This threat is higher in the Sea of Cortés but is also present along the Pacific Coast of Central America and in the Caribbean (Tambutti et al. 2020).

The region has a uniquely productive marine area, representing a significant portion of global marine biodiversity. It includes the second-largest barrier reef in the world and the Caribbean, which is one of the world's primary centres of endemic biodiversity (Tambutti et al. 2020). Marine pollution originates primarily from land-based sources. Hypoxia affects the Large Marine Ecosystems across LAC jurisdictional boundaries and cannot be effectively addressed without multinational collaboration (**Figure 8.24**) (Diaz 2013; Tambutti et al. 2020).

Pharmaceutical and personal-care-product residues in aquatic ecosystems are an emerging concern.

Figure 8.24: Eutrophication and hypoxic zones in Latin America and the Caribbean and parts of the United States of America



Source: Diaz (2013)

There is no comprehensive assessment for the region (Pemberthy et al. 2020), but examples from Colombia (Pemberthy et al. 2020) and Brazil (Mello et al. 2022) indicate that pharmaceuticals such as ibuprofen can be found in low concentrations in coastal waters. While these chemicals were not detected in the marine organisms sampled in Colombia, they were found to bioaccumulate in certain seafood species in Brazil.

Micro- and macroplastics are the primary sources of marine pollution in LAC, with their amounts increasing (Tambutti et al. 2020). In the Atlantic area, the abundance of floating plastic is 100 times higher than in any other LAC Large Marine Ecosystem (Tambutti et al. 2020). In the Caribbean, pollution is further exacerbated by the cruise ship industry. A single medium-sized ship can produce 140,808 m^3 of waste annually, with the majority comprising greywater and treated sewage that can be legally dumped at sea (Kotrikla et al. 2021). In 2023, around 150 cruise ships sailed in the Caribbean, making it the top destination for cruise travellers (CLIA 2024).

Land degradation results from coastal development, offshore pollution, erosion and salinization of coastal soils, as well as landslides and the retreat and erosion of estuary deltas (Zhou et al. 2022). Chile, Mexico and Argentina, among others, are highly exposed to coastal erosion that imperils their beaches. Climate-related storms contribute to beach erosion and flooding that exacerbate inland degradation (Vallarino et al. 2023).

Degradation of coastal and marine resources affects natural and human systems.

The Ocean Health Index (OHI) measures the capacity of oceans to deliver benefits to people, both in the present and in the future (Halpern et al. 2012). It incorporates the capacity of oceans to provide benefits such as food, a sense of place, livelihoods and economies, clean water, coastal protection, carbon storage, tourism and recreation. Its value ranges from 0 to 100, and lower values mean less sustainable use. The OHI global value for 2023 was 73. In LAC, OHI values for the same year range from 61 to 82, with the lowest values reported in the Caribbean (**Figure 8.25**).

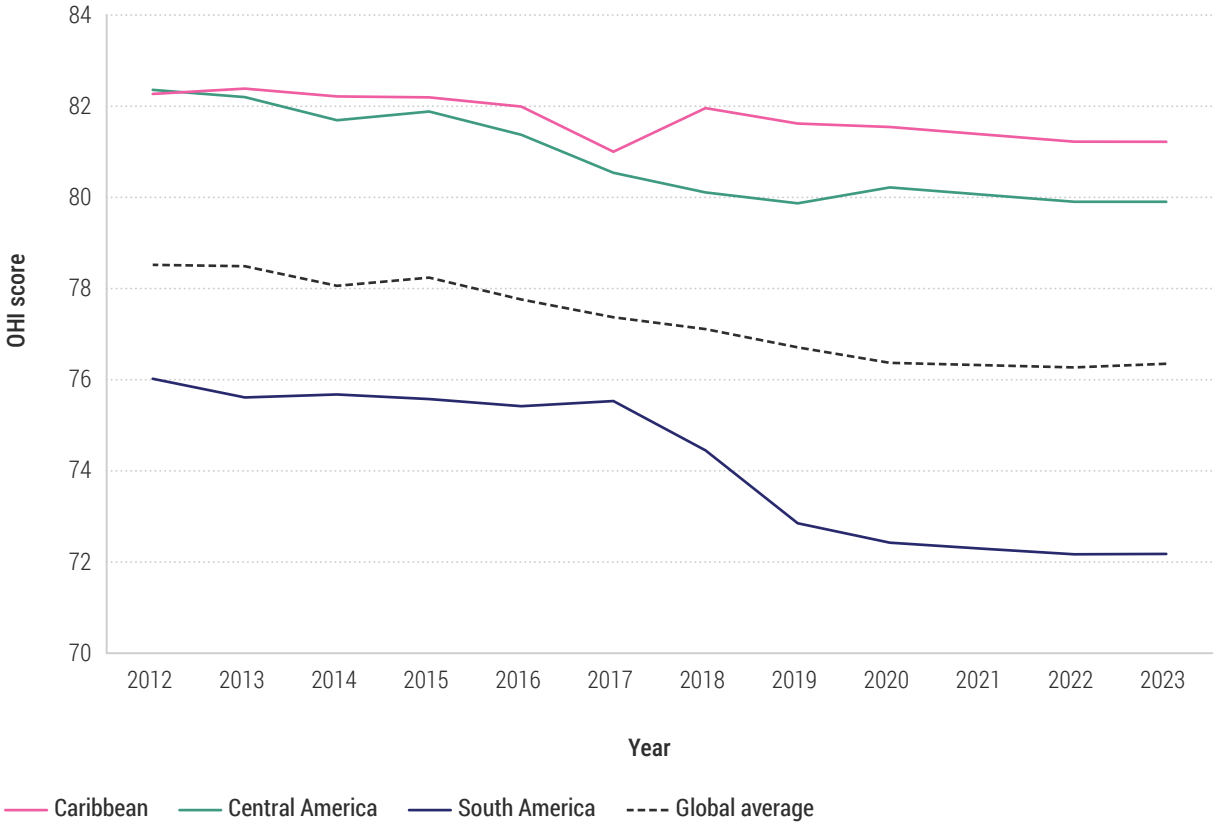
In 2023, the OHI for the LAC region was around 72.5 per cent, slightly lower than the global average of 73 per cent. Scores are higher in South (75.35) and Central America (73.8) and lower in the Caribbean (71.29) (OHI 2023). The region's 2023 scores generally fall below

global averages in food provision, natural products, and tourism and recreation. However, some OHI components are improving in specific subregions, indicating positive developments in certain areas (2012–2023) (OHI 2023); for example, OHI food provisioning increases in South America and decreases slightly in Central America and the Caribbean, while the OHI natural products component and the tourism and recreation component increase in all regions.

Coastal regions heavily reliant on groundwater for irrigation and human consumption are experiencing increased saline intrusion, particularly in the drier areas of South America and the Caribbean (Dupar 2019; Taleisnik and Lavado 2020). In areas such as the Yaqui Valley in Mexico, groundwater withdrawals exceeding recharge rates lead to aquifer contamination by saline water, a problem also observed in arid and semi-arid coastal regions of Chile, Colombia and Argentina (Vigglizo and Ricard 2020). The situation is expected to worsen in many areas as climate change continues to reduce rainfall (Dupar 2019). Coastal soils are increasingly susceptible to salinity changes due to climate-change-induced shifting rainfall and discharge patterns, for example, saline intrusion in the northeastern coast of Brazil, and significant changes to coastal ecosystems (Soares et al. 2021). Additional contributors to coastal degradation in LAC include port and marina development, driven by the intensification of tourism and trade at global, regional and local levels (Anbleyth-Evans 2023; OECD 2023). Sand extraction has been identified as a factor that reduces beach integrity and defence against extreme events (Vallarino et al. 2023). Land-use changes also affect freshwater availability in coastal regions. For instance, the impounding and management of the São Francisco River for hydroelectric power in Brazil has increased the salinity of its estuarine environment, affecting both land and coastal ecosystems (Paiva et al. 2024).

Coastal areas face significant erosion due to various processes (Villate Daza 2020; Mesquita et al. 2022; Zhou et al. 2022; Anbleyth-Evans 2023; Botero 2023;

Figure 8.25: Ocean Health Index trends (biodiversity component) for Latin America and the Caribbean from 2012 to 2023



Note: For clear comparison across the sub-regions, the values of the vertical axis start at 70

Source: OHI (2023)

Vallarino et al. 2023), including beach tourism, port and tourism infrastructure development, and nearshore and offshore oil and gas exploration. For example, in Belize, the use of fill material from sea floor dredging to support tourism infrastructure development affects both coastal and marine environments (Sweetman et al. 2019).

Coastal and marine biodiversity is threatened by extreme environmental events, through habitat loss and the increased vulnerability of valuable ecosystems (CARICOM 2020). The OHI biodiversity component (Halpern et al. 2012) indicates the status of habitats and species. For LAC, there is a declining trend with a more significant reduction in South America (**Figure 8.25**). However, there are countries – Peru, Chile and the Bahamas – with a rising trend in this indicator, suggesting the outcome from improved management.

Mangroves provide many ecosystem services, including protection against climate change and extreme events (Del Valle et al. 2019; Rastogi et al. 2021; Ferreira et al. 2022). In LAC, mangrove extents have increased due to restoration projects, but also because of better data collection (FAO 2020; FAO 2023). Between 2010 and 2020, there was a net gain in mangrove areas in South America and the Caribbean, with a slight decrease in Central America (FAO 2020; FAO 2023b) (**Figure 8.26**).

The Caribbean has been significantly damaged by the invasion of Sargassum, smothering beaches, coastlines and the marine environment (Kanhai et al. 2022).

Despite some positive trends in specific subregions, ecosystem services such as coastal protection and livelihoods are degraded, alongside declines in macrofauna, seagrasses and brown algae, and increases in cyanobacteria (Climate Studies Group Mona 2020; França et al. 2020; Malone and Newton 2020; Carroll et al. 2023). Algal blooms and hypoxia are becoming more frequent, as observed in Venezuela's estuary-like Lake Maracaibo (Maberly et al. 2020).

Ocean acidification is evident in coral reefs, with the Mesoamerican Barrier Reef experiencing a net erosion of 37 per cent. Other marine changes include ecosystem reshaping, disruption of natural food webs due to the introduction of exotic invasive species, and coral diseases (Tambutti et al. 2020).

The discovery of offshore oil deposits in the Guyana basin contributes to the expansion of fossil fuel production (Wong et al. 2020). The operation of

Figure 8.26: Subregional trends in mangrove forests in Latin America and the Caribbean from 1990 to 2020

Source: FAO (2020)

offshore platforms generates pollution and causes disturbances that can have long-term implications for marine and coastal ecosystems (Zhou et al. 2022).

Oceans and coastal areas are key ecosystems for livelihoods and food security in the LAC region. The importance of fisheries in nutrition is particularly relevant for coastal communities in the Caribbean, where 16.5 per cent of the total animal protein consumption comes from coastal fishing. This proportion is lower in Central America at 9.44 per cent and South America at 5.96 per cent (Tambutti et al. 2020). For the period 2012–2024, Southern Cone countries, including Colombia, Panama and Venezuela, have exhibited a positive annual trend in wild fisheries. In contrast, Central America and the Caribbean, except for the Bahamas and some of the Lesser Antilles, have shown negative values, indicating overharvesting (OHI 2025).

Climate change negatively impacts fisheries in key fishing areas, for example, the Gulf of California and Humboldt Current upwelling zones (Tambutti et al. 2020). In the Caribbean, the adverse effects of climate change are expected to intensify by 2050 (Carroll et al. 2023), exacerbating losses in livelihoods that depend on fisheries and marine resources. Increasing coastal flooding and erosion could make the Caribbean one of the fastest-displaced communities globally, with severe implications for economic activities (Global Americas 2019).

In LAC, SIDS rely heavily on their marine and coastal assets for economic growth and livelihoods, through fisheries and tourism (Tambutti et al. 2020). The Caribbean Sea, covering less than 1 per cent of the world's ocean area, contributes an estimated 27 per cent to the global ocean economy. Tourism accounts for over 15 per cent of GDP and 13 per cent of employment in the region (UNDP Latin America and the Caribbean 2023).

The global environmental crises affect fisheries through ocean warming, acidification, coral bleaching (Mendehall et al. 2020; Lam et al. 2020), coastal habitat transformation, and pollution (Cortes et al. 2020), among other factors. Small-scale fisheries represent over 90 per cent of the catches in the Caribbean, over 40 per cent in Central America, and more than 20 per cent in South America. In terms of value, small-scale fisheries account for about 80 per cent of commercial value in the Caribbean, while more than 60 per cent and about 50 per cent in Central America and South America, respectively (Tambutti et al. 2020). Despite its socioeconomic relevance, small-scale fisheries do not have guaranteed access to adequate resources and face significant inequality (Tambutti et al. 2020). The LAC region loses approximately US$5.8 billion annually compared to its optimal economic yield, accounting for around 7 per cent of global losses (Tambutti et al. 2020). The Southeast Pacific is the only LAC marine region where over 50 per cent of fishery stocks are harvested unsustainably (FAO 2022). Although the LAC region has declared 20 per cent of its marine surface as marine protected areas, exceeding the SDG 14.5 target, the distribution is uneven and over 20 countries have yet to achieve this goal. The effectiveness of these protected areas depends on adequate financial resources to support management plans (Tambutti et al. 2020).

8.6 Western Europe and Others Group and subregions

8.6.1 Introduction

The Western Europe and Others Group (WEOG) includes 28 middle- and high-income member states and their territories. This diverse region encompasses a broad range of ecosystems, including temperate forests, tundra, high mountains, grasslands, drylands and deserts, as well as coastal and freshwater environments. Numerous cultural communities maintain deep connections to their local landscapes and seascapes, and these ties are threatened by the global environmental crises of climate change, biodiversity loss and land degradation, and pollution and waste. Words from Canada resonate across WEOG: "First Nations, Métis, and Inuit recognize the existential threat that climate change poses to their cultural survival" (UNEP-WCMC and IUCN 2021; Lulham et al. 2023; Li et al. 2024), stating that "…climate change constitutes a state of emergency for our lands, waters, animals, and people" (Assembly of First Nations 2019).

Despite economic and technological advantages, the environmental outlook for WEOG remains deeply concerning due to the long-term impacts of industrialization and high consumption. Three priority issues, which can have differing local manifestations, dominate the region's

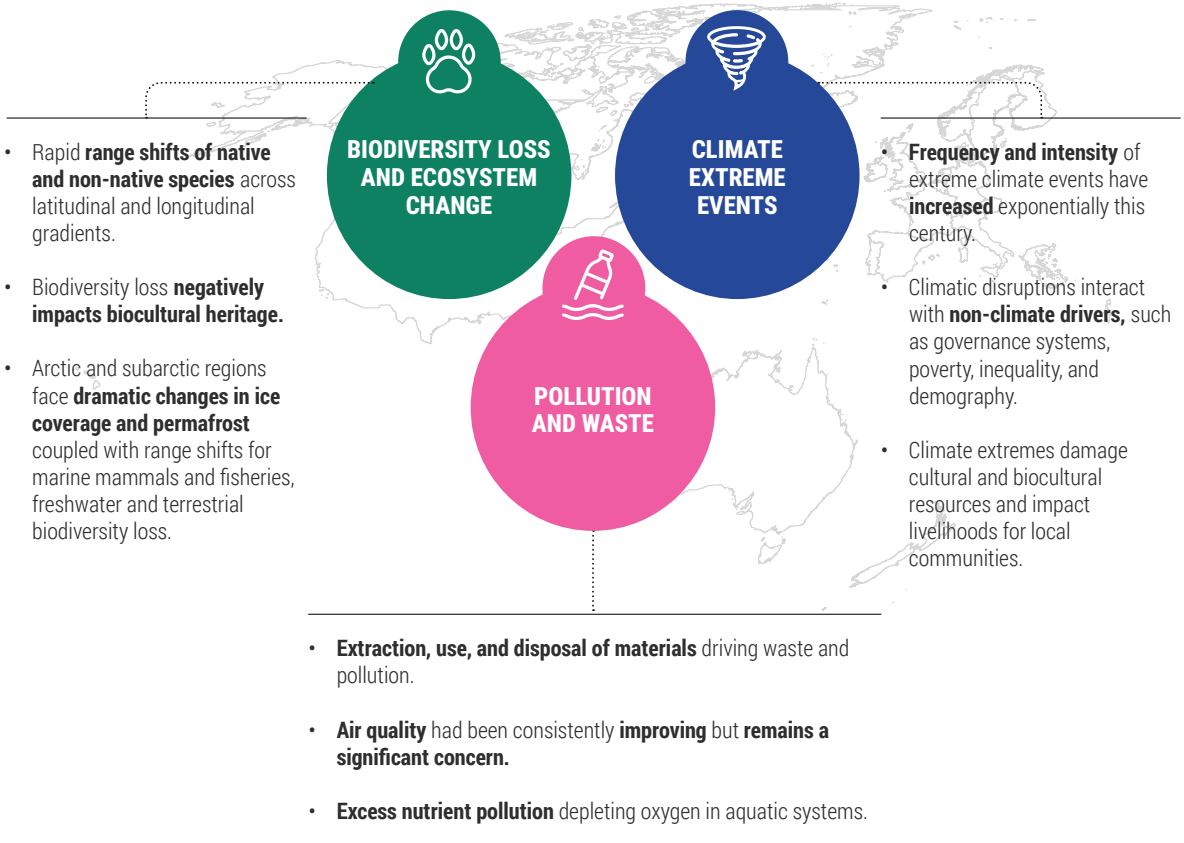
environmental trajectory: biodiversity loss and ecosystem change, extreme climatic events, and pollution and waste. These are closely interlinked, reflecting broader environmental crises (**Figure 8.27**).

Biodiversity loss and ecosystem change

Biodiversity loss and ecosystem change pose risks to food security, and human health and well-being. These changes are accelerating throughout the region, driven by climate change, land-use transformation, and shifting species distributions across latitudinal and longitudinal gradients. For example, different organisms, particularly invertebrate pollinators, are experiencing sharp declines and significant range shifts (Otto et al. 2025; Richards et al. 2025). Ecosystems are being transformed through the interactions of multiple factors such as invasive alien species, changes in fire and flood regimes, and melting permafrost. For example, invasive alien grasses have fuelled extreme fires in Hawaii, and melting permafrost promotes the expansion of new species in the Arctic. Diseases carried by ticks and other vectors are extending beyond their historical regions. These profound ecological changes are deeply disruptive to biocultural heritage and human livelihoods.

WEOG countries have taken steps to address these threats to biodiversity, including expanding the number of protected areas across land, coastal and marine environments since 2010. Indigenous communities across the WEOG continue to demonstrate effective environmental stewardship grounded in local communities and cultural knowledge. For example, in Australia, Langaliki Robin, Indigenous leader of Walalkara – the country's oldest Indigenous Protected Area – highlights the importance of Tjukurpa (Dreaming Law) as the foundation of conservation efforts (Robin et al. 2022). In Canada, First Nations, Métis, and Inuit peoples have developed effective, culturally informed community-based monitoring and protection programmes, including successful caribou monitoring and breeding initiatives ((Lamb et al. 2022; Priadka 2025) and monitoring for contaminants in traditional foods (Goldzadeh et al. 2021; Baker 2021).

Figure 8.27: The interplay of the global environmental crises and regional priority issues: effects on Western Europe and Others Group's biodiversity and ecosystems, climate extreme events, and pollution and waste



Credit: bortescristian/Envato

Extreme events

The frequency and severity of extreme climatic events – especially heatwaves, floods and wildfires – have increased dramatically in recent decades, causing loss of life, disruption of communities and destruction of infrastructure. In Europe, heat-related mortality has surged, with 61,000 deaths recorded in 2022 alone (van Daalen et al. 2022; Ballester et al. 2023; European Commission 2023). Across the United States of America, extended heat events have shattered records, particularly summer night-time temperatures (NOAA 2024). The intensification of wildfires, floods and extreme storms has been well documented and affects both urban and rural residents (Qian et al. 2022; Donatti 2024). Extreme events amplify existing inequities, disproportionately impacting already vulnerable populations. Communities with fewer resources face greater mortality risks and slower recovery processes following disasters (U.S. Government Accountability Office 2021).

Pollution and waste

Despite ongoing interventions, WEOG countries continue to experience excessive waste and persistent pollution driven by high resource consumption, rapid turnover of consumer goods, and industrialized agriculture. Synthetic substances, such as per- and polyfluoroalkyl substances and microplastics, are pervasive in WEOG, and many have unknown health effects (EEA 2022b; UNEP and Secretariat of the Basel, Rotterdam and Stockholm Conventions 2023). Despite ongoing efforts in WEOG to promote sustainable agriculture, nutrient pollution and pesticides continue to threaten both ecological and human health (Baron et al. 2014; Mosley et al. 2023; Zhou et al. 2023). Trends in air quality across WEOG are encouraging, yet 90 per cent of Europeans living in cities are still breathing unhealthy levels of fine particles (EEA 2023a). Overconsumption and waste, largely associated with lifestyles of high-income countries, are underlying drivers of the global environmental crises of climate change, biodiversity loss and land degradation, and pollution and waste. The convergence of biodiversity loss, intensifying extreme events and persistent pollution presents a deeply challenging environmental outlook for WEOG.

8.6.2 Interlinkages between the global environmental crises and regional priorities

The global environmental crises have disrupted ecosystem services and functions, particularly in the northern and southern temperate latitudes of the biomes within WEOG. Extreme heat events, catastrophic wildfires, land degradation, and invasive alien species are all interlinked and result in measurable impacts on both human and ecosystem health (Hantson et al. 2022; Chowdhury et al. 2024). Legacy industrial activities pose a threat to human and ecosystem health through the persistence of chemicals and metals (Adewumi and Ogundele 2024) in the environment, which contributes to long-term pollution and health

Credit: bortescristian/Envato

issues. Without intervention, many organisms face an extinction risk (Goulson 2019; Ceballos et al. 2020).

WEOG countries also have a long legacy of mineral and fossil fuel extraction, consuming over 30 per cent of global energy. Material consumption footprints are well above the global average, associated with elevated standards of living, excessive consumption and waste production (Oswald et al. 2020). Food production using intensive, industrial-scale agriculture impedes ecosystem services, such as pollination, which underpins 30 per cent of the global food supply (IPBES 2019; Vujić et al. 2022). Excess fertilizers impair freshwater systems, contaminate groundwater and contribute to the loss of biodiversity and soil organisms (Tibbett, Fraser and Duddigan 2020; Bolster et al. 2023). In addition, excessive and continued use of pesticides such as neonicotinoids is known to have adverse effects on bees and other pollinators (Camp and Lehmann 2021; Zhang et al. 2023; Mamy et al. 2024). They are banned for outdoor use in the European Union (European Commission 2024), but they continue to be used elsewhere. Similarly, organophosphates and carbamate pesticides can have severe ecological consequences, such as in vulture populations (Ives et al. 2022; Santangeli et al. 2022) but continue to be in widespread use. The status and trends of many invertebrate and non-vascular plants, such as mosses and lichens, which comprise a large proportion of the world's biodiversity (Secretariat of the Convention on Biological Diversity 2020), and the impacts of legacy chemicals on these groups, are largely unknown. Such data uncertainty compounds the urgency of addressing biodiversity loss (IUCN 2024).

In summary, the global environmental crises affecting WEOG countries are complex; however, interventions in three priority areas have shown some progress. For example, emerging technologies, such as non-expert digital data sets, aid in identifying areas of biodiversity loss and species changes and can help determine the response of different taxa to changing environmental conditions. Policy interventions can reduce the presence of chemical pollutants and fertilizers (Zacharias and Kaplan 2023; de Vries et al. 2024). New strategies for adaptation and early warning systems are identifying potential climate extremes, such as severe weather and storm forecasting, supporting adaptation for infrastructure (EEA 2024a). Additionally, increasing the extent of protected areas – to 30 per cent by 2030 (UN-CBD 2022; Kunming-Montreal Global Biodiversity Framework 2022) – and of heritage sites creates priority strategies to address

habitat and land degradation, as well as biodiversity loss (Day et al. 2020; Hilty et al. 2020).

8.6.3 Priority issue: biodiversity loss and ecosystem change

Biodiversity continues to decline while ecosystems are being transformed by habitat loss, invasive alien species and range shifts of native and naturalized species.

WEOG countries are ecologically and environmentally diverse, with well-documented areas of high endemism (Costello et al. 2017; Harrison and Noss 2017; Sabatini et al. 2022; UNEP-WCMC 2022). However, there are over 37,000 known and established invasive alien species worldwide, with a disproportionate number found in the boreal and temperate forests and agricultural areas that dominate WEOG (IPBES 2023). New invasions are reported regularly, despite substantial efforts by many countries to control the movement of invasive species across their borders. Ecosystems are continually being transformed by human activity, land degradation and pollutants that collectively contribute to biodiversity loss, impeding terrestrial and coastal ecosystems and local livelihoods (IPBES 2019; Secretariat of the Convention on Biological Diversity 2020; WWF 2024). Additionally, hypoxia caused by nutrient pollution is a widespread problem throughout WEOG, with notable examples including anoxic "black water" events in Australia (Mosley et al. 2023; Waddington et al. 2023) and expanding hypoxia in the Gulf of Mexico (Rabalais and Turner 2019). Changes in sea currents and range shifts for associated species are common throughout WEOG, particularly in its Arctic and sub-Arctic regions (Chan et al. 2019; Talloni-Álvarez et al. 2019; Krause-Jensen et al. 2020; Ingvaldsen et al. 2021).

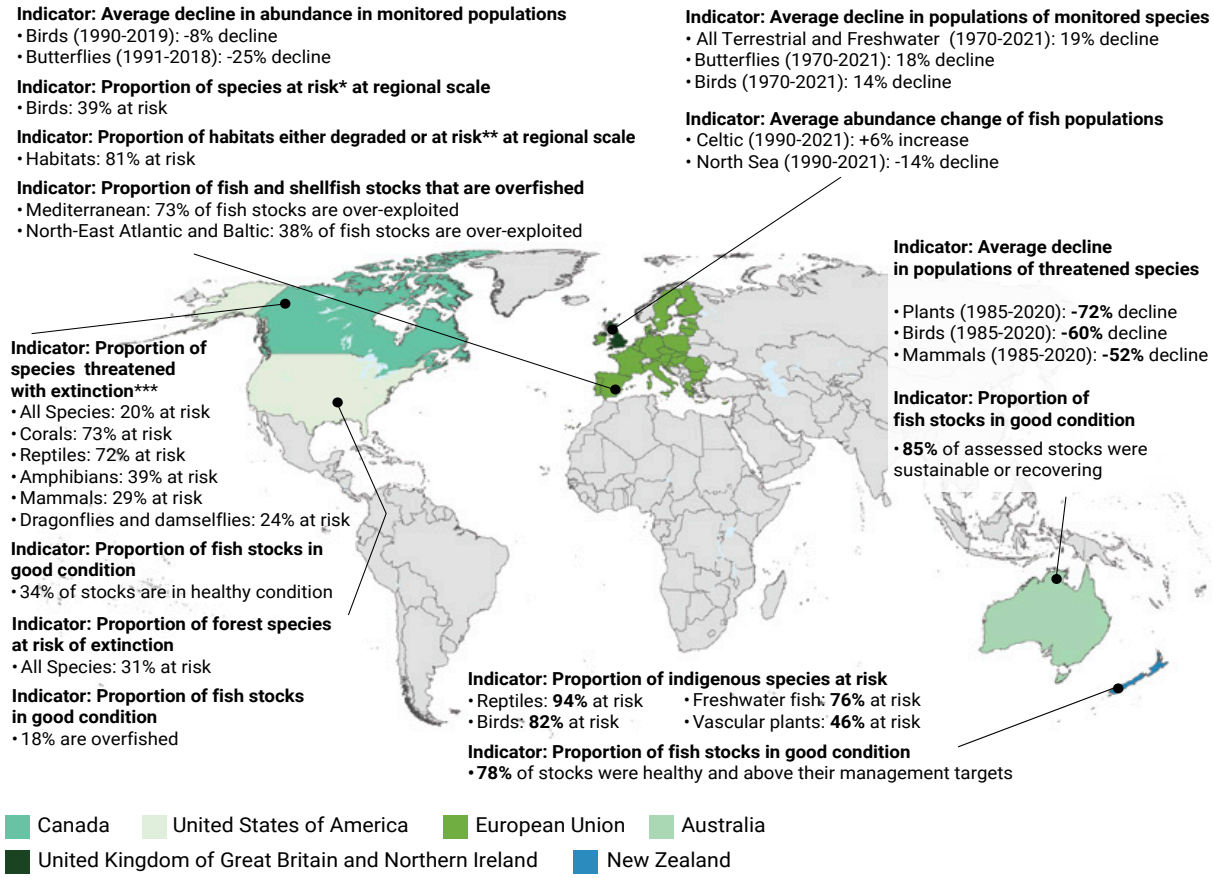
Changes to ecosystem composition and diversity are occurring at unprecedented rates, leading to ecosystem transformations. Rapid range shifts of native and non-native species are occurring across latitudinal gradients and various habitat types (McElwee et al. 2023). Invasive alien species can transform ecosystems by altering the fuel basis for wildland fires or displacing native species, as exemplified by changes in pollinator species composition driven by the introduction of domesticated honeybees (Page and Williams 2023). The economic costs of invasive alien species can be significant, estimated at US$20 billion annually in the United States of America alone (Fantle-Lepczyk et al. 2022). The economic and ecological damage from invasive alien species is well-recognized, and several ambitious national and international strategies have been adopted to reduce and prevent the spread of invasive species (New Zealand Department of Conservation 2020; European Union 2014; U.S. Department of the Interior 2021; European Union 2022; IPBES 2023; Environment and Climate Change Canada 2024).

Species compositions are shifting throughout temperate biomes as many species migrate poleward due to rising temperatures, such as tropical wetland mangroves in a northward shift along the coastal regions of the southern United States of America (Osland et al. 2021). Similar trends occur across elevation gradients, where organisms in the European Alps have shifted upward in elevation by an average of 18–25 metres per decade since 1970 (Vitasse et al. 2021). Despite the long history of research within WEOG, information on species loss and range shifts is limited for many smaller taxa, such as invertebrates and non-vascular plants, due to a lack of data on these organisms to determine population trends (**Figure 8.28**) (IPBES 2019). The cascading repercussions of climate change, invasive alien species, depletion of natural resources, and land-based pollution contribute to the loss of species that are important for ecosystem functions and of biocultural importance (Mattalia et al. 2024).

Arctic and sub-Arctic habitats – including boreal regions, permafrost and tundra – are degrading, and coastal zones are experiencing shifts in currents and ocean warming events. The loss of permafrost and Arctic habitats has severe implications for local communities (IPCC 2022; Pörtner et al. 2023). There are 1,162 permafrost settlements with 5 million inhabitants in the Arctic circumpolar region, of which 1 million live along a coast, with 45 per cent of these settlements at risk of thawing permafrost (Ramage et al. 2021). More than 60 per cent of Alaska Native communities are estimated to be at risk of losing culturally important organisms (McElwee et al. 2023; Mucioki 2024). Permafrost loss in Alaska, for example, has increased by 60 per cent since 1950, associated with climate change and wildfires (Chen et al. 2021).

Warmer temperatures are driving the expansion of boreal forests and subarctic shrubs northward by up to 100 metres per year in Western Europe (Rees et al. 2020; Nill et al. 2022). These transformations in Arctic tundra may simultaneously increase above-

Figure 8.28: Selected indicators of biodiversity status and trends across WEOG, from recent government assessments or government-supported reports



* Regionally Extinct, Critically Endangered, Vulnerable, or Neat Threatened on the IUCN red list over the EU28 region.
** Defined as habitats rated "bad" or "poor" per EEA assessment
*** Species rated as "critically imperilled", "imperilled" or "vulnerable" by Canadian Endangered Species Conservation Council

Sources: EEA (2020); Cresswell, Danke, and Johnston (2021); EEA (2021); Ministry for the Environment and Stats NZ (2022); Canadian Endangered Species Conservation Council (2022); Burns et al. (2023b); McGinley et al.(2023); EEA (2024d); Environment and Climate Change Canada (2024);Ministry for Primary Industries (2024); National Marine Fisheries Service (2024); Roelofs (2024)

ground carbon stocks while depleting soil carbon due to changes in soil microbial communities (Parker et al. 2021). Ocean current shifts around Greenland have cascading effects on ice-flow patterns (McPherson et al. 2024), and consequently, on the movement patterns of marine species (van Weelden, Towers and Bosker 2021; Heide-Jørgensen et al. 2023). Similarly, rapid transformations are occurring in Arctic marine ecosystems as warmer waters are carried further north, leading to an increase in warm-water species, including crustaceans such as lobsters (McElwee et al. 2023). For example, the biomass of cold-water kelp beds off Nova Scotia, Canada, has declined by 85–99 per cent since 1950 and has been replaced by non-native algae that are more tolerant of warmer waters (Venegas et al. 2023).

One-third of the protected areas in Europe and the United States of America lost more than 10 per cent of their protected habitats between 2003 and 2019 (Li et al. 2024). Integrated systems of protected areas show promise for vertebrate species. However, additional interventions are needed to slow biodiversity loss for other taxonomic groups, as there is a significant risk that protected areas will provide only limited benefits to biodiversity (IPBES 2019; IUCN – World Commission on Protected Areas 2024). Western Europe's terrestrial protected areas covered 26 per cent of the land in 2021, for example. However, within these areas, 63 per cent of species have a poor conservation status, 27 per cent have a good conservation status, and only 6 per cent have an improving conservation status (EEA 2023a). Within the United States of America, birds are declining across all habitats except wetlands (North American Bird Conservation Initiative 2022), while pollinators and other invertebrates are too data-deficient to be assessed adequately (IPBES 2019; McElwee et al. 2023; Richards et al. 2025). In Mediterranean countries, protected areas associated with biologically diverse hotspots are one strategy to prevent species losses,

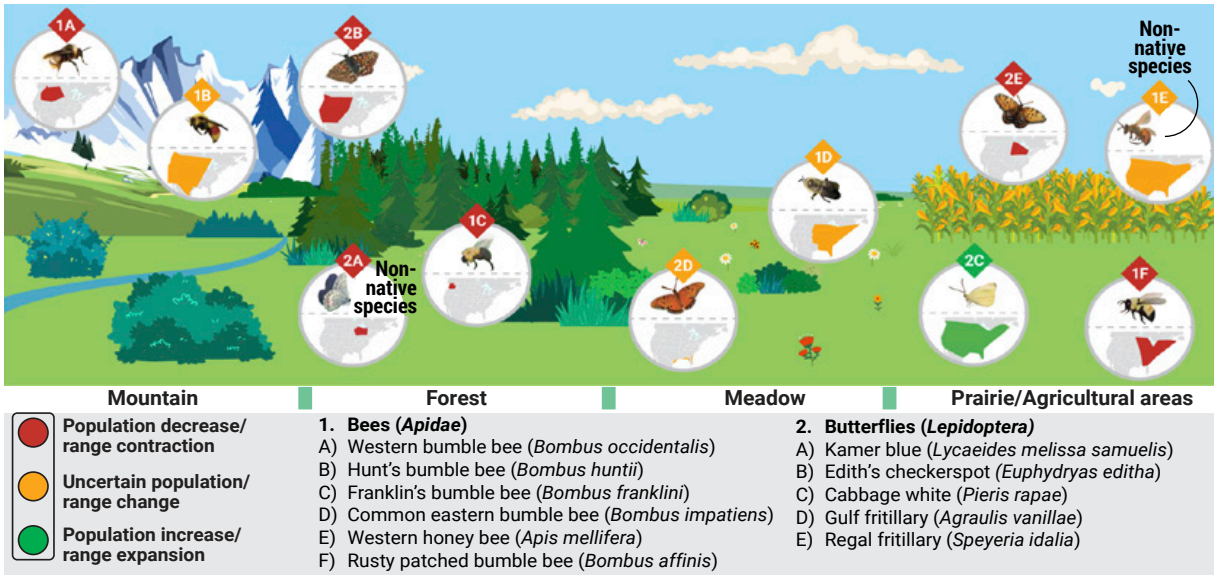
but those areas are fragmented (Assis et al. 2021; Donnelly and Rodríguez-Rodríguez 2022), and rare but exceptionally diverse landscapes, such as karst ground-water-dependent ecosystems, are increasingly under pressure from human disturbance, climate change and water extraction (Siegel et al. 2023). The protection of marine and coastal areas has also increased as part of the global commitment to protect 30 per cent of land and territorial waters by 2030 (Wolff et al. 2018; NOAA 2020; Convention on Biological Diversity 2022; Gignoux-Wolfsohn et al. 2024). Within the United States of America, 12 per cent of the land is in some form of protected status. However, some groups, such as birds, continue to decline within these protected areas, apart from wetlands (North American Bird Conservation Initiative 2022).

The rapid changes and losses of species undermine ecosystem services. Changing seasonal patterns contribute to range shifts of some species and declining populations of others. These declines occur particularly at higher elevations and latitudes in boreal systems where glacial retreat and loss of snow cover transform downslope processes across the Arctic and in cold-water marine ecosystems, such as cold-water fisheries in Canada (Boldt et al. 2021). Similarly, warming ocean currents shift marine species' movements and impair coral reef resilience in Australia (Cresswell et al. 2021; Mekonnen et al. 2021).

Range shifts and population declines are also occurring for terrestrial systems among invertebrates, particularly wild pollinators (**Figure 8.29**) and soil organisms across Western Europe and North America (Goulson 2019; Sánchez-Bayo and Wyckhuys 2019; van der Sluijs 2020; Dicks et al. 2021; Phillips et al. 2024). Such declines contribute to reduced yields in fruit and nut production, affecting 5–8 per cent of commercial crops with a US$577 billion market value (IPBES 2019; Jansson and Hofmockel 2020; Riggi et al. 2023). In New Zealand, declines of domesticated pollinators such as the western honeybee Apis mellifera impede honey exports and local economies (World Integrated Trade Solution – UNSD Comtrade 2024), in contrast with global honey production increases (Hall et al. 2021; Stahlmann-Brown, Manaaki Whenua and Robertson 2024).

Biodiversity loss affects Indigenous Peoples. Changes in the abundance and distribution of cultural keystone species, such as salmon, pose a threat to food security, particularly in the Arctic (Anderson et al. 2023; Mattalia 2024). Changes in species distribution in the Arctic, and especially the presence of invasive species in the Barents Sea, have impaired the livelihoods and cultural basis of local and Saami populations along the Norwegian coast. Climate change in Sápmi has increased the risk of hazards, injuries, food insecurity, and disease for the Saami (The Saami Council 2023), leading to fewer opportunities for cultural practices

Figure 8.29: Pollinator shifts in response to changing climate conditions



Note: Insect pollinators, even those within the same group, show a wide range of reactions to environmental pressures. Recent climate changes over the past few decades have driven complex shifts in where species are found. The bumble bee species have responded differently over the last decade, including moving within their current habitats, contracting their ranges, or facing extinction risks. Similar patterns have been observed in butterflies, with some species declining or shifting within their ranges, while others are expanding across the country.

Source: McElwee et al. (2023)

Credit: dibrova/Envato

and knowledge transmission, as well as ecological grief (Markkula et al. 2024). Additionally, warming temperatures leading to the loss of sea ice and reduced snow cover produce range shifts in cold-water species, threatening the economic security of many Indigenous Peoples (Arctic Monitoring and Assessment Programme 2018; Galappaththi et al. 2019; Zhang et al. 2019; Reed et al. 2024).

Climate change particularly disrupts the livelihoods and well-being of communities dependent on natural resources (Bolster et al. 2023; Domke et al. 2023; Jay et al. 2023; May et al. 2023; EEA 2024a). Agricultural employment throughout WEOG is affected by cascading and compounding consequences from invasive species, extreme weather events and shifting water resources that threaten local community livelihoods (Bolster et al. 2023; Jay et al. 2023). Heat, changing rainfall patterns and loss of pollinators are all interlinked and potentially disrupt local community livelihoods throughout the WEOG.

Invertebrate, such as mosquitoes and ticks, and vertebrate, such as rodents, disease vectors have been increasing. The spread and range shifts of invasive alien and native disease vectors have direct consequences for human health and well-being (Caminade et al. 2019; Baker et al. 2022). Outbreaks of disease have increased in range and intensity, associated with expanding populations of disease vectors that occur throughout WEOG, including West Nile fever, Tick-borne encephalitis, Lyme disease, bluetongue, leishmaniasis, and malaria (Brugueras et al. 2020; Rocklöv and Dubrow 2020; Hauser et al. 2021; Semenza and Paz 2021; van Daalen et al. 2022; McElwee et al. 2023). Population trends of disease vectors are often associated with warmer temperatures that increase the reproductive rate and range of vectors and pathogens alike (**Figure 8.30**) (Caminade et al. 2019; Semenza and Paz 2021; Baker et al. 2022). Disease risk is exacerbated by the interconnectivity of global transport systems, urbanization, and human movements (Rocklöv and Dubrow 2020; Baker et al. 2022). In addition, increased disease risk can be linked to ageing infrastructure and poor sanitation that promote disease vectors, such as mosquitoes thriving in stagnant stormwater drainage, and exacerbate existing health inequities (Ebi and Hess 2020; Baker et al. 2022; Berberian et al. 2022; Lansbury Hall and Crosby 2022). Biosecurity is a rising issue within Australia and the United States of America, where the spread of vectors and pests has major human and economic repercussions for agriculture and endemic biota.

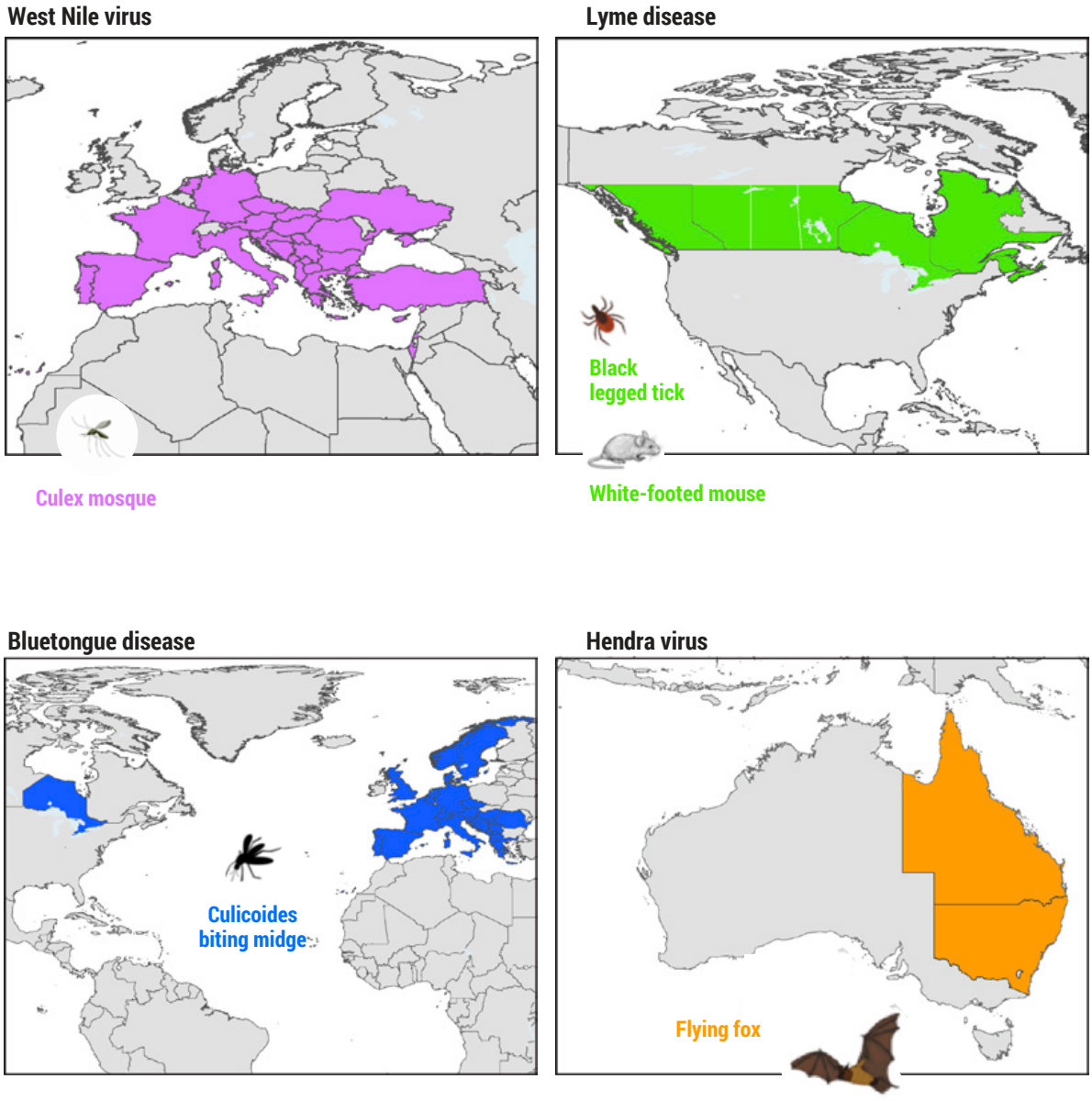
Biodiversity loss adversely affects biocultural heritage. Conservation and protection of eco-cultural resources is challenging (Rotherham 2022) because of the concomitant loss of cultural knowledge, critical information, and traditional management practices that are required for sustainable land management (Lindholm and Ekblom 2019). For example, medieval hedgerow networks in central Spain have been degraded, leading to a decline in many hedge species (Arnaiz-Schmitz et al. 2018).

8.6.4 Priority issue: climate extreme events

Climate disruptions interact with non-climate drivers, such as governance systems, poverty, inequality and demography, amplifying the impacts of extreme events, such as heatwaves, wildfires, floods and severe storms across WEOG (Chancel et al. 2023; Parks et al. 2023; Bouchama et al. 2024; United States of America, Department of Labor and Occupational Safety and Health Administration 2024; La 2024; Galvez-Hernandez et al. 2025). Heatwaves are among the deadliest climate events, with heat index records regularly broken across WEOG (Ebi et al. 2021; Romanello et al. 2023; Zachariah et al. 2023). In the United States of America, heatwaves have increased in frequency,

duration and intensity every decade since the 1960s, with the number of annual heatwaves tripling (United States Environmental Protection Agency [EPA] 2024), along with increasing average temperature and precipitation. Over 800 excess deaths were attributed to a 2021 heat dome along the Pacific coast of North America (White et al. 2023). A year later, heat-related mortality exceeded 60,000 in Europe (Ballester et al. 2023; La 2024). Notably, despite even higher temperatures in 2023, European heat-related mortality was slightly lower, likely due to better preparation (Gallo et al. 2024). Agricultural, construction, and other outdoor workers experience heightened risk of heat exposure, stress and health effects, as well as decreased productivity (European Academies' Science Advisory Council 2019; International Labour Office 2019). The adverse effects of heat are amplified in urban areas, particularly in those lacking shade trees, parks or green spaces (Kabisch et al. 2023).

Figure 8.30: Selected case studies of diseases, disease vectors and significant changes in range or prevalence in response to climate change

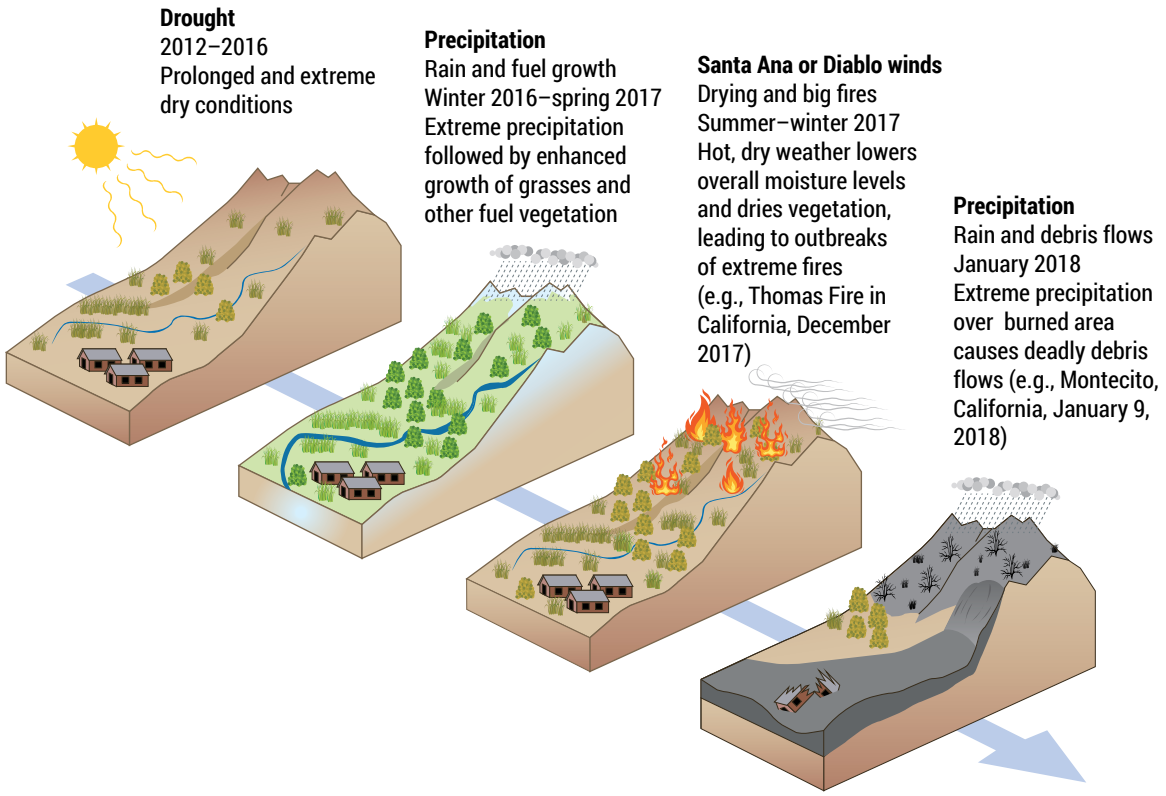


Data sources: Caminade et al. (2019); Semenza and Paz (2021); Baker et al. (2022); ECDC (2025); Government of Canada (2025); WOAH (2025)

Extreme heat contributes to biodiversity loss for both terrestrial and marine organisms. Critical marine environments, such as coral reefs and kelp forests, are vulnerable to marine heatwaves (Wolff et al. 2018; Leggat et al. 2019; Smith et al. 2023; NOAA 2024). The Great Barrier Reef in Australia has suffered mass bleaching events tied to high temperatures in 2020, 2022 and 2024 (Henley et al. 2024). Documented impacts of extreme marine heat on the Pacific coast of North America include decreased phytoplankton production, toxic algal blooms and disrupted food webs, leading to mortality of fish, pinnipeds, baleen whales and seabirds (Jones et al. 2018; Piatt et al. 2020; Arimitsu et al. 2021; Gomes et al. 2024). Heat is a contributing factor to toxic algal blooms in marine and freshwater systems in Australia, North America and Europe (Facey et al. 2022; Perry et al. 2023).

Extreme wildfires have detrimental impacts on land and soil systems, as well as human health. The frequency and intensity of wildfires have increased exponentially in the 21st century in western American conifer forests, northern boreal forests, and the southeastern Australian bush (Abram et al. 2021; Cunningham et al. 2024). These trends are overwhelming the resilience of even historically fire-adapted ecosystems (McLauchlan et al. 2020). Massive wildfires have also occurred in Greece in 2023, Türkiye in 2021, Canada in 2023 and the southern and western United States of America in 2023 and 2025, respectively. The Canadian fires were driven by high temperatures, early snowmelt and a multiannual drought. They burned 150,000 km^2 and released about 65 million tons of carbon (Byrne et al. 2024; Jain et al. 2024). Since 1980, the length of the "fire weather" season – conditions conducive to the ignition and spread of fires – has expanded dramatically in the Mediterranean region, southeastern Australia, and western North America (Jones et al. 2022; Parks Canada 2024). Evidence suggests that climate change is driving the striking expansion of fire weather in recent decades and exacerbating its ensuing repercussions (**Figure 8.31**) (Jones et al. 2022; Cunningham et al. 2024; Hetzer et al. 2024).

Figure 8.31: Drivers and impacts of wildfires, which are accentuated by climate change, based on an example from Southern California in 2012–2018



Note: This example illustrates the phenomenon of a cascading hazard, a form of compound climate hazard in which interactions among consecutive climate extreme events result in the amplification of their impacts

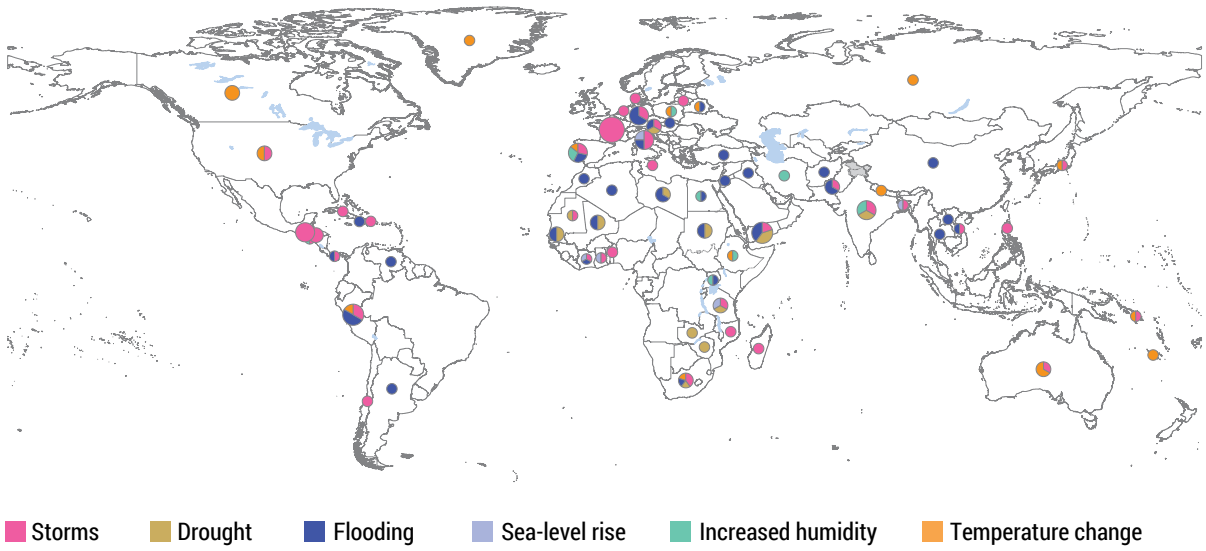
Source: AghaKouchak et al. (2020)

Wildfires damage cultural and biocultural resources and disrupt the livelihoods of local communities. Recent wildfires in the United States of America have destroyed cultural heritage sites in Lahaina, Hawaii, including the Na ʻAikane o Maui Cultural and Research Centre, which contained Native Hawaiian genealogical records and maps (Arango 2023). In summer 2024, fires destroyed 90 per cent of the ancient Turkish port city of Assos, which was founded in the 8th century B.C.E. and was a popular tourist site (Bassler 2024). In addition, wildfires destroyed 50 km^2 of the unique Laurisilva of Madeira Forest in Portugal in 2024, part of the EU Natura 2000 protected areas (European Commission: Joint Research Centre et al. 2023; BirdLife International 2024; European Parliament 2024).

Extreme precipitation, hurricanes and other storm events across WEOG are increasing in intensity and frequency (Seneviratne et al. 2021; Clarke et al. 2022). Although in the past the primary hazard from hurricanes was coastal storm surges, between 2013 and 2024, freshwater flooding caused 57 per cent of direct fatalities from hurricanes in the United States of America, with lasting damage to local communities (Brennan et al. 2023). Excess mortality persists for 15 years after a major tropical cyclone (Young and Hsiang 2024). In Germany and Belgium, extreme rainfall and flooding in 2021, enhanced by climate change, caused extensive damage to infrastructure, including railway lines, houses and roads, with 200 fatalities (Szymczak et al. 2022; Tradowsky et al. 2023). In September 2023, Storm Daniel produced extreme rainfall over Greece and parts of Türkiye, causing floods in both countries, and flooding 30 per cent of the cotton crop in the Thessalian plain (He et al. 2024; WMO 2024). The highest recorded rainfall event in Spain's history, which occurred in October 2024, resulted in catastrophic flooding, leading to 232 deaths in Valencia (Galvez-Hernandez et al. 2025). Storms are also the principal cause of damage to UNESCO World Heritage Sites in Europe (Clarke et al. 2025) (**Figure 8.32**). In 2023, one-third of European rivers exceeded the flood threshold (Copernicus Climate Change Service 2024). Such events are likely to increase in frequency. Record-breaking rainfall and flooding in Eastern Australia in 2022 have been attributed to prolonged La Niña conditions (Gillett et al. 2023; Huang et al. 2024; Malan et al. 2024). New Zealand's North Island suffered extreme rainfall and flooding in January and February 2023 from ex-tropical cyclones Hale and Gabrielle, resulting in 15 deaths (WMO 2024). Climate change is driving the rapid intensification and increased rainfall of Gulf of Mexico hurricanes, as seen in Hurricane Milton in 2024 (Clarke et al. 2024; World Weather Attribution 2024).

In coastal regions, extreme events have intensified consequences for ecosystems and infrastructure due

Figure 8.32: Global distribution of climatic hazards documented by UNESCO to have climate change impacts on World Heritage Sites by country



Note: The size of the circle represents the number of sites affected per country, while the pie slices represent the number and type

Source: Modified from UNESCO (2025)

to the compounding effects of sea level rise, storm surges, heavy precipitation and river floods. Coastal storms and storm surges, exacerbated by sea level rise, and associated saltwater intrusions, are converting forested wetlands in the southeastern United States of America to marshes, shrublands or "ghost forests" with loss of stored carbon (Smart et al. 2020; Ury et al. 2021; Powell et al. 2022; White et al. 2022; Sacatelli et al. 2023). Saltwater intrusions are affecting nutrient cycling and degrading the productivity of coastal farmland in the eastern United States of America (Weissman and Tully 2020; O'Donnell et al. 2024). For example, a survey of 15 coastal counties in the mid-Atlantic United States of America found that the percentage of farmland within 100 metres of a salt patch nearly doubled from 350 km^2 in 2012 to 680 km^2 in 2017 (Mondal et al. 2023). Storms have further compounding effects in the Arctic, where the landfast ice that has typically protected coastlines is melting in the warming climate (Hošeková et al. 2021; Henke et al. 2024). As a result, some coastlines in northern and western Alaska are eroding by over 20 metres per year (Huntington et al. 2023). In the Arctic, saltwater intrusion accelerates the loss of coastal permafrost, which in turn degrades infrastructure such as roads and runways (Guimond et al. 2021; Huntington et al. 2023). Some Northern European coastlines are suffering from erosion. For example, the North Norfolk towns of Happisburgh, Eccles and Hemsby in the United Kingdom of Great Britain and Northern Ireland have lost buildings and infrastructure to the sea, with an indicative property loss of 90 residential and commercial spaces (Coastwise 2023).

Ageing and inadequate infrastructure compounds the risk of extreme events in WEOG. Occurring with increased frequency and intensity, extreme weather events damage transportation, energy production and water treatment systems, and other infrastructure. (Zamuda et al. 2023, Zachariah et al. 2023) (Figure 8.33). One third of Canada's infrastructure is in need of updating or replacement to withstand new climate conditions (Lulham et al. 2023). In the United States of America coastal areas, ageing infrastructure combined with human modification of coastal ecosystems has increased the likelihood of coastal flooding (May et al. 2023). Protecting cultural heritage sites from climate extremes is especially challenging (Sesana et al. 2021; Blavier et al. 2023). In European Union countries, the introduction of housing renovation targets (European Commission 2020) offers a key opportunity to enhance climate resilience.

The increasing incidence of floods, droughts, wildfires, heatwaves and other events has adverse economic impacts, including supply chain disruptions, decreased economic output and changes in the geographic distribution of economic opportunities (Hsiang et al. 2023; Jay et al. 2023; EEA 2024a). Food production is already critically threatened by heat and drought in southern and central Europe. Impacts are unevenly distributed across economic sectors and socioeconomic groups (Hsiang et al. 2023). For example, in Canada, climate change is contributing to the unpredictability of supply chains, especially in Indigenous fly-in communities in the Arctic, which are compromised by ageing infrastructure, hazardous sea ice, thawing permafrost and loss of winter roads using frozen waterways (Reed et al. 2022; Lulham et al. 2023). Indigenous Peoples in Australia were more than four times more likely to report flooding and displacement than non-Indigenous Australians (Matthews et al. 2019; Cresswell et al. 2021).

Distinct local communities, such as the Gullah Geechee, who inhabit coastal lowlands of the southeastern United States of America, are threatened by multiple climate change hazards, including sea level rise, more frequent storms and increased coastal erosion (Ghahramani et al. 2020). Arctic Indigenous communities face a series of interrelated challenges to food security and are among those most affected by the consequences of climate change, which increase vulnerability in food systems (Kovacs et al. 2021; Jørgensen 2024). The loss of sea ice is undermining traditional Inuit lifeways by limiting the ability to hunt seals and whales (Inuit Tapiriit Kanatami 2019; Hauser et al. 2021; Adger et al. 2022).

8.6.5 Priority issue: pollution and waste

WEOG countries have progressed in addressing waste and pollution issues. However, high-consumption lifestyles continue to produce excessive waste.

The material footprint of WEOG countries greatly exceeds the global average of 13.0 metric tons per capita. In 2021, Canada produced 40.0 tons, New Zealand produced 33.3 tons, the United States of America produced 31.6 tons, Australia produced 31.9 tons, and the European Union averaged 15.0 tons per capita (2022) (Vienna University of Economics and Business – Institute for Ecological Economics n.d.). Particle emissions from combustion, especially

Figure 8.33: Climate impacts on infrastructure sector in Europe

Climate risks	Urgency to act	Risk severity			Policy characteristics		
		Current	Mid-century	Late century (low/high warming scenario)	Policy horizon	Policy readiness	Risk ownership
Infrastructure							
Pluvial and fluvial flooding	Urgent action needed	+++	+++	++ / +++	Long	Medium	Co-owned
Coastal flooding	More action needed	+++	+++	+++	Long	Advanced	Co-owned
Damage to infrastructure and buildings (**)	More action needed	++	++	++	Long	Medium	Co-owned
Energy disruption due to heat and drought (hotspot region: southern Europe)	More action needed	++	++	++	Medium	Medium	Co-owned
Energy disruption due to heat and drought	Further investigation	++	++	+	Medium	Medium	Co-owned
Energy disruption due to flooding	Further investigation	++	++	++	Long	Advanced	Co-owned
Marine transport	Further investigation	++	++	++	Medium	Medium	Co-owned
Land-based transport	Further investigation	++	++	++	Medium	Medium	Co-owned
Economy and finance							
European solidarity mechanisms	Urgent action needed	+++	++	++	Short	Medium	Co-owned
Public finances	More action needed	++	++	++ / ++	Medium	Medium	Co-owned
Property and insurance markets	More action needed	++	++	++ / ++	Medium	Medium	Co-owned
Population/economy due to water scarcity (hotspot region: southern Europe)	More action needed	++	++	++ / ++	Medium	Medium	Co-owned
Population/economy due to water scarcity	Further investigation	++	++	++	Medium	Medium	Co-owned
Pharmaceutical supply chains (*)	Further investigation	++	+	+ / +	Short	Medium	EU
Supply chains for raw materials and components (*)	Further investigation	++	++	++	Short	Medium	EU
Financial markets	Further investigation	+	+	+ / +	Short	Medium	Co-owned
Winter tourism	Sustain current action	+++	+++	++ / ++	Medium	Advanced	National

Urgency to act
- Urgent action needed
- More action needed
- Further investigation
- Sustain current action

Risk severity
- Catastrophic
- Critical
- Substantial
- Limited

Confidence
- \+ Low
- ++ Medium
- +++ High

(*) Wide range of evaluations by authors and risk reviewers.
(**) Urgency based on high warming scenario (late century).

Source EEA 2024

$PM_{2.5}$, remain the most significant environmental health threat in Europe, with over 50 per cent of the population exposed to levels above 10 µg/m^3 (Yang et al. 2022; EEA 2023d). While management of hazardous materials in WEOG countries is improving, unanticipated risks continue to emerge. For example, perfluoroalkyl and polyfluoroalkyl substances include about 5,000 compounds that are ubiquitous in industry and consumer goods, while risk analyses of these chemicals are relatively recent (DeWitt et al. 2024).

The effects of air, water and soil pollution are not equitable across WEOG. Low-income, homeless and historically marginalized people are at heightened risk (Goodling 2019; Hausman and Stolper 2021; Liu et al. 2021). Historical restrictive zoning based on racial and ethnic factors in the United States of America continues to manifest as increased risk from floods (Bidadian et al. 2024; Salazar-Miranda et al. 2024), air pollution (Lane et al. 2022), heatwaves (Li et al. 2024), pollution from proximity to oil and gas wells (Cushing et al. 2023; Gonzalez et al. 2023), and exposure to pesticides (Donley et al. 2022). Similar trends are observed in Europe, where minority ethnic groups in London are exposed to concentrations of nitrogen dioxide that are up to 27 per cent higher than those of the general population (EEA 2018; Cushing et al. 2023; van den Brekel et al. 2024). Half of London's

hospital admissions for asthma are children from these groups (London Assembly 2022). Throughout the WEOG region, migrants are increasingly vulnerable due to discrimination, precarious housing, hazardous work environments, and limited access to essential services (Méndez et al. 2020; Fong and Bell 2021; Rana et al. 2022; United States of America, Centers for Disease Control and Prevention 2024).

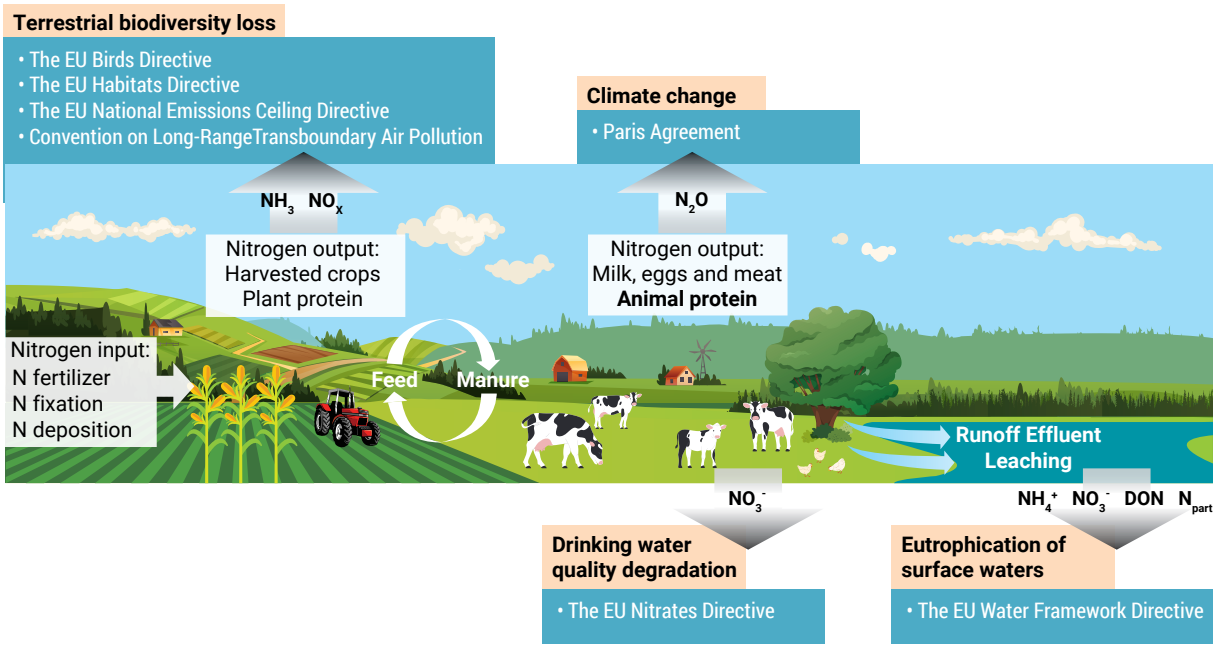
Impacts of pollution on Indigenous Peoples within WEOG are multifaceted. Indigenous lands have been exploited, often without prior and informed consent, for fossil fuel and mineral extraction, causing lingering polluted lands, air and waters (Fernández-Llamazares et al. 2020). For example, people of the Yellowknives Dene First Nation in Canada were subject to arsenic contamination from gold mining long after the nearby Giant Mine closed (Sandlos and Keeling 2017). The Arctic has been disproportionately affected by persistent organic pollutants, which bioaccumulate in marine mammals, fish and birds – species that are crucial for the sustenance and culture of Indigenous communities (Fernández-Llamazares et al. 2020). For example, East Greenland Inuit hunters have the highest blood-serum concentrations of polyfluoroalkyl compounds recorded outside industrially polluted sites (Sonne et al. 2023).

Cultural heritage is at particular risk from air pollution and associated acid deposition (Spezzano 2021). Air pollution is degrading the world's oldest and most prominent example of petroglyphs, the Dampier Rock Art Complex in northwestern Australia. Comprising approximately one million carvings across 400 km^2, the site is tens of thousands of years old and depicts extinct species, including the Tasmanian Tiger (Neumann et al. 2022; Smith et al. 2022).

Human disruption of the nitrogen cycle has been severe in WEOG, primarily driven by unsustainable agricultural practices. Applications of synthetic fertilizer increased rapidly from the mid-20th century, peaking around the 1990s, and leaving excess nitrogen in soils and groundwater (**Figure 8.34**) (Tian et al. 2020; Tian et al. 2022). Although deposition of reactive nitrogen from the atmosphere began to decrease in Europe in the 1980s and the United States of America in the 1990s with environmental regulations and incentives, levels still exceed thresholds that threaten forests and plant biodiversity (UNEP 2019; FAO and UNEP 2021; Schulte-Uebbing et al. 2022; Chen, Xiao and Chen 2023; de Vries et al. 2024).

Significant efforts in the United States of America have focused on reducing nutrients released to waterways as agricultural run-off from current and historical over-fertilized croplands, as well as from livestock manure accumulations (Van Meter, Byrnes and Basu 2023). This excess nutrient pollution, including both nitrogen and phosphorus, depletes oxygen, creating hypoxia in

Figure 8.34: Nitrogen cycle and impacts of excess nitrogen on human and natural systems, as well as European Union directives and international agreements aiming to reducethese impacts



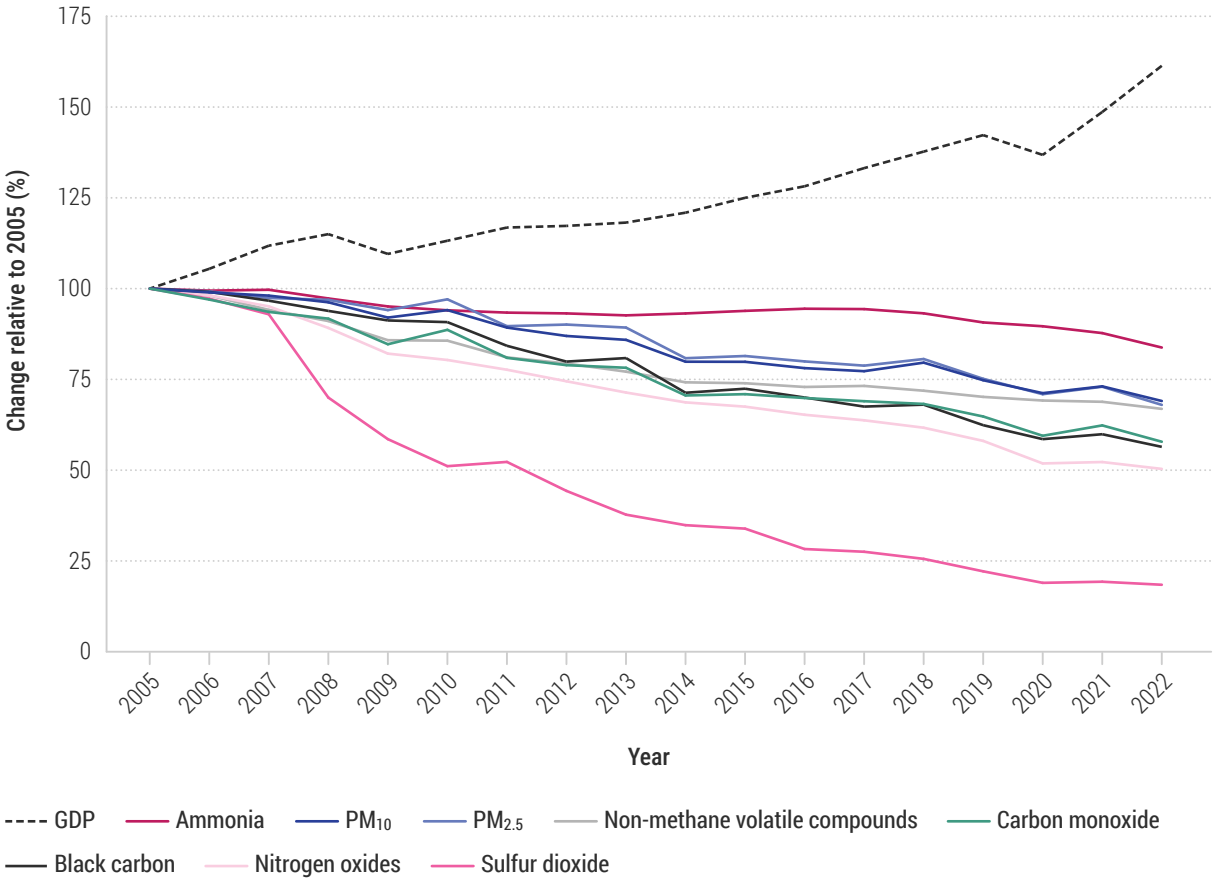
aquatic systems that damages freshwater and coastal environments and results in harmful algal blooms, decreased fish biodiversity, and loss of estuarine species (Baron et al. 2014; Mosley et al. 2023; Zhou et al. 2023). Extensive hypoxic zones have been documented in the Gulf of Mexico, Baltic Sea, and the Coorong estuary of Australia (Rabalais and Turner 2019; Mosley et al. 2023; EEA 2024b). Excess nitrogen also manifests as elevated nitrate levels in groundwater, degrading drinking water sources (Ortmeyer, Hansen and Banning 2023; Van Meter, Schultz and Chang 2023) and contributing to socioeconomic inequities, for example, by contaminating many traditional aquifers of Aboriginal Australians (Balasooriga et al. 2023). Despite legislation addressing nutrient pollution, the average nitrate concentration in European Union groundwater did not change significantly from 2000 to 2021, and 14 per cent of groundwater stations exceeded the maximum allowable concentration in 2019 (EEA 2023b). Finally, excess nitrogen in the soil induces the release of nitrous oxide, a potent greenhouse gas (Canadell et al. 2021; Cheng et al. 2022; Wang, Faloona and Houlton 2023). Due to nitrogen's multifaceted roles as a necessary nutrient, an air pollutant, a greenhouse gas component and a disruptor of plant biodiversity, its influences reach inextricably to the global food system, ecosystem health, and human well-being (Schulte-Uebbing et al. 2022).

A strong association has been documented between pesticide exposure and declines in populations of beneficial species (Mamy et al. 2022; EEA 2023c). In 2020, nearly a quarter of all freshwater monitoring sites across Europe found one or more pesticides above the thresholds of concern, while 83 per cent of agricultural soils contained pesticide residues (EEA 2023c). A 33 per cent decrease in pesticide use and a 2021 shift towards targeted products in Western Europe from a 2015–2017 baseline (EEA 2023c) may not immediately correlate with reduced toxicity for pollinators and other non-target organisms. In the United States of America, while the total mass of applied insecticides has decreased by 40 per cent since the 1990s, and harm to birds and mammals has decreased, both broad-spectrum and newer selective pesticides are highly toxic to non-targeted beneficial species such as native bees, beetles, dragonflies and wasps (Dicks et al. 2021; Schulz et al. 2021; Mata et al. 2024).

Exposure to synthetic chemicals and plastics is pervasive; many are persistent, and health impacts are still emerging (EEA 2022b; UNEP and Secretariat of the Basel, Rotterdam and Stockholm Conventions 2023). More than 3,000 chemicals of concern are found in plastic consumer goods (UNEP and Secretariat of the Basel, Rotterdam and Stockholm Conventions 2023). In New Zealand, polyfluorinated alkyl substances are found in soil, water and human serum (Coakley et al. 2018; Lenka et al. 2022), despite efforts to phase out the most toxic of them (UNEP and Secretariat of the Basel, Rotterdam and Stockholm Conventions 2023). Wastewater biosolids from treatment plants have been applied to agricultural soils for many decades, and the recent discovery in the United States of America of accumulated polyfluorinated alkyl substances from this practice has become an emerging health crisis (Buttle et al. 2023; Pozzebon and Seifert 2023; Gewurtz et al. 2024; Saliu and Sauvé 2024; Zhou et al. 2024). Current evidence links exposure to polyfluoroalkyl compounds with decreased antibody responses and reduced infant and fetal growth (United States of America, National Academies of Sciences, Engineering, and Medicine et al. 2022). Microplastics have been implicated as drivers of colorectal cancer (Li et al. 2023; Bruno et al. 2024). Although acute poisoning by pesticides in WEOG is below global rates, these substances are widely distributed throughout the population (Tudi et al. 2022). Vulnerable individuals, notably farmworkers and their families, experience heightened exposure. Pesticides, polyfluorinated alkyl substances, and other persistent organic pollutants have been detected in over 90 per cent of people sampled in Europe (Ottenbros et al. 2023), the United States of America (Kurwadkar et al. 2022) and Canada (Gibson 2020). A large-scale human biomonitoring study conducted between 2014 and 2021 across five European countries found that at least two pesticides were detected in the bodies of 84 per cent of survey participants, with higher pesticide levels in children (EEA 2023c). Strong or suspected links have been established between pesticide exposure and an increased risk of several chronic diseases (Leemans et al. 2019; Rayasam et al. 2022; EEA 2023c).

Air quality has been consistently improving in WEOG countries, but it remains a significant concern. In Western Europe, airborne emissions of pollutants have decreased significantly over the past two decades, though trends for ammonia are weaker (**Figure 8.35**) (Tang et al. 2021; Van Damme et al. 2022; Burns et al. 2023; Wang et al. 2023a; EEA 2024c; Liu et al. 2024). Yet, more than 90 per cent of urban Europeans

Figure 8.35: Trends in emissions of major air pollutants from 2005 to 2022 for the European Union



Source: EEA (2024d)

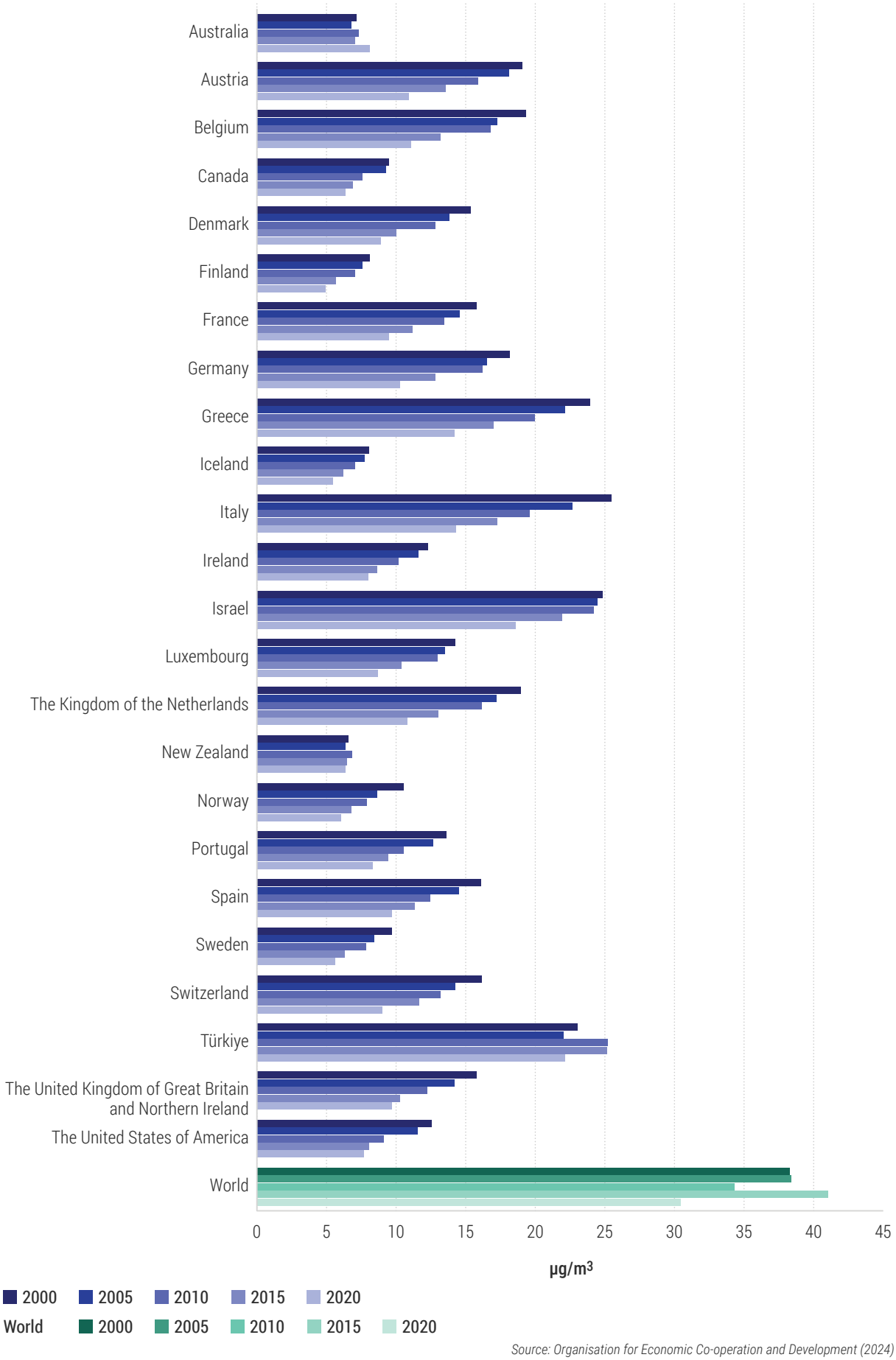
still breathe harmful levels of fine particulate matter, causing more than 200,000 premature deaths per year (EEA 2023d). Air pollution remains a critical health hazard, particularly for children, older people, marginalized communities, urban residents, and agricultural and industrial workers (EEA 2018; Lane et al. 2022; Zalzal and Hatzopoulou 2022; EEA 2023d; Romanello et al. 2023; de Souza et al. 2024).

Between 2000 and 2020, the exposure to $PM_{2.5}$ decreased by 34 per cent on average across the WEOG region, with all countries except Australia showing decreases (**Figure 8.36**) (OECD 2024a). Wildfire smoke can reverse that trend intermittently. For example, in 2023, smoke from wildfires crossed international borders between Canada and the United States of America, substantially decreasing air quality and resulting in a 30 per cent increase in asthma emergencies in New York City, United States of America, alone (Chen et al. 2023; Thurston, Yu and Luglio 2023).

Extraction, use and disposal of materials drive waste and pollution in the high-consumption societies of WEOG. Countries within the WEOG region are characterized by very high per capita levels of domestic material consumption and material footprint (UNEP and International Resource Panel 2024). Despite a 17 per cent reduction observed since 2000, North America's material footprint totalled 30 tons per capita in 2020, almost three times the global average. Western Europe showed 10 per cent reductions in material footprint between 2000 and 2020, moving from 19 to 17 tons per capita (UNEP and International Resource Panel 2024). Per capita volumes of municipal solid waste generated within WEOG are also among the highest in the world, at 1.0–1.5 kg/day in Western Europe and Australia/New Zealand and 2.25 kg/day in North America (UNEP 2024). Over 35 per cent of municipal waste is recycled in WEOG countries. In Western Europe, much of the balance is burned for energy, while the rest of WEOG relies on landfills (UNEP 2024).

Between 2010 and 2020, countries within the European Union reduced total waste generation by four per cent, partially attributed to the effect of the COVID-19

Figure 8.36: Mean population-weighted exposure to PM2.5 from 2000 to 2020



Source: Organisation for Economic Co-operation and Development (2024)

Credit: nd3000/Envato

pandemic and lower production of mineral wastes (EEA 2023e). Recent spikes in waste production have occurred across several WEOG countries – Austria, Belgium, Finland, Norway, Luxembourg – while the United States of America has consistently high volumes, and some keep increasing over time, as demonstrated by the United States of America, Denmark, New Zealand and Switzerland (EEA 2022c; OECD 2024b). However, data gaps and heterogeneity in reporting standards affect the quality of these data sets, limiting direct comparability.

The high material consumption of most WEOG residents drives a rapid turnover of consumer goods, which contributes to waste generation at every stage of the supply chain. For example, the fast-fashion industry expanded dramatically in the late 1990s, primarily based on polyester plastic fibres (Niinimäki et al. 2020). Textiles cause environmental damage during fibre production using pesticides and emissions from polyester fabrication, manufacture and dying of materials, and distribution along the supply chain (Niinimäki et al. 2020). Clothing purchases have increased, while their usage timespan has decreased, resulting in a commensurate increase in waste generation. Each United States of America citizen typically purchases a new item of clothing every 5.5 days. In 2018, each discarded an average of about 47 kg of textiles, excluding clothing donated to charities, marking an 80 per cent increase since 2000 (Schumacher and Forster 2022). Approximately 85 per cent of discarded clothing in WEOG countries ended up in landfills or were incinerated (EEA 2022d; Schumacher and Forster 2022). Several countries across the WEOG region have been increasingly active in promoting and fostering the uptake of circular-economy principles, regulations and business models (Australia Department of Climate Change, Energy, the Environment and Water 2024; EEA 2024d; EPA 2024; Government of Canada 2025; Didiezic et al. 2025). Since 2015, a comprehensive set of policies has been introduced and implemented across EU countries, which are showing positive trends but limited long-term improvements (EEA 2024d). Between 2010 and 2022, the EU economy showed only a slight increase in the circularity rate, from 10.5 to 11.5 per cent, yet confirming Europe as the world region that consumes the highest proportion of its recycled materials (EEA 2024d).

8.7 Telecoupling

8.7.1 Introduction

Across regions and subregions, interlinkages are growing between human and natural systems,

driven by processes such as trade, investment, tourism, migration, species invasion, and flows of ecosystem services (Liu 2020), as well as armed conflict (UNEP 2024). These interconnections are referred to as telecoupling – an umbrella concept that encompasses socioeconomic and environmental interactions spanning distances (Liu et al. 2013). Telecoupling offers a valuable opportunity to examine how decisions or activities in one country or region can have environmental and socioeconomic implications in other places. Through the application of the telecoupling framework (Liu et al. 2013) with five major components – systems such as countries or regions, flows, agents, causes such as drivers, and effects including feedback – it is possible to characterize and better understand these complex relationships.

Within the scope of this section, it is not possible to cover the full range of telecoupling. Special focus is placed on four types of telecoupling to highlight notable regional interconnections: trade, foreign direct investment, migration, and tourism (**Figure 8.37**).

Trade flows across regions between 2017 and 2021 totalled more than US$7 trillion (**Table 8.3**). AP is the largest sending system and the second-largest receiving system, while WEOG was the largest receiving system and the second-largest sending system. Africa was both the smallest sending and receiving system. EE ranked third, and LAC was fourth in both imports and exports. The top three trade relationships were between AP and WEOG, EE and WEOG, and WEOG and LAC.

According to the total investments sent and received (**Table 8.4**), WEOG ranked the highest, followed by AP, LAC, EE and Africa, respectively. In terms of paired relationships, AP and WEOG had the largest investment flows, followed by WEOG and LAC, and then by WEOG and EE.

In terms of migration (**Table 8.5**), WEOG was the smallest sending system and the largest receiving system. EE was the largest sending system and the fourth largest receiving system. AP, Africa, and LAC ranked 2nd, 3rd and 4th in sending, and 2nd, 5th and 3rd in receiving, respectively. In terms of paired relationships, AP and WEOG had the strongest relationship, followed by EE and WEOG, and Africa and WEOG.

Regarding international tourism (**Table 8.6**), WEOG was both the largest sending and receiving system, and Africa was the smallest sending and receiving system. In terms of paired relationships, EE and WEOG

Figure 8.37: Conceptual diagram illustrating four types of telecoupling among the five UN regions

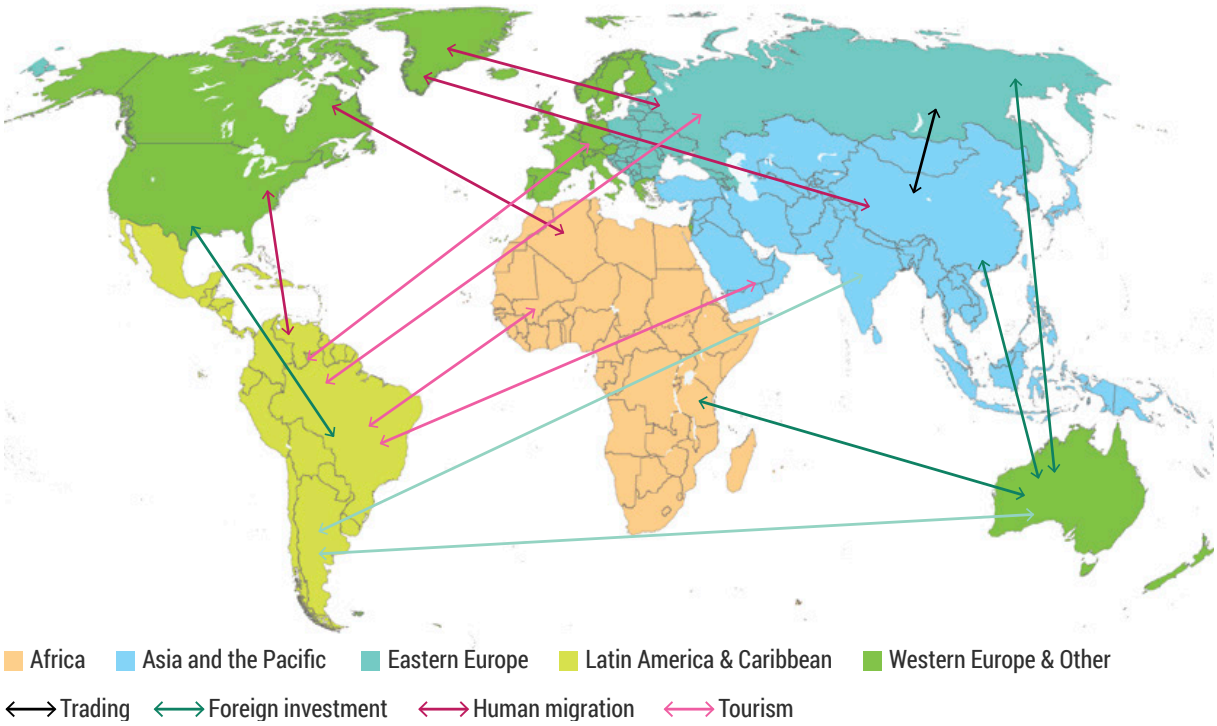


Table 8.3: Trade among the five United Nations regions (2017–2021) (unit: billion US$)

	Africa	Asia	Eastern Europe	Western Europe	Latin America
Africa	41	165	9	182	7
Asia	134	2,601	217	2,042	240
Eastern Europe	19	173	262	655	14
Western Europe	130	1,370	507	4,107	360
Latin America	10	234	14	548	111

Table 8.4: Foreign direct investment in the five United Nations regions during 2017–2021 (unit: billion US$)

	Africa	Asia	Eastern Europe	Western Europe	Latin America
Africa	57	119	3	121	1
Asia	111	1,421	186	1,741	53
Eastern Europe	1	150	86	226	1
Western Europe	262	1,879	874	16,435	1,199
Latin America	5	33	21	354	103

Table 8.5: Human migration among the five United Nations regions in 2021 (unit: million persons)

	Africa	Asia	Eastern Europe	Western Europe	Latin America
Africa	12.9	1.6	0.0	11.2	0.0
Asia	0.4	32.9	0.9	18.1	0.3
Eastern Europe	0.0	4.9	8.8	17.2	0.1
Western Europe	0.3	1.1	0.9	19.9	2.0
Latin America	0.0	0.4	0.0	6.3	8.7

Table 8.6: International tourism among the five United Nations regions from 2017 to 2021 (unit: million persons)

	Africa	Asia	Eastern Europe	Western Europe	Latin America
Africa	17.9	4.4	0.2	4.8	0.1
Asia	3.3	148.1	10.3	48.6	1.2
Eastern Europe	2.8	10.6	46.8	55.0	0.9
Western Europe	12.8	36.7	40.4	345.2	53.8
Latin America	0.3	1.0	0.4	28.1	22.6

had the strongest flow, followed by WEOG and LAC, and then AP and WEOG.

8.7.2 Effects of telecoupling

Activities and decisions in one place influence environmental and socioeconomic conditions in distant places. These effects of telecoupling on human and natural systems are complex and can be negative or positive. They vary across sending, receiving and spillover systems. Sending and receiving systems are places that send and receive flows of goods, products, people, information, species and financial capital. Spillover systems refer to other systems that are affected by the interactions between sending and receiving systems (Liu et al. 2018). For example, soybean production in Brazil and trade with China and some European countries generate a substantial amount of GHGs, which affect the climate worldwide, including countries that do not trade soybeans with Brazil (da Silva et al. 2021). To date, studies on the effects of foreign direct investment, tourism and migration have primarily focused on receiving systems, with relatively less attention to sending and spillover systems (Duan et al. 2022; Liu 2023). In contrast, research on trade has focused mainly on sending systems, with less attention paid to receiving and spillover systems (Silva et al. 2023). Overall, spillover systems have received the least attention, so many of their effects are unknown or underestimated (Liu et al. 2018; Sachs et al. 2024).

Trade

Trade has been extensively studied. Recent research shows that, in the context of the SDGs, developed countries received more environmental benefits from international trade while developing countries benefited less or even suffered (Xu et al. 2020; Xiao et al. 2024). Additionally, trade between distant countries has had higher positive effects than trade between neighbouring countries (Xu et al. 2020; Xiao et al. 2024). Trade can have both positive and negative socioeconomic and environmental effects in various ways. For example, oil palm expansion for trade has benefited both producing and non-producing countries' economies by providing employment opportunities and promoting the export of crude palm oil, leading to poverty reduction and enhanced food security in producer countries. Negative effects in producing countries, such as those in Southeast Asia, include conflicts between local communities and oil palm companies, increased domestic economic inequality and environmental harm, including the emission of GHGs and biodiversity loss. Environmental benefits or positive effects in receiving countries come from saving resources and avoiding pollution by importing products from producing countries.

Foreign direct investment

Studies on foreign direct investment (FDI) have primarily focused on receiving systems and indicate that FDI increases financial capital stock, promotes

Credit: Bluesandisland/Envato

technological innovations, provides employment opportunities and increases per capita income (Destek and Okumus 2019). On natural systems, FDI has a non-linear effect on the environmental quality of EE countries (Christoforidis and Katrakilidis 2022), increases CO_2 emissions and total GHGs in African countries (Opoku and Boachie 2020), and increases the chemical oxygen demand but reduces the emissions of SO_2 and smoke dust in China through technological innovation (Hao et al. 2019). Between 1990 and 2018, FDI significantly increased CO_2 emissions in AP and Africa, but had insignificant effects in the LAC and European regions (Azam and Raza 2022).

Migration

Migration has mixed effects on the sending and receiving systems. It can reduce pressures on the environment and natural resources in sending systems, the origins of migrants, by reducing population sizes (Adger et al. 2024). In contrast, migration can increase environmental pollution and resource competition in the receiving systems due to consumption (Dedeoğlu et al. 2021; Ahmed et al. 2024; Delazeri et al. 2022; Chen and Goutte 2025). Migration also has substantial socioeconomic impacts. For example, the departure of skilled individuals can lead to a loss of human capital in the sending countries and a gain for the receiving countries (Beine et al. 2001; Stark et al. 1997; Bharadwaj et al. 2023; Nabulsi 2025).

Tourism

Many telecoupling studies have estimated carbon emissions – a major indicator of tourism's environmental impacts – in receiving systems but have disregarded the emissions in tourists' sending systems or spillover systems. To address this knowledge gap, Duan et al. (2022) applied the telecoupling framework and found that for China's international tourism, sending systems had a significant reduction in emissions, while spillover systems had large increases in emissions.

Four well-documented examples of different types of telecoupling are highlighted in **Table 8.7.**

Finally, the effects of telecoupling may also vary over time or development stages. For example, To et al. (2019) found that in 25 emerging markets in Asia between 1980 and 2016, FDI increased CO_2 emissions during the early stage. However, levels subsequently decreased during the late stage, consistent with the Environmental Kuznets Curve hypothesis. Additional research on telecoupling will bolster current understanding of the complexity of these types of relationships and their implications for policy and action.

Table 8.7: Implications of four selected telecoupling types on natural and human systems

Telecoupling type	Trade	Foreign direct investment (FDI)	Migration	Tourism
Example	International tomato trade	Belt and Road Initiative	Transnational labour migration	International tourism
Sending systems	Spain, The Netherlands	China	Myanmar	Canada, China, Denmark, Finland, France, Germany, Norway, Poland, Sweden, United Kingdom of Great Britain and Northern Ireland, United States of America
Receiving systems	Germany	More than 150 countries receive investment from the Initiative	China	Iceland

Table 8.7: Implications of four selected telecoupling types on natural and human systems (cont.)

Telecoupling type	Trade	Foreign direct investment (FDI)	Migration	Tourism
Spillover systems	West Africa, Poland	Other countries affected by the Initiative (e.g. United States of America)	Countries and regions that receive cash crops produced in China by labour migrants from Myanmar	• Countries with layover flights (transit) for tourists to Iceland • Countries where tourism cruise ships go through such as Argentina • Other countries affected by CO_2 emissions from tourism
Effects	**Sending systems:** • Water use and pollution • CO_2 emissions • Land-use change • Varying effects on biodiversity • Negative effects on landscape aesthetics • Farmers' income from tomato production • Contribution to national economy (GDP) **Receiving systems:** • Increased per capita tomato consumption by nearly fivefold • Nutritional benefits • Saving water and other resources **Spillover systems:** • Higher wages for and remittances from migrant workers	**Sending system:** • Political and economic gains (e.g. internationalization of China's currency, promotion of exports) **Receiving systems:** • Substantial loss of natural land • Environmental pollution from construction • Increase in built-up land • Financial support for infrastructure projects • Improved economic development • Largely positive public sentiment towards the projects • Debt stress in some countries **Spillover systems** • Environmental and geopolitical concerns by the United States of America and many other wealthy countries	**Sending systems:** • Increasing remittances **Receiving systems:** • Agricultural expansion and intensification of upland for cash crops **Spillover systems:** • Received cash crops produced by migrants from Myanmar	**Sending systems:** • Financial loss by tourists' spending in receiving and spillover systems **Receiving systems:** • Elevated CO_2 emissions from international flights and ships, and travel in Iceland via rental cars • Over 10% of Iceland's GDP from tourism industry • Need for safety infrastructure **Spillover systems:** • Financial gain from tourists who make layovers • Negative effects from CO_2 emissions from tourism
References	Ibarrola-Rivas et al. (2020)	Coenen et al. (2020); Li et al. (2021); Chinapower (2023)	Hua et al. (2019)	Remer and Liu (2022)

References

Introduction

Bennett, E.M., Biggs, R., Peterson, G.D. and Gordon, L.J. (2021). Patchwork Earth: navigating pathways to just, thriving, and sustainable futures. One Earth 4(2), 172-176. https://doi.org/10.1016/j.oneear.2021.01.004

European Commission (2023). European Green Capital Award Good Practices - Kraków - Air protection. https://environment.ec.europa.eu/topics/urban-environment/european-green-capital-award/inspiration/krakow-air-protection_en Accessed 19 March 2024

Fassinou, F.J.C., Cesaro, J.-D., Nungi-Pambu, M., Fensholt, R., Brandt, M., Akodewou, A. et al. (2024). Quantifying the impact of Great Green Wall and Corporate plantations on tree density and biomass in Sahelian Senegal. Trees, Forests and People 16, 100569 https://doi.org/10.1016/j.tfp.2024.100569

FiBL (2024). Cultivating change with agroecology and organic agriculture in the tropics: Bridging science and policy for sustainable production systems. https://doi.org/10.5281/zenodo.10521540

Food and Agriculture Organization of the United Nations (2020). Global Forest Resources Assessment 2020: Main Report. Rome: FAO. https://www.sprep.org/sites/default/files/documents/publications/forest-resources-assessment-main-report.pdf

Liu, S. (2020). Interactions between industrial development and environmental protection dimensions of Sustainable Development Goals (SDGs): Evidence from 40 countries with different income levels. Environmental & Socio-economic Studies 8(3), 60-67. https://doi.org/10.2478/environ-2020-0018

United Nations Convention to Combat Desertification (2020). The Great Green Wall: Implementation Status and Way Ahead to 2030 (Advanced Version). https://www.unccd.int/resources/publications/great-green-wall-implementation-status-and-way-ahead-2030

United Nations Department of Economic and Social Affairs (2023). The Sustainable Development Goals Report 2023: Special Edition - July 2023. New York: United Nations Publications. https://unstats.un.org/sdgs/report/2023/

United Nations Economic and Social Commission for Asia and the Pacific, United Nations Environment Programme International Labour Organization, The Regional Collaboration Center for Asia and the Pacific of the Secretariat of the United Nations Framework Convention on Climate Change and United Nations Industrial Development Organization (2023). 2023 review of climate ambition in Asia and the Pacific: just transition towards regional net-zero climate resilient development. https://hdl.handle.net/20.500.12870/6535

Vicente-Serrano, S.M., Pricope, N.G., Toreti, A., Morán-Tejeda, E., Spinoni, J., Ocampo-Melgar, A. et al. (2024). The Global Threat of Drying Lands: Regional and global aridity trends and future projections. A Report of the Science-Policy Interface. Bonn: United Nations Convention to Combat Desertification (UNCCD). https://www.unccd.int/sites/default/files/2024-12/aridity_report.pdf

World Wide Fund For Nature (2024). Living Planet Report 2024 – A System in Peril. Switzerland: WWF. https://www.worldwildlife.org/publications/2024-living-planet-report

Africa

Abulude, F.O., Damodharan, U., Acha, S., Adamu, A. and Arifalo, K.M. (2020). Preliminary Assessment of Air Pollution Quality Levels of Lagos, Nigeria. Environmental Sciences Proceedings 5(1), 20. https://dx.doi.org/10.3390/IECG2020-08549

Acheampong, A.O. and Opoku, E.E.O. (2023). Environmental degradation and economic growth: Investigating linkages and potential pathways. Energy Economics 123, 106734. https://dx.doi.org/10.1016/j.eneco.2023.106734

Adeleke, B.O. (2022). Need for Emergency response to Wetlands Loss in Southwestern Nigeria: A Review. Ghana Journal of Geography 14(3), 90-114. https://dx.doi.org/10.4314/gjg.v14i3.4

Adesete, A.A., Olanubi, O.E. and Dauda, R.O. (2023). Climate change and food security in selected Sub-Saharan African Countries. Environment, Development and Sustainability 25(12), 14623-14641. https://dx.doi.org/10.1007/s10668-022-02681-0

Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G.E., Morecroft, M.D. et al. (2023). Cross-Chapter Paper 5: Mountains. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A. et al. (eds.). Cambridge and New York: Cambridge University Press. 2273-2318. https://dx.doi.org/10.1017/9781009325844.022

Africa Center for Strategic Studies (2016). Selected Effects of Climate Change on Africa. https://africacenter.org/spotlight/selected-effects-climate-change-africa/ Accessed 8 October 2025

Africa Center for Strategic Studies (2022). Cyclones and More Frequent Storms Threaten Africa. https://africacenter.org/spotlight/cyclones-more-frequent-storms-threaten-africa/Accessed 12 December 2023

African Development Bank (2022). The African Development Bank's Just Transition Initiative to Address Climate Change in the African Context: Discussion Paper. https://www.afdb.org/sites/default/files/2022/12/09/just_transition_in_the_african_context.pdf

Ahmed, A.I., Bryant, R.G. and Edwards, D.P. (2021). Where are mines located in sub Saharan Africa and how have they expanded overtime? Land Degradation and Development 32(1), 112-122. https://dx.doi.org/10.1002/ldr.3706

Ahmed, I., Parikh, P., Sianjase, G. and Coffman, D.M. (2020). The impact decades-long dependence on hydropower in El Niño impact-prone Zambia is having on carbon emissions through backup diesel generation. Environmental Research Letters 15(12), 124031. https://dx.doi.org/10.1088/1748-9326/abb6a1

Akindele, E.O. and Alimba, C.G. (2021). Plastic pollution threat in Africa: current status and implications for aquatic ecosystem health. Environmental Science and Pollution Research 28(7), 7636-7651. https://dx.doi.org/10.1007/s11356-020-11736-6

Aloo, P.A., Njiru, J., Balirwa, J.S. and Nyamweya, C.S. (2017). Impacts of Nile Perch, Lates niloticus, introduction on the ecology, economy and conservation of Lake Victoria, East Africa. Lakes and Reservoirs: Science, Policy and Management for Sustainable Use 22(4), 320-333. https://dx.doi.org/10.1111/lre.12192

Archer, S.R., Andersen, E.M., Predick, K.I., Schwinning, S., Steidl, R.J. and Woods, S.R. (2017). Woody Plant Encroachment: Causes and Consequences. In: Rangeland Systems. Processes, Management and Challenges. Briske, D. (eds.). Springer Cham. 25-84. https://dx.doi.org/10.1007/978-3-319-46709-2_2

Arias, P.A., Bellouin, N., Coppola, E., Jones, R.G., Krinner, G., Marotzke, J. et al. (2023). Technical Summary. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (eds.). Cambridge and New York: Cambridge University Press. 35-144. https://dx.doi.org/10.1017/9781009157896.002

Awadh, S.M. (2023). Impact of North African Sand and Dust Storms on the Middle East Using Iraq as an Example: Causes, Sources, and Mitigation. Atmosphere 14(1), 180. https://dx.doi.org/10.3390/atmos14010180

Ayeleru, O.O., Dlova, S., Akinribide, O.J., Ntuli, F., Kupolati, W.K., Marina, P.F. et al. (2020). Challenges of plastic waste generation and management in sub-Saharan Africa: A review. Waste Management 110, 24-42. https://dx.doi.org/10.1016/j.wasman.2020.04.017

Barbier, E.B. and Hochard, J.P. (2018). The Impacts of Climate Change on the Poor in Disadvantaged Regions. Review of Environmental Economics and Policy, Association of Environmental and Resource Economists 12(1), 26-47. https://dx.doi.org/10.1093/reep/rex023

Bari, M. and Dessus, S. (2022). Climate adaptation in Africa offers investment opportunities for private sector. https://www.howwemadeitinafrica.com/climate-adaptation-in-africa-offers-investment-opportunities-for-private-sector/148691/. Accessed 9 December 2023

Belayneh, A. and Tessema, Z.K. (2017). Mechanisms of bush encroachment and its inter-connection with rangeland degradation in semi-arid African ecosystems: a review. Journal of Arid Land 9(2), 299-312. https://dx.doi.org/10.1007/s40333-016-0023-x

Beltran-Peña, A. and D'Odorico, P. (2022). Future Food Security in Africa Under Climate Change. Earth's Future 10(9). https://dx.doi.org/10.1029/2022EF002651

Benton, T.G., Bieg, C., Harwatt, H., Pudasaini, R. and Wellesley, L. (2021). Food system impacts on biodiversity loss. Three levers for food system transformation in support of nature. London: Chatham House. https://www.unep.org/resources/publication/food-system-impacts-biodiversity-loss

Bradshaw, C.J.A. and Di Minin, E. (2019). Socio-economic predictors of environmental performance among African nations. Scientific Reports 9(1), 9306. https://dx.doi.org/10.1038/s41598-019-45762-3

Caminade, C., McIntyre, K.M. and Jones, A.E. (2019). Impact of recent and future climate change on vector-borne diseases. Annals of the New York Academy of Sciences 1436(1), 157-173. https://dx.doi.org/10.1111/nyas.13950

Caminade, C., Ndione, J., Diallo, M., Macleod, D., Faye, O., Ba, Y. et al. (2014). Rift Valley Fever Outbreaks in Mauritania and Related Environmental Conditions. International Journal of Environmental Research and Public Health 11(1), 903-918. https://dx.doi.org/10.3390/ijerph110100903

Centre for Research on the Epidemiology of Disasters (2022). The interplay of drought-flood extreme events in Africa over the last twenty years (2002-2021). https://reliefweb.int/report/world/cred-crunch-newsletter-issue-no-69-december-2022-interplay-drought-flood-extreme-events-africa-over-last-twenty-years-2002-2021

Chapman, C.A., Abernathy, K., Chapman, L.J., Downs, C., Effiom, E.O., Gogarten, J.F. et al. (2022). The future of sub-Saharan Africa's biodiversity in the face of climate and societal change. Frontiers in Ecology and Evolution 10. https://dx.doi.org/10.3389/fevo.2022.790552

Chelea, M., Patrice, B., Germaine, Y., Huguette, C.Y.M. and Bonglaisin, J.N. (2022). Water Shortages: Cause of Water Safety in Sub-Saharan Africa. In: Drought - Impacts and Management. Murat, E., Ahmed, A., Mesut, T. and Ercan, G. (eds.). Rijeka: IntechOpen. Chapter 10. https://doi.org/10.5772/intechopen.103927

Chen, S.S., Kimirei, I.A., Yu, C., Shen, Q. and Gao, Q. (2022). Assessment of urban river water pollution with urbanization in East Africa. Environmental Science and Pollution Research 29(27), 40812-40825. https://dx.doi.org/10.1007/s11356-021-18082-1

Chomba, S., Sinclair, F., Savadogo, P., Bourne, M. and Lohbeck, M. (2020). Opportunities and Constraints for Using Farmer Managed Natural Regeneration for Land Restoration in Sub-Saharan Africa. Frontiers in Forests and Global Change 3. https://dx.doi.org/10.3389/ffgc.2020.571679

Climate Action Tracker (2022). Natural gas in Africa: Why fossil fuels cannot sustainably meet the continent's growing energy demand. https://climateactiontracker.org/publications/natural-gas-in-africa-why-fossil-fuels-cannot-sustainably-meet-the-continents-growing-energy-demand/

Convention on Biological Diversity (2018). Report of the African Ministerial Summit on Biodiversity. https://www.cbd.int/doc/c/1eb6/0339/1892b7c3aa648a63e3d7cd05/cop-14-inf-50-en.docx

Convention on Wetlands (2022). Wetlands and agriculture: impacts of farming practices and pathways to sustainability. Gland: Secretariat of the Convention on Wetlands. https://www.ramsar.org/sites/default/files/documents/library/bn13_agriculture_e.pdf

Cooperation for International Waters in Africa (2022). Improving Water Quality in Lake Victoria Basin: Sustainable Land and Water Management. Washington: World Bank. https://www.ciwaprogram.org/rcv1/improving-water-quality-in-lake-victoria-basin-sustainable-land-and-water-management/

D'Amato, G., Pawankar, R., Vitale, C., Lanza, M., Molino, A., Stanziola, A. et al. (2016). Climate Change and Air Pollution: Effects on Respiratory Allergy. Allergy, Asthma and Immunology Research 8(5), 391–395. https://doi.org/10.4168/aair.2016.8.5.391

de Coning, C.H. and Krampe, F. (2020). Multilateral cooperation in the area of climate-related security and development risks in Africa. Norwegian Institute of International Affairs. https://www.nupi.no/en/publications/cristin-pub/multilateral-cooperation-in-the-area-of-climate-related-security-and-development-risks-in-africa

De Melo, J. and Solleder, J.M. (2023). The landscape of CO_2 emissions across Africa: A comparative perspective. The World Economy 46(11), 3392-3418. https://doi.org/10.1111/twec.13498

Dimobe, K., Ouédraogo, A., Soma, S., Goetze, D., Porembski, S. and Thiombiano, A. (2015). Identification of driving factors of land degradation and deforestation in the Wildlife Reserve of Bontioli (Burkina Faso, West Africa). Global Ecology and Conservation 4, 559-571. https://dx.doi.org/10.1016/j.gecco.2015.10.006

Dudley, N., Eufemia, L., Fleckenstein, M., Periago, M.E., Petersen, I. and Timmers, J.F. (2020). Grasslands and savannahs in the UN Decade on Ecosystem Restoration. Restoration Ecology 28(6), 1313-1317. https://dx.doi.org/10.1111/rec.13272

Duporge, I., Hodgetts, T., Wang, T. and Macdonald, D.W. (2020). The spatial distribution of illegal hunting of terrestrial mammals in Sub-Saharan Africa: a systematic map. Environmental Evidence 9(1). https://dx.doi.org/10.1186/s13750-020-00195-8

Ekumah, B., Armah, F.A., Afrifa, E.K.A., Aheto, D.W., Odoi, J.O. and Afitiri, A.-R. (2020). Geospatial assessment of ecosystem health of coastal urban wetlands in Ghana. Ocean and Coastal Management 193, 105226. https://dx.doi.org/10.1016/j.ocecoaman.2020.105226

Elagib, N.A., Zayed, I.S.A., Saad, S.A.G., Mahmood, M.I., Basheer, M. and Fink, A.H. (2021). Debilitating floods in the Sahel are becoming frequent. Journal of Hydrology 599, 126362. https://doi.org/10.1016/j.jhydrol.2021.126362

Fassinou, F.J.C., Cesaro, J.-D., Nungi-Pambu, M., Fensholt, R., Brandt, M., Akodewou, A. et al. (2024). Quantifying the impact of Great Green Wall and Corporate plantations on tree density and biomass in Sahelian Senegal. Trees, Forests and People 16, 100569. https://dx.doi.org/10.1016/j.tfp.2024.100569

Fisher, S., Bellinger, D.C., Cropper, M.L., Kumar, P., Binagwaho, A., Koudenoukpo, J.B. et al. (2021). Air pollution and development in Africa: impacts on health, the economy, and human capital. The Lancet Planetary Health 5(10), e681-e688. https://dx.doi.org/10.1016/S2542-5196(21)00201-1

Fitchett, J.M., Grant, B. and Hoogendoorn, G. (2016). Climate change threats to two low-lying South African coastal towns: Risks and perceptions. South African Journal of Science 112(5/6), 9. https://dx.doi.org/10.17159/sajs.2016/20150262

Food and Agriculture Organization of the United Nations (2019). The State of the World's Biodiversity for Food and Agriculture. Bélanger, J. and Pilling, D. (eds.). Rome: FAO Commission on Genetic Resources for Food and Agriculture Assessments. https://www.fao.org/3/CA3129EN/ca3129en.pdf

Food and Agriculture Organization of the United Nations (2020). The State of Food and Agriculture 2020. Overcoming water challenges in agriculture. Rome: FAO. https://doi.org/10.4060/cb1447en

Food and Agriculture Organization of the United Nations (2021). The State of Food and Agriculture 2021. Making agrifood systems more resilient to shocks and stresses. Rome: FAO. https://doi.org/10.4060/cb4476en

Food and Agriculture Organization of the United Nations (2023). Global Information and Early Warning Systems on Food and Agriculture; Country

Brief for The Republic of Tunisia. https://www.fao.org/giews/countrybrief/country.jsp?code=TUN Accessed 1 April 2025

Food and Agriculture Organization of the United Nations, United Nations Economic Commission for Africa and African Union Commission (2021). Africa – Regional Overview of Food Security and Nutrition Accra: Food & Agriculture Org. https://doi.org/10.4060/cb7496en

Garelick, S., Russell, J., Richards, A., Smith, J., Kelly, M., Anderson, N. et al. (2022). The dynamics of warming during the last deglaciation in high-elevation regions of Eastern Equatorial Africa. Quaternary Science Reviews 281, 107416. https://dx.doi.org/10.1016/j.quascirev.2022.107416

Gbohoui, W., Ouedraogo, R. and Some, Y.M. (2023). Sub-Saharan Africa's Risk Perception Premium: In the Search of Missing Factors. Washington: IMF WP. https://www.imf.org/en/Publications/WP/Issues/2023/06/23/Sub-Saharan-Africas-Risk-Perception-Premium-In-the-Search-of-Missing-Factors-534885

Global Center on Adaptation (2022). State and Trends in Adaptation Reports 2021 and 2022: Executive Summaries and Syntheses. https://gca.org/reports/sta22/

Gxokwe, S., Dube, T. and Mazvimavi, D. (2024). An assessment of long-term and large-scale wetlands change dynamics in the Limpopo transboundary river basin using cloud-based Earth observation data. Wetlands Ecology and Management 32(1), 89-108. https://dx.doi.org/10.1007/s11273-023-09963-y

Hahn, K. and Leßmeister, A. (2021). Sustainable use of Savanna Vegetation in West Africa in the Context of Climate and Land use Change. In: Nachhaltige Entwicklung in einer Gesellschaft des Umbruchs. Blättel-Mink, B., Hickler, T., Küster, S. and Becker, H. (eds.). Wiesbaden: Springer VS. 45-64. https://dx.doi.org/10.1007/978-3-658-31466-8_4

High Volume Transport (2019). State of Knowledge Final Report on Long Distance Strategic Road and Rail Transport. https://transport-links.com/hvt-publications/state-of-knowledge-final-report-on-long-distance-strategic-road-and-rail-transport

Hill, M. and Ndlovu, R. (2019). Power-Starved Zimbabwe, Zambia Face Further Drought-Induced Blackouts. https://www.bloomberg.com/news/articles/2019-08-05/power-starved-zimbabwe-zambia-face-further-drought-induced-dark Accessed 11 January 2024

Hinzmann, A., Mölg, T., Braun, M., Cullen, N.J., Hardy, D.R., Kaser, G. et al. (2024). Tropical glacier loss in East Africa: recent areal extents on Kilimanjaro, Mount Kenya, and in the Rwenzori Range from high-resolution remote sensing data. Environmental Research: Climate 3(1), 011003. https://dx.doi.org/10.1088/2752-5295/ad1fd7

Hiropoulos, A. (2020). South Africa, migration and xenophobia. Deconstructing the perceived migration crisis and its influence on the xenophobic reception of migrants. Contemporary Justice Review 23(1), 104-121. https://dx.doi.org/10.1080/10282580.2019.1700368

Huang, B., Liu, C., Banzon, V., Freeman, E., Graham, G., Hankins, B. et al. (2021). Improvements of the Daily Optimum Interpolation Sea Surface Temperature (DOISST) Version 2.1. Journal of Climate 34(8), 2923-2939. https://dx.doi.org/10.1175/JCLI-D-20-0166.1.

Integrated African Health Observatory (2024). Climate change is impacting health in Africa. Analytical Fact Sheet. https://files.aho.afro.who.int/afahobckpcontainer/production/files/iAHO_Climate_change_in_health_Fact_Sheet-April_2024.pdf

Intergovernmental Panel on Climate Change (2019). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C. et al. (eds.). Geneva: IPCC. https://www.ipcc.ch/srccl/

Intergovernmental Panel on Climate Change (2022a). Fact sheet - Food and Water. Climate Change Impacts and Risks. https://www.ipcc.ch/report/ar6/wg2/downloads/outreach/IPCC_AR6_WGII_FactSheet_FoodAndWater.pdf

Intergovernmental Panel on Climate Change (2022b). Factsheet - Africa. Climate Change Impacts and Risks. https://www.ipcc.ch/report/ar6/wg2/downloads/outreach/IPCC_AR6_WGII_FactSheet_Africa.pdf

Intergovernmental Panel on Climate Change (2022c). Changing Ocean, Marine Ecosystems, and Dependent Communities. In: The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. 447-588. https://doi.org/10.1017/9781009157964.007

Intergovernmental Panel on Climate Change (2022d). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Pörtner, H.O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A. et al. (eds.). Cambridge and New York: IPCC. https://dx.doi.org/10.1017/9781009325844

Intergovernmental Panel on Climate Change (2023). Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Lee, H. and Romero, J. (eds.). Geneva: IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647.001

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2018). The IPBES regional assessment report on biodiversity and ecosystem services for Africa. Archer, E., Dziba, L., Mulongoy, K.J., Maoela, M.A. and Walters, M. (eds.). Bonn: Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://doi.org/10.5281/zenodo.3236177

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn: Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://files.ipbes.net/ipbes-web-prod-public-files/inline/files/ipbes_global_assessment_report_summary_for_policymakers.pdf

Internal Displacement Monitoring Centre (2019). Africa Report on Internal Displacement. Geneva: IDMC. https://api.internal-displacement.org/sites/default/files/publications/documents/201912-Africa-report.pdf

International Energy Agency (2019). Africa Energy Outlook. World Energy Outlook series. https://www.iea.org/reports/world-energy-outlook-2019.

International Energy Agency (2020). World Energy Outlook. Paris: IEA. https://www.iea.org/reports/world-energy-outlook-2020

International Energy Agency (2022). World Energy Outlook 2022. Paris: IEA. https://www.iea.org/reports/world-energy-outlook-2022

International Monetary Fund (2020). Adapting to Climate Change in Sub-Saharan Africa. In: Sub-Saharan Africa Regional Economic Outlook (REO). Chapter 2. https://www.imf.org/en/-/media/files/publications/reo/afr/2020/april/english/ch2.pdf

International Union for Conservation of Nature (2023). The IUCN Red List of Threatened Species. https://www.iucnredlist.org

Ite, A.E., Ibok, U.J., Ite, M.U. and Petters, S.W. (2013). Petroleum exploration and production: Past and present environmental issues in the Nigeria's Niger Delta. American Journal of Environmental Protection 1(4), 78-90. https://pubs.sciepub.com/env/1/4/2/index.html

Jackson, M.S., Kelly, M.A., Russell, J.M., Doughty, A.M., Howley, J.A., Chipman, J.W. et al. (2020). Glacial fluctuations in tropical Africa during the last glacial termination and implications for tropical climate following the Last Glacial Maximum. Quaternary Science Reviews 243, 106455. https://dx.doi.org/10.1016/j.quascirev.2020.106455

James, C. and Zeufack, A. (2023). Africa's Resource Future: Harnessing Natural Resources for Economic Transformation during the Low-Carbon Transition. Washington: Africa Development Forum. https://dx.doi.org/doi:10.1596/978-1-4648-1743-4

Jones, E.R., Bierkens, M.F.P., Van Puijenbroek, P.J.T.M., Van Beek, L.P.H., Wanders, N., Sutanudjaja, E.H. et al. (2023). Sub-Saharan Africa will increasingly become the dominant hotspot of surface water pollution. Nature Water 1(7), 602-613. https://dx.doi.org/10.1038/s44221-023-00105-5.

Kalele, D.N., Ogara, W.O., Oludhe, C. and Onono, J.O. (2021). Climate change impacts and relevance of smallholder farmers' response in arid and semi-arid lands in Kenya. Scientific African 12, e00814. https://dx.doi.org/10.1016/j.sciaf.2021.e00814

Kirenga, B., Meng, Q., Van Gemert, F., Aanyu-Tukamuhebwa, H., Chavannes, N., Katamba, A. et al. (2015). The State of Ambient Air Quality in Two Ugandan Cities: A Pilot Cross-Sectional Spatial Assessment. International Journal of Environmental Research and Public Health 12(7), 8075-8091. https://dx.doi.org/10.3390/ijerph120708075

Kogo, B.K., Kumar, L. and Koech, R. (2021). Climate change and variability in Kenya: a review of impacts on agriculture and food security. Environment, Development and Sustainability 23(1), 23-43. https://dx.doi.org/10.1007/s10668-020-00589-1

Kossin, J.P., Knapp, K.R., Olander, T.L. and Velden, C.S. (2020). Global increase in major tropical cyclone exceedance probability over the past four decades. Proceedings of the National Academy of Sciences 117(22), 11975-11980. https://dx.doi.org/10.1073/pnas.1920849117

Kunda, J.J., Gosling, S.N. and Foody, G.M. (2024). The effects of extreme heat on human health in tropical Africa. International Journal of Biometeorology 68(6), 1015-1033. https://dx.doi.org/10.1007/s00484-024-02650-4

Laker, M.C. (2023). Environmental Impacts of Gold Mining—With Special Reference to South Africa. Mining 3(2), 205-220. https://dx.doi.org/10.3390/mining3020012

Leisher, C., Robinson, N., Brown, M., Kujirakwinja, D., Schmitz, M.C., Wieland, M. et al. (2022). Ranking the direct threats to biodiversity in sub-Saharan Africa. Biodiversity and Conservation 31, 1329-1343. https://dx.doi.org/10.1007/s10531-022-02394-w

Lemrabott, S.Y., Van Leeuwen, A., Piersma, T., Braham, C.-B., Ball, A.C., Araujo, A. et al. (2024). The chronology of overfishing in a remote West-African coastal ecosystem. Ecology and Society 29(1). https://dx.doi.org/10.5751/ES-13902-290109

Liu, C., Shi, R.X., Zhang, Y.H., Shen, Y., Ma, J.H., Wu, L.Z. et al. (2019). Land Areas, and How Long of Shorelines in the World?—Vector Data Based on Google Earth Images. Journal of Global Change Data and Discovery 3(2), 124-148. https://doi.org/10.3974/geodp.2019.02.03

Lunstrum, E. and Givá, N. (2020). What drives commercial poaching? From poverty to economic inequality. Biological Conservation 245, 108505. https://dx.doi.org/10.1016/j.biocon.2020.108505

MacAlister, C., Baggio, G., Perera, D., Qadir, M., Taing, L. and Smakhtin, V. (2023). Global Water Security 2023 Assessment. Hamilton: United Nations and University Institute for Water, Environment and Health. https://collections.unu.edu/eserv/UNU:9107/n23-116_UNU_Water_Security_WEB_Final_updated.pdf

Mafaranga, H. (2020). Sea level rise may erode development in Africa. https://doi.org/10.1029/2020EO151568 Accessed 28 April 2025

Makgoba, L., Abrams, A., Röösli, M., Cissé, G. and Dalvie, M.A. (2024). DDT contamination in water resources of some African countries and its impact on water quality and human health. Heliyon 10(7), e28054. https://dx.doi.org/10.1016/j.heliyon.2024.e28054

Malherbe, J., Engelbrecht, F.A. and Landman, W.A. (2013). Projected changes in tropical cyclone climatology and landfall in the Southwest Indian Ocean region under enhanced anthropogenic forcing. Climate Dynamics 40(11-12), 2867-2886. https://dx.doi.org/10.1007/s00382-012-1635-2

Mamabolo, M.A. (2015). Drivers of community xenophobic attacks in South Africa: poverty and unemployment. The Journal for Transdisciplinary Research in Southern Africa 11(4), 8. https://dx.doi.org/10.4102/td.v11i4.49

Manes, S., Costello, M.J., Beckett, H., Debnath, A., Devenish-Nelson, E., Grey, K.-A. et al. (2021). Endemism increases species' climate change risk in areas of global biodiversity importance. Biological Conservation 257, 109070. https://dx.doi.org/10.1016/j.biocon.2021.109070

Mansourian, S. and Berrahmouni, N. (2021). Review of forest and landscape restoration in Africa. Accra: FAO and AUDA-NEPAD. https://doi.org/10.4060/cb6111en

Masindi, V. and Foteinis, S. (2021). Groundwater contamination in sub-Saharan Africa: Implications for groundwater protection in developing countries. Cleaner Engineering and Technology 2, 100038. https://dx.doi.org/10.1016/j.clet.2020.100038

Mastrorillo, M., Licker, R., Bohra-Mishra, P., Fagiolo, G., D. Estes, L. and Oppenheimer, M. (2016). The influence of climate variability on internal migration flows in South Africa. Global Environmental Change 39, 155-169. https://dx.doi.org/10.1016/j.gloenvcha.2016.04.014

Mbow, C., Rosenzweig, C., Barioni, L.G., Benton, T.G., Herrero, M., Krishnapillai, M. et al. (2019). Food Security. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C. et al. (eds.). https://www.ipcc.ch/site/assets/uploads/2019/11/08_Chapter-5.pdf

Mead, M.I., Okello, G., Mbandi, A.M. and Pope, F.D. (2023). Spotlight on air pollution in Africa. Nature Geoscience 16(11), 930-931. https://dx.doi.org/10.1038/s41561-023-01311-2

Merceron, T., Clément, T., Gabrié, C., Staub, F., Ba, T. and Traore, M.S. (2024). State of West African marine protected areas 2022. Gland: IUCN. https://doi.org/10.2305/BXRM8651

Mlambo, C., Ngonisa, P., Ntshangase, B., Ndlovu, N. and Mvuyana, B. (2023). Air Pollution and Health in Africa: The Burden Falls on Children. Economies 11(7), 196. https://dx.doi.org/10.3390/economies11070196

Mokwakwa, N. (2021). Corporate Social Responsibility in a Diamond-Mining Company in Botswana. In: Corporate Citizenship. Business and Society in Botswana. Springer International Publishing. 227-254. https://dx.doi.org/10.1007/978-3-030-67766-4_7

Morsy, K.M., Mishra, A.K. and Galal, M.M. (2020). Water Quality Assessment of the Nile Delta Lagoons. Air, Soil and Water Research 13, 117862212096307. https://dx.doi.org/10.1177/1178622120963072

Mostefaoui, M., Ciais, P., McGrath, M.J., Peylin, P., Patra, P.K. and Ernst, Y. (2024). Greenhouse gas emissions and their trends over the last 3 decades across Africa. Earth System Science Data 16(1), 245-275. https://doi.org/10.5194/essd-16-245-2024

Moustahfid, H., Marsac, F. and Gangopadhyay, A. (2017). Climate change impacts, vulnerabilities and adaptations: Western Indian Ocean marine fisheries. In: Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. Barange, M., Bahri, T., Beveridge, M.C.M., Cochrane, K.L., Funge-Smith, S. and Poulain, F. (eds.). Rome: FAO Fisheries and Aquaculture. 251. http://www.fao.org/3/i9705en/I9705EN.pdf

Mozer, A. and Prost, S. (2023). An introduction to illegal wildlife trade and its effects on biodiversity and society. Forensic Science International: Animals and Environments 3, 100064. https://dx.doi.org/10.1016/j.fsiae.2023.100064

Muthige, M.S., Malherbe, J., Englebrecht, F.A., Grab, S., Beraki, A., Maisha, T.R. et al. (2018). Projected changes in tropical cyclones over the South West Indian Ocean under different extents of global warming. Environmental Research Letters 13(6), 065019. https://dx.doi.org/10.1088/1748-9326/aabc60

Naidu, R., Biswas, B., Willett, I.R., Cribb, J., Kumar Singh, B., Paul Nathanail, C. et al. (2021). Chemical pollution: A growing peril and potential catastrophic risk to humanity. Environment International 156, 106616. https://www.sciencedirect.com/science/article/pii/S0160412021002415?via%3Dihub

Nakweya, G. (2022). Rising air pollution in African cities. Nature Africa. https://dx.doi.org/10.1038/d44148-022-00053-4

Nhantumbo, B.J., Dada, O.A. and Ghomsi, F.E. (2023). Sea Level Rise and Climate Change - Impacts on African Coastal Systems and Cities. IntechOpen. https://dx.doi.org/10.5772/intechopen.113083

Nguyen, T.T., Grote, U., Neubacher, F., Rahut, D.B., Do, M.H. and Paudel, G.P. (2023). Security risks from climate change and environmental degradation: implications for sustainable land use transformation in the Global South. Current Opinion in Environmental Sustainability 63, 101322. https://doi.org/10.1016/j.cosust.2023.101322

Nolte, K., Sipangule, K. and Wendt, N. (2022). Agricultural households in times of crisis. The COVID-19 pandemic, livelihoods and land-use decisions. Journal of Land Use Science 17(1), 134-160. https://dx.doi.org/10.1080/1747423X.2021.2020922

Nyahunda, L., Makhubele, J.C., Mabvurira, V. and Matlakala, F.K. (2021). Vulnerabilities and Inequalities Experienced by Women in the Climate Change Discourse in South Africa's Rural Communities: Implications for Social Work. The British Journal of Social Work 51(7), 2536-2553. https://dx.doi.org/10.1093/bjsw/bcaa118

Nyamweya, C.S., Natugonza, V., Taabu-Munyaho, A., Aura, C.M., Njiru, J.M., Ongore, C. et al. (2020). A century of drastic change: Human-induced changes of Lake Victoria fisheries and ecology. Fisheries Research 230, 105564. https://dx.doi.org/10.1016/j.fishres.2020.105564

Obahoundje, S. and Diedhiou, A. (2022). Potential impacts of climate, land use and land cover changes on hydropower generation in West Africa:

a review. Environmental Research Letters 17(4), 043005. https://dx.doi.org/10.1088/1748-9326/ac5b3b

Olsson, L.H., Barbosa, S., Bhadwal, A., Cowie, K., Delusca, D., Flores-Renteria, K.H. et al. (2019). Land degradation. In: Climate Change and Land: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C. et al. (eds.). Cambridge: Cambridge University Press. 345-436. https://www.cambridge.org/core/product/47C1BEABC8A0A7C4E08B5AB6DD4C20CE

Otto, F., Minnerop, P., Raju, E., Harrington, L., Stuart-Smith, R., Boyd, E. et al. (2022). Causality and the fate of climate litigation: The role of the social superstructure narrative. Global Policy 13, 736-750. https://dx.doi.org/10.1111/1758-5899.13113

Owonikoko, S.B. and Momodu, J.A. (2020). Environmental degradation, livelihood, and the stability of Chad Basin Region. Small Wars and Insurgencies 31(6), 1295-1322. https://dx.doi.org/10.1080/09592318.2020.1776092

Pecl, G.T., Araújo, M.B., Bell, J.D., Blanchard, J., Bonebrake, T.C., Chen, I.C. et al. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. Science 355(6332), eaai9214. https://dx.doi.org/10.1126/science.aai9214

Ragavan, M.I., Culyba, A.J., Muhammad, F.L. and Miller, E. (2020). Supporting Adolescents and Young Adults Exposed to or Experiencing Violence During the COVID-19 Pandemic. Journal of Adolescent Health 67(1), 18-20. https://dx.doi.org/10.1016/j.jadohealth.2020.04.011

Ranasinghe, R., Ruane, A.C., Vautard, R., Arnell, N., Coppola, E., Cruz, F.A. et al. (2021). Climate Change Information for Regional Impact and for Risk Assessment. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (eds.). Cambridge and New York: Cambridge University Press. 1767–1926. https://dx.doi.org/10.1017/9781009157896.014

Ransom, C. (2022). From droughts to loss of glaciers: Here's the state of African climate ahead of COP27. https://www.weforum.org/agenda/2022/11/water-worries-the-state-of-the-african-climate-ahead-of-cop27/

Richardson, K., Calow, R., Pichon, F., New, S. and Osborne, R. (2022). Climate risk report for the East Africa region. https://www.metoffice.gov.uk/services/government/international-development/east-africa-climate-risk-report

Rocha-Santos, L., Mayfield, M.M., Lopes, A.V., Pessoa, M.S., Talora, D.C., Faria, D. et al. (2020). The loss of functional diversity: A detrimental influence of landscape-scale deforestation on tree reproductive traits. Journal of Ecology 108(1), 212-223. https://dx.doi.org/10.1111/1365-2745.13232

Sadan, Z. and De Kock, L. (2021). Plastic Pollution in Africa: Identifying policy gaps and opportunities. Cape Town: WWF South Africa. https://www.wwf.org.za/our_research/publications/?38342/plastic-pollution-in-africa

Sam, K., Zabbey, N., Gbaa, N.D., Ezurike, J.C. and Okoro, C.M. (2023). Towards a framework for mangrove restoration and conservation in Nigeria. Regional Studies in Marine Science 66, 103154. https://dx.doi.org/10.1016/j.rsma.2023.103154

Sam, K. and Zibima, T. (2023). Inclusive Environmental Decision-making in a Developing Nation: Insights from the Ogoni Remediation Project, Niger Delta, Nigeria. Environmental Management 73, 323-337. https://dx.doi.org/10.1007/s00267-023-01885-y

Sami, S.I.S.S. and Taiwo, M. (2023). Effect of Crude Oil Prices and Production on the Performance of Nigerian Gross Domestic Product: A Conceptual Framework. Journal of Human Resource and Sustainability Studies 11(03), 698-711. https://dx.doi.org/10.4236/jhrss.2023.113038

Samuel, O.O. and Sylvia, T.S. (2019). Establishing the nexus between climate change adaptation strategy and smallholder farmers' food security status in South Africa: A bi-casual effect using instrumental variable approach. Cogent Social Sciences 5(1), 1656402. https://dx.doi.org/10.1080/23311886.2019.1656402

Scheiter, S., Moncrieff, G.R., Pfeiffer, M. and Higgins, S.I. (2020). African biomes are most sensitive to changes in CO_2 under recent and near-future CO_2 conditions. Biogeosciences 17(4), 1147-1167. https://dx.doi.org/10.5194/bg-17-1147-2020

Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A. et al. (2021). Weather and Climate Extreme Events in a Changing Climate. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (eds.). Cambridge and New York: Cambridge University Press. 1513-1766. https://dx.doi.org/10.1017/9781009157896.013

Sintayehu, D.W. (2018). Impact of climate change on biodiversity and associated key ecosystem services in Africa: a systematic review. Ecosystem Health and Sustainability 4(9), 225-239. https://dx.doi.org/10.1080/20964129.2018.1530054

Spalding-Fecher, R., Joyce, B. and Winkler, H. (2017). Climate change and hydropower in the Southern African Power Pool and Zambezi River Basin: System-wide impacts and policy implications. Energy Policy 103, 84-97. https://dx.doi.org/10.1016/j.enpol.2016.12.009

Sylla, M.B., Pal, J.S., Faye, A., Dimobe, K. and Kunstmann, H. (2018). Climate change to severely impact West African basin scale irrigation in 2 °C and 1.5 °C global warming scenarios. Scientific Reports 8(1), 14395. https://doi.org/10.1038/s41598-018-32736-0

Tall, A., Dampha, N.K., Ndayiragije, N., Von Berg, M., Raina, L. and Manirambona, A. (2022). Tackling Climate Change, Land Degradation and Fragility – Diagnosing Drivers of Climate and Environmental Fragility in Burundi's Colline Landscapes: Towards a Multi-Sector Investment Plan to Scale up Climate Resilience. Washington: The World Bank, International Bank for Reconstruction and Development. http://documents1.worldbank.org/curated/en/099930006302237433/pdf/P17682007885e00780b1cc093a09277df1a.pdf.

Tibane, L.V. and Mamba, D. (2022). Ecological risk of trace metals in soil from gold mining region in South Africa. Journal of Hazardous Materials Advances 7, 100118. https://dx.doi.org/10.1016/j.hazadv.2022.100118

Trisos, C.H., Adelekan, I.O., Totin, E., Ayanlade, A., Efitre, J., Gemeda, A. et al. (2022). Africa. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A. (eds.). Cambridge and New York: Cambridge University Press. 1285–1455. https://www.ipcc.ch/report/ar6/wg2/chapter/chapter-9/

Tuholske, C., Caylor, K., Funk, C., Verdin, A., Sweeney, S., Grace, K. et al. (2021). Global urban population exposure to extreme heat. Proceedings of the National Academy of Sciences 118(41), e2024792118. https://doi.org/10.1073/pnas.2024792118

Turner, R.E. and Ohimain, E.I. (2024). Dredged Canals, Wetland Loss, and Legacy. Estuaries and Coasts 47(8), 2147-2159. https://dx.doi.org/10.1007/s12237-024-01427-7

Tyukavina, A., Hansen, M.C., Potapov, P., Parker, D., Okpa, C., Stehman, S.V. et al. (2018). Congo Basin Forest loss dominated by increasing smallholder clearing. Science Advances 4(11), eaat2993. https://dx.doi.org/10.1126/sciadv.aat2993

Udinmade Ighedosa, S. (2019). Climate Change: Vulnerability of the Niger Delta Region, in Nigeria. International Journal of Environment and Climate Change 764-788. https://dx.doi.org/10.9734/ijecc/2019/v9i1230156

United Nations Conference on Trade and Development (2023). Economic Development in Africa Report 2023: The Potential of Africa to Capture Technology-Intensive Global Supply Chains. https://unctad.org/system/files/official-document/aldcafrica2023_en.pdf

United Nations Convention to Combat Desertification (2020). The Great Green Wall: Implementation Status and Way Ahead to 2030 (Advanced Version). https://www.unccd.int/resources/publications/great-green-wall-implementation-status-and-way-ahead-2030

United Nations Department of Economic and Social Affairs Population Division (2024). World Population Prospects 2024: Summary of Results. https://desapublications.un.org/publications/world-population-prospects-2024-summary-results

United Nations Environment Programme (2016). GEO-6 regional assessment for Africa: Factsheet. https://wedocs.unep.org/bitstream/handle/20.500.11822/7595/geo_6_africa_factsheet_revised_version_061016.pdf?sequence=5

United Nations Environment Programme (2021). Making Peace with Nature: A Scientific Blueprint to Tackle the Climate Change, Biodiversity and Pollution

Emergencies. Nairobi: UNEP. https://www.unep.org/resources/making-peace-nature

United Nations Environment Programme (2022). Freshwater Strategic Priorities 2022–2025 to Implement UNEP's Medium-Term Strategy. Nairobi: UNEP. https://wedocs.unep.org/20.500.11822/39607

United Nations Office for the Coordination of Humanitarian Affairs (2020). South Sudan: Flooding Snapshot. https://reliefweb.int/report/south-sudan/south-sudan-flooding-snapshot-21-october-2020

Vanlauwe, B., Descheemaeker, K., Giller, K.E., Huising, J., Merckx, R., Nziguheba, G. et al. (2015). Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. SOIL 1(1), 491-508. https://dx.doi.org/10.5194/soil-1-491-2015

Vousdoukas, M.I., Clarke, J., Ranasinghe, R., Reimann, L., Khalaf, N., Duong, T.M. et al. (2022). African heritage sites threatened as sea-level rise accelerates. Nature Climate Change 12(3), 256-262. https://dx.doi.org/10.1038/s41558-022-01280-1

Wei, F., Wang, S., Brandt, M., Fu, B., Meadows, M.E., Wang, L. et al. (2021). Responses and feedbacks of African dryland ecosystems to environmental changes. Current Opinion in Environmental Sustainability 48, 29-35. https://doi.org/10.1016/j.cosust.2020.09.004

Wekesa, C., Ndufa, J.K. and Tuwei, P. (2023). Mangrove Deaths in Kenya: Causes and Recommended Management Interventions. Muguga: KEFRI. https://kefri.org/assets/publications/tech/MangrovedeathinKenya.pdf

Williams, B.A., Watson, J.E.M., Beyer, H.L., Grantham, H.S., Simmonds, J.S., Alvarez, S.J. et al. (2022). Global drivers of change across tropical savannah ecosystems and insights into their management and conservation. Biological Conservation 276, 109786. https://dx.doi.org/10.1016/j.biocon.2022.109786

Wineman, A., Jayne, T.S. and Stevens, C. (2021). The relationship between medium-scale farms and deforestation in Sub-Saharan Africa. A United States Agency for International Development (USAID) Paper on the relationship between medium-scale farms and deforestation in Sub-Saharan Africa. https://www.researchgate.net/publication/359480007_The_Relationship_Between_Medium-Scale_Farms_and_Deforestation_in_Sub-Saharan_Africa_A_Concept_Note

World Bank (2017). Enhancing the climate resilience of Africa's infrastructure: The roads and bridges sector. Cervigni, R., Losos, A., Chinowsky, P. and Neumann, J.E. (eds.). Africa Development Forum series. Washington: World Bank. https://documents.worldbank.org/curated/en/270671478809724744/pdf/110137-WP-PUBLIC-ECRAI-Transport-CLEAN-WEB.pdf. https://doi.org/10.1596/978-1-4648-0466-3

World Bank (2021). The Natural Resource Degradation and Vulnerability Nexus: An Evaluation of the World Bank's Support for Sustainable and Inclusive Natural Resource Management (2009–19). Washington: World Bank: Independent Evaluation Group. https://ieg.worldbankgroup.org/evaluations/natural-resource-degradation-and-vulnerability-nexus

World Bank (2022). Coastal and marine biodiversity and ecosystems: Blue Economy for Resilient Africa Program. Washington: The World Bank Group. https://thedocs.worldbank.org/en/doc/a0053a27595217fd04745ae65f88e092-0320012022/original/Coastal-and-Marine-Biodiversity-and-Ecosystems.pdf

World Health Organization (2023a). Regional data and trends briefing kit: World malaria report 2023. https://cdn.who.int/media/docs/default-source/malaria/world-malaria-reports/world-malaria-report-2023-regional-briefing-kit-eng.pdf?sfvrsn=299150e7_15&download=true

World Health Organization Regional Office for Africa (2023b). Cholera in the WHO African Region: Cholera situation bulletin: Regional update for week 21. https://iris.who.int/bitstream/handle/10665/372036/AFRO%20Cholera%20Bulletin.21_Final.pdf Accessed 1 April 2025

World Health Organization (2023c). Dengue in the WHO African Region. Consolidated Regional Situation Report. https://www.afro.who.int/countries/burkina-faso/publication/dengue-who-african-region-situation-report-01-19-december-2023

World Meteorological Organization (2021). State of the Climate in Africa 2021. Addis Ababa: WMO Regional Office for Africa. https://www.uneca.org/sites/default/files/ACPC/2022/CCAD-X/Presentations/State%20of%20the%20Climate%20in%20Africa%202021_0.pdf

World Meteorological Organization (2022). State of the Global Climate 2021. Geneva: WMO. https://library.wmo.int/viewer/56300/download?file=1290_Statement_2021_en.pdf&type=pdf&navigator=1

World Meteorological Organization (2023). State of the Global Climate 2022. Geneva: WMO. https://library.wmo.int/viewer/66214/download?file=Statement_2022.pdf&type=pdf&navigator=1

World Wide Fund for Nature (2024). Living Planet Report 2024 – A System in Peril. Gland: WWF. https://www.worldwildlife.org/publications/2024-living-planet-report

Wudil, A.H., Usman, M., Rosak-Szyrocka, J., Pilař, L. and Boye, M. (2022). Reversing Years for Global Food Security: A Review of the Food Security Situation in Sub-Saharan Africa (SSA). International Journal of Environmental Research and Public Health 19(22), 14836. https://dx.doi.org/10.3390/ijerph192214836

Yilmaz, H. and Njora, B. (2021). Analysis of The Impact of Agricultural Policies on Food Security in Kenya. Eurasian Journal of Agricultural Research 5(2), 66-83. https://dergipark.org.tr/en/pub/ejar/issue/66343/959656

Zamboni, N.S., Noleto Filho, E.M. and Carvalho, A.R. (2021). Unfolding differences in the distribution of coastal marine ecosystem services values among developed and developing countries. Ecological Economics 189, 107151. https://dx.doi.org/10.1016/j.ecolecon.2021.107151

Zeufack, A.G., Calderon, C., Kubota, M., Korman, V., Cantu, C.C. and Kabundi, A.N. (2021). An Analysis of Issues Shaping Africa's Economic Future. Africa's Pulse. Washington: World Bank. http://hdl.handle.net/10986/36332

Zhao, S., Cook, K.H. and Vizy, E.K. (2023). How shrinkage of Lake Chad affects the local climate. Climate Dynamics 61(1-2), 595-619. https://dx.doi.org/10.1007/s00382-022-06597-3

Asia and the Pacific

AFoCo (2023). Sustaining an Abudance of Forest Ecosystems (SAFE). AFoCo/041/2023. https://afocosec.org/project/041/

AFoCo (n.d.). Areas of Work. https://afocosec.org/programs-projects/areas-of-work/

Ahmad, QuA., Moors, E., Biemans, H. et al. (2023). Climate-induced shifts in irrigation water demand and supply during sensitive crop growth phases in South Asia. Climatic Change 176, 150. https://doi.org/10.1007/s10584-023-03629-7

Ahmed, F., Ali, I., Kousar, S. and Ahmed, S. (2022). The environmental impact of industrialization and foreign direct investment: empirical evidence from Asia and the Pacific region. Environmental Science and Pollution Research 29(20), 29778-29792. https://doi.org/10.1007/s11356-021-17560-w

Ajiang, C., Pengli, C., Yajuan, L., Holdaway, J. and Wuyi, W. (2020). Chinese "Cancer Villages": Rural Development, Environmental Change and Public Health. Amsterdam University Press. https://doi.org/10.2307/j.ctv15vwk8t

Ajilogba, C.F. and Walker, S. (2021). Climate Change Adaptation: Implications for Food Security and Nutrition. In: African Handbook of Climate Change Adaptation. Oguge, N., Ayal, D., Adeleke, L. and da Silva, I. (eds.). Springer, Cham. https://doi.org/10.1007/978-3-030-45106-6_142

Alavaisha, E., Mbande, V., Börjeson, L. and Lindborg, R. (2021). Effects of Land Use Change Related to Small-Scale Irrigation Schemes in Kilombero Wetland, Tanzania. Frontiers in Environmental Science 9. https://doi.org/10.3389/fenvs.2021.611686

Agamuthu, P. and Babel, S. (2023). Waste management developments in the last five decades: Asian perspective. Waste Management and Research 41(12), 1699-1716. https://doi.org/10.1177/0734242X231199938

Aryan, Y., Pon, T., Panneerselvam, B. and Dikshit, A.K. (2023). A comprehensive review of human health risks of arsenic and fluoride contamination of groundwater in the South Asia region. Journal of Water and Health 22(2), 235-267. https://doi.org/10.2166/wh.2023.082

Berger, T., Chundeli, F.A., Pandey, R.U., Jain, M., Tarafdar, A.K. and Ramamurthy, A. (2022). Low-income residents' strategies to cope with urban heat. Land Use Policy 119, 106192. https://doi.org/10.1016/j.landusepol.2022.106192

Bhattarai, N., Lobell, D.B., Fishman, R., Kustas, W.P., Pokhrel, Y. and Jain, M. (2023). Warming temperatures exacerbate groundwater depletion rates in

India. Science Advances 9(35), eadi1401. https://doi.org/10.1126/sciadv.adi1401

Cabernard, L., Pfister, S., Oberschelp, C. and Hellweg, S. (2022). Growing environmental footprint of plastics driven by coal combustion. Nature Sustainability 5, 139–148. https://doi.org/10.1038/s41893-021-00807-2

Cao, A., Esteban, M., Valenzuela, V.P.B., Onuki, M., Takagi, H., Thao, N.D. et al. (2021). Future of Asian Deltaic Megacities under sea level rise and land subsidence: current adaptation pathways for Tokyo, Jakarta, Manila, and Ho Chi Minh City. Current Opinion in Environmental Sustainability 50, 87-97. https://doi.org/10.1016/j.cosust.2021.02.010

Citaristi, I. (2022). The Europa Directory of International Organizations 2022. London: Routledge. 453-457. https://doi.org/10.4324/9781003292548

Climate and Clean Air Coalition (2019). Air Pollution in Asia and the Pacific: Science-based solutions. https://www.ccacoalition.org/content/air-pollution-measures-asia-and-pacific

Cheema, M.A., Hanif, M., Albalawi, O., Mahmoud, E. and Nabi, M. (2024). Evaluating water-related health risks in East and Central Asian Islamic Nations using predictive models (2020–2030). Scientific Reports 14, 16837. https://doi.org/10.1038/s41598-024-67775-3

Chu, X., Wang, Q. and Su, C. (2023). Indoor air pollution: An important risk factor for lung cancer among Asian women without a history of smoking. Chinese Medical Journal Pulmonary and Critical Care Medicine 1(4), 198-199. https://doi.org/10.1016/j.pccm.2023.10.002

Convention on Wetlands (2021). Global Wetland Outlook. https://www.global-wetland-outlook.ramsar.org/

Curren, E. and Leong, S.C.Y. (2019). Profiles of bacterial assemblages from microplastics of tropical coastal environments. Science of The Total Environment 655,313-320. https://doi.org/10.1016/j.scitotenv.2018.11.250

Dangar, S., Asoka, A. and Mishra, V. (2021). Causes and implications of groundwater depletion in India: A review. Journal of Hydrology 596, 126103. https://doi.org/10.1016/j.jhydrol.2021.126103

Dewan, C. and Sibilia, E.A. (2023). Introduction to special issue: "Scaled ethnographies of toxic flows". Environment and Planning C: Politics and Space 42(1), 5-12. https://doi.org/10.1177/23996544231218826

Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Agard, J., Arneth, A. et al. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. Science 366(6471), eaax3100. https://doi.org/10.1126/science.aax3100

Daout, S., Dini, B., Haeberli, W., Doin, M.-P. and Parsons, B. (2020). Ice loss in the Northeastern Tibetan Plateau permafrost as seen by 16 yr of ESA SAR missions. Earth and Planetary Science Letters 545, 116404. https://doi.org/10.1016/j.epsl.2020.116404

Ducusin, R.J.C., Espaldon, M.V.O., Rebancos, C.M. and De Guzman, L.E.P. (2019). Vulnerability assessment of climate change impacts on a Globally Important Agricultural Heritage System (GIAHS) in the Philippines: the case of Batad Rice Terraces, Banaue, Ifugao, Philippines. Climatic Change 153(3), 395-421. https://doi.org/10.1007/s10584-019-02397-7

Duncan, J.M.A., Haworth, B., Boruff, B., Wales, N., Biggs, E.M. and Bruce, E. (2020). Managing multifunctional landscapes: Local insights from a Pacific Island Country context. Journal of Environmental Management 260, 109692. https://doi.org/10.1016/j.jenvman.2019.109692

United Nations Economic and Social Commission for Asia and the Pacific (2018). Inequality in Asia and the Pacific in the era of the 2030 agenda for sustainable development. https://www.unescap.org/publications/inequality-asia-and-pacific-era-2030-agenda-sustainable-development

United Nations Economic and Social Commission for Asia and the Pacific (2022a). SDG 15: Life on land. https://www.unescap.org/sites/default/d8files/event-documents/SDG%2015%20Profile.pdf

United Nations Economic and Social Commission for Asia and the Pacific (2022b). 2022 Review of Climate Ambition in Asia and the Pacific: Raising NDC targets with enhanced nature-based solutions. https://hdl.handle.net/20.500.12870/5085

United Nations Economic and Social Commission for Asia and the Pacific (2023). Seizing the moment: targeting transformative disaster risk resilience. https://hdl.handle.net/20.500.12870/6258

Fan, X., Chen, X., Chen, T., Liu, X., Song, Y., Tan, S. et al. (2023). Effects of substituting synthetic nitrogen with organic amendments on crop yield, net greenhouse gas emissions and carbon footprint: A global meta-analysis. Field Crops Research 301, 109035. https://doi.org/10.1016/j.fcr.2023.109035

Feng, Z., Xu, Y., Kobayashi, K., Dai, L., Zhang, T., Agathokleous, E. et al. (2022). Ozone pollution threatens the production of major staple crops in East Asia. Nature Food 3(1), 47-56. https://doi.org/10.1038/s43016-021-00422-6

Food and Agriculture Organization of the United Nations and United Nations Environment Programme (2021). Global assessment of soil pollution. https://www.fao.org/documents/card/en/c/cb4894en

Food and Agriculture Organization of the United Nations (2024). Overview of the Asia and the Pacific Region. https://www.fao.org/3/W4388E/w4388e03.htm

Fluet-Chouinard, E., Stocker, B.D., Zhang, Z., Malhotra, A., Melton, J.R., Poulter, B. et al. (2023). Extensive global wetland loss over the past three centuries. Nature 614(7947), 281-286. https://doi.org/10.1038/s41586-022-05572-6

Hanna, N., Tamhankar, A.J. and Stålsby Lundborg, C. (2023). Antibiotic concentrations and antibiotic resistance in aquatic environments of the WHO Western Pacific and South-East Asia regions: a systematic review and probabilistic environmental hazard assessment. Lancet Planet Health 7(1), e45-e54. https://doi.org/10.1016/s2542-5196(22)00254-6

Huang, Z., Yuan, X., Sun, S., Leng, G. and Tang, Q. (2023). Groundwater Depletion Rate Over China During 1965–2016: The Long-Term Trend and Inter-annual Variation. Journal of Geophysical Research: Atmospheres 128(11), e2022JD038109. https://doi.org/10.1029/2022JD038109

International Federation of the Red Cross and United Nations Office for the Coordination of Humanitarian Affairs (2022). Extreme heat: preparing for the heatwaves. https://www.ifrc.org/sites/default/files/2022-10/Extreme-Heat-Report-IFRC-OCHA-2022.pdf

Intergovernmental Panel on Climate Change (2022a). Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. 321-446. https://www.cambridge.org/core/product/5D756335C9C3A6DDFAE0219073349E8D

Intergovernmental Panel on Climate Change (2022b). Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. https://doi.org/10.1017/9781009157940.001

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2018). Regional assessment report on biodiversity and ecosystem services for Asia and the pacific. https://files.ipbes.net/ipbes-web-prod-public-files/2018_asia_pacific_full_report_book_v3_pages.pdf

Internal Displacement Monitoring Centre (2022). Global Report on Internal Displacement https://www.internal-displacement.org/publications/2022-global-report-on-internal-displacement-grid/

International Institute for Applied Systems Analysis (2023). The cost of inaction: tackling air pollution in the ASEAN region. https://iiasa.ac.at/policy-briefs/oct-2023/cost-of-inaction-tackling-air-pollution-in-asean-region Accessed on 20 April 2025

Ivy, N., Mukherjee, T., Bhattacharya, S., Ghosh, A. and Sharma, P. (2023). Arsenic contamination in groundwater and food chain with mitigation options in Bengal delta with special reference to Bangladesh. Environmental Geochemistry and Health 45(5), 1261-1287. https://doi.org/10.1007/s10653-022-01330-9

Islam, M.O. and Ghorai, M. (2024). The impact of water quality on children 's education: evidence from 39 districts in the Ganges Basin of India. Environment and Development Economics 29(5), 359-378. https://doi.org/10.1017/S1355770X24000123

Jabbar, A. S., Qadar, T. L., Ghafoor, S., Rasheed, L., Sarfraz, Z., Sarfraz, A. et al. (2022). Air Quality, Pollution and Sustainability Trends in South Asia: A Population-Based Study. International Journal of Environmental Research and Public Health 12. https://doi.org/10.3390/ijerph19127534

Jain, M., Fishman, R., Mondal, P., Galford, G.L., Bhattarai, N., Naeem, S. et al. (2021). Groundwater depletion will reduce cropping intensity in India. Science Advances 7(9), eabd2849. https://doi.org/10.1126/sciadv.abd2849

Japan International Research Center for Agricultural Sciences (2024). Climate change making heat waves in Asia more extreme. https://www.jircas.go.jp/en/program/proc/blog/20240521

Kadaverugu, R., Dhyani, S., Purohit, V., Dasgupta, R., Kumar, P., Hashimoto, S. et al. (2022). Scenario-based quantification of land-use changes and its impacts on ecosystem services: A case of Bhitarkanika mangrove area, Odisha, India. Journal of Coastal Conservation 26(4), 30. https://doi.org/10.1007/s11852-022-00877-0

Kaza, S., Yao, L., Bhada-Tata, P. and Van Woerden, F. (2018). What a waste 2.0: a global snapshot of solid waste management to 2050. World Bank Publications. https://datatopics.worldbank.org/what-a-waste/

Kishore, A, Alvi, M. and Krupnik, T. J. (2021). Development of balanced nutrient management innovations in South Asia: Perspectives from Bangladesh, India, Nepal, and Sri Lanka. Global Food Security 28, 100464. https://doi.org/10.1016/j.gfs.2020.100464

Kondo, M., Sitch, S., Ciais, P., Achard, F., Kato, E., Pongratz, J. et al. (2022). Are Land-Use Change Emissions in Southeast Asia Decreasing or Increasing? Global Biogeochemical Cycles 36(1), e2020GB006909. https://doi.org/10.1029/2020GB006909

Kumar, S., Sasidharan, A. and Bagepally, B.S. (2023). Air Pollution and Cardiovascular Disease Burden: Changing Patterns and Implications for Public Health in India. Heart Lung and Circulation 32(1), 90-94. https://doi.org/10.1016/j.hlc.2022.10.012

Lal, R. (2023). Restoring South Asia's degraded soils and ecosystems for peace and prosperity. Journal of Soil and Water Conservation 78(5), 97A. https://doi.org/10.2489/jswc.2023.0327A

Lee, S-J., Song, C-K. and Choi, S-D. (2024). Past and recent changes in the pollution characteristics of PM_{10} and SO_2 in the largest industrial city in South Korea. Atmospheric Environment 319, 120310. https://doi.org/s1352-2310(23)00736-7

Liu, Y., Wang, P., Gojenko, B., Yu, J., Wei, L., Luo, D. et al. (2021). A review of water pollution arising from agriculture and mining activities in Central Asia: Facts, causes and effects. Environmental Pollution 291, 118209. https://doi.org/10.1016/j.envpol.2021.118209

Ma, J., Zhou, Z., Guo, Q., Zhu, S., Dai, Y. and Shen, Q. (2019). Spatial Characterization of Seawater Intrusion in a Coastal Aquifer of Northeast Liaodong Bay, China. Sustainability 24. https://doi.org/10.3390/su11247013

Maggi, F., Tang, F.H.M. and Tubiello, F.N. (2023). Agricultural pesticide land budget and river discharge to oceans. Nature 620(7976), 1013-1017. https://doi.org/10.1038/s41586-023-06296-x

Mao, D., Yang, H., Wang, Z., Song, K., Thompson, J.R. and Flower, R.J. (2022). Reverse the hidden loss of China's wetlands. Science 376(6597), 1061-1061. https://doi.org/10.1126/science.adc8833

Mathew, E. (2021). Ship recycling, market imperfections and the relevance of a consortium of ship recycling nations in the Indian subcontinent. Journal of International Maritime Safety, Environmental Affairs, and Shipping 5(2), 23-31. https://doi.org/10.1080/25725084.2021.1921994

Greenstone, M. and Hasenkopf, C. (2023). Air Quality Life Index Annual Update. https://aqli.epic.uchicago.edu/wp-content/uploads/2023/08/AQLI_2023_Report-Global.pdf

Aung, M.T., Ek, F. and Jintarith, P. (2021). Microplastics: from ocean to table. Stockholm Environment Institute. https://www.sei.org/features/microplastics-from-ocean-to-table/

Mihai, F.-C., Gündoğdu, S., Markley, L.A., Olivelli, A., Khan, F.R., Gwinnett, C. et al. (2022). Plastic Pollution, Waste Management Issues, and Circular Economy Opportunities in Rural Communities. Sustainability 14(1), 20. https://www.mdpi.com/2071-1050/14/1/20

The Nature Conservancy (2022). Study reveals dramatic loss of global wetlands. https://www.nature.org/en-us/newsroom/dramatic-loss-of-global-wetlands/

Ng, C.H., Mistoh, M.A., Teo, S.H., Galassi, A., Ibrahim, A., Sipaut, C.S. et al. (2023). Plastic waste and microplastic issues in Southeast Asia. Frontiers in Environmental Science 11. https://doi.org/10.3389/fenvs.2023.1142071

Organisation for Economic Co-operation and Development and Food and Agriculture Organization of the United Nations (2017). OECD-FAO Agricultural Outlook 2017-2026. https://www.oecd-ilibrary.org/content/publication/agr_outlook-2017-en

Kaÿmierczak, A. (2018). Unequal exposure and unequal impacts: social vulnerability to air pollution, noise and extreme temperatures in Europe. In: EEA Report. 97. https://www.eea.europa.eu/publications/unequal-exposure-and-unequal-impacts/

Nansai, K., Tohno, S., Chatani, S., Kanemoto, K., Kagawa, S., Kondo, Y. et al. (2021). Consumption in the G20 nations causes particulate air pollution resulting in two million premature deaths annually. Nature Communications 12, 6286. https://doi.org/10.1038/s41467-021-26348-y

Nanyang Technological University (2024). Deforestation in Southeast Asia. https://blogs.ntu.edu.sg/hp3203-1718-s2-04/hello/

Oppenheimer, M., Glavovic, B.C., Hinkel, J., van de Wal, R., Magnan, A.K., Abd-Elgawad, A. et al. (2019). Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E. et al. (eds.). Cambridge and New York: Cambridge University Press. 321-445. https://doi.org/10.1017/9781009157964.006

Paciência, I., Cavaleiro Rufo, J. and Moreira, A. (2022). Environmental inequality: Air pollution and asthma in children. Pediatric Allergy and Immunology 33(6). https://doi.org/10.1111/pai.13818

Pereira, P., Muñoz-Rojas, M., Bogunovic, I. and Zhao, W. (2023). Impact of Agriculture on Soil Degradation I. https://doi.org/10.1007/978-3-031-32168-9

Phuong, N.N., Duong, T.T., Le, T.P.Q., Hoang, T.K., Ngo, H.M., Phuong, N.A. et al. (2022). Microplastics in Asian freshwater ecosystems: Current knowledge and perspectives. Science of The Total Environment 808, 151989. https://doi.org/10.1016/j.scitotenv.2021.151989

Rahmayani, D., Sugiharti, R.R., Rahman, Y.A. and Vikia, Y.M. (2023). The dynamic linkage among carbon emissions, energy consumption, and economic sustainability in the Asia Pacific. IOP Conference Series: Earth and Environmental Science 1180(1), 012028. https://dx.doi.org/10.1088/1755-1315/1180/1/012028

Rana, S.V.S. (2022). Chemoprevention of Arseniasis-Past, Present and Future (Mini Review). Austin Environmental Sciences 7(4), 1084. https://austinpublishinggroup.com/environmental-sciences/fulltext/aes-v7-id1084.php

Ross, H., Adhuri, D.S., Abdurrahim, A.Y. and Phelan, A. (2019). Opportunities in community-government cooperation to maintain marine ecosystem services in the Asia and the Pacific and Oceania. Ecosystem Services 38, 100969. https://doi.org/10.1016/j.ecoser.2019.100969

Saif, S. and Anwar, S. (2023). Unraveling the South Asian enigma: concurrent manifestations of child anthropometric failures and their determinants in selected South Asian countries. BMC Nutrition 9(1), 120. https://doi.org/10.1186/s40795-023-00771-4

Sapkota, T. and Takele, R. (2022). Improving nitrogen use efficiency and reducing nitrogen surplus through best fertilizer nitrogen management in cereal production: The case of India and China. In: Advances in Agronomy. Elsevier. 233-294. https://doi.org/10.1016/bs.agron.2022.11.006

Schar, D., Zhao, C., Wang, Y., Joakim Larsson, D.G, Gilbert, M., Van Boeckel, T.P. (2021). Twenty-year trends in antimicrobial resistance from aquaculture and fisheries in Asia. Nature Communications 12, 5384. https://www.nature.com/articles/s41467-021-25655-8

Scheyvens, H., Shivakoti, B., Takeda, T., Mitra, B., Prabhakar, S.V.R.K., Kawasaki, J. et al. (2019). Asia and the Pacific Landscape Transformations: Solutions for Sustainability. Institute for Global Environmental Strategies. https://www.iges.or.jp/en/pub/Asia and the Pacific-landscape-transformations/en

Shupler, M., Hystad, P., Birch, A., Miller-Lionberg, D., Jeronimo, M., Arku, R.E. et al. (2020). Household and personal air pollution exposure measurements from 120 communities in eight countries: results from the PURE-AIR study. Lancet Planet Health 4(10), e451-e462. https://doi.org/10.1016/s2542-5196(20)30197-2

Sibt-e-Ali, M., Weimin, Z., Javaid, M.Q. and Khan, M.K. (2023). How natural resources depletion, technological innovation, and globalization impact the environmental degradation in East and South Asian regions. Environmental Science and Pollution Research 30(37), 87768-87782. https://doi.org/10.1007/s11356-023-28677-5

Simpson, A. (2018). The Environment in Southeast Asia: Injustice, Conflict and Activism. https://research-repository.griffith.edu.au/bitstream/handle/10072/386578/Simpson246534Accepted.pdf

Shaw, R., James, H., Sharma, V. and Lukasiewicz, A. (2022). Disaster Risk Reduction and Resilience: Practices and Challenges in Asia Pacific. In: Disaster Risk Reduction in Asia Pacific. Disaster Risk, Resilience, Reconstruction and Recovery. James, H., Shaw, R., Sharma, V., Lukasiewicz, A. (eds.). Singapore: Palgrave Macmillan. https://doi.org/10.1007/978-981-16-4811-3_1

Ship breaking platform (2023). South Asia Quarterly Update No. 35. https://shipbreakingplatform.org/wp-content/uploads/2023/11/SAQU-35.pdf

Stankovic, M., Mishra, A.K., Rahayu, Y.P., Lefcheck, J., Murdiyarso, D., Friess, D.A. et al. (2023). Blue carbon assessments of seagrass and mangrove ecosystems in South and Southeast Asia: Current progress and knowledge gaps. Science of the Total Environment 904, 166618. https://doi.org/10.1016/j.scitotenv.2023.166618

Sun, X., Ge, F., Chen, Q., Fraedrich, K. and Li, X. (2023). How Striking Is the Intergenerational Difference in Exposure to Compound Heatwaves Over Southeast Asia? Earth's Future 11(6), e2022EF003179. https://doi.org/10.1029/2022EF003179

Takeuchi, Y., Muraoka, H., Yamakita, T., Kano, Y., Nagai, S., Bunthang, T. et al. (2021). The Asia and the Pacific Biodiversity Observation Network: 10-year achievements and new strategies to 2030. Ecological Research 36(2), 232-257. https://doi.org/10.1111/1440-1703.12212

Tang, B., Hu, W. and Duan, A. (2021). Assessment of Extreme Precipitation Indices over Indochina and South China in CMIP6 Models. Journal of Climate 34(18), 7507-7524. https://doi.org/10.1175/JCLI-D-20-0948.1.

Ullah, R., Sharma, S., Inoue, M., Asghar, S., and Shivakoti, G. (2021). Natural Resource Governance in Asia: From Collective Action to Resilience Thinking. Elsevier. https://doi.org/10.1016/B978-0-323-85729-1.09984-9

United Nations (2023). Blueprint for Acceleration: Sustainable Development Goal 6 Synthesis Report on Water and Sanitation 2023. https://www.unwater.org/publications/sdg-6-synthesis-report-2023

United Nations Development Programme (2024) On the Path to a Green Transformation in the Pacific: Insights from Regional Knowledge Sharing Workshop on Green Transformation Actions. https://www.undp.org/Asia and the Pacific/news/path-green-transformation-pacific

United Nations Economic and Social Commission for Asia and the Pacific (2022). Asia and the Pacific disaster report 2022 for ESCAP sub-regions – Pathways to adaptation and resilience in Pacific SIDS. https://www.unescap.org/kp/2022/Asia and the Pacific-disaster-report-2022

United Nations Economic and Social Commission for Asia and the Pacific (2023a). Review of climate action in Asia and the Pacific. https://www.unescap.org/kp/2023/review-climate-action-asia-and-pacific

United Nations Economic and Social Commission for Asia and the Pacific (2023b). Review of Climate Ambition in Asia and the Pacific: Just Transition Towards Regional Net Zero. https://www.unescap.org/kp/2023/2023-review-climate-ambition-asia-and-pacific-just-transition-towards-regional-net-zero

United Nations Environment Programme (2016). GEO-6 Regional Assessment for Asia and the Pacific. Nairobi: UNEP. https://www.unep.org/resources/report/geo-6-global-environment-outlook-regional-assessment-asia-and-pacific

United Nations Environment Programme (2021). Food Waste Index Report 2021. Nairobi: UNEP. https://www.unep.org/resources/report/unep-food-waste-index-report-2021

United Nations Environment Programme (2022a). Our impact in Asia Pacific. https://www.unep.org/regions/asia-and-pacific/our-impact-Asia and the Pacific

United Nations Environment Programme (2023). Measuring Progress. Water-related ecosystems and the SDGs. https://wesr.unep.org/measuring-progress/water-related-ecosystems-and-sdgs/index.html

United Nations Framework Convention on Climate Change (2022). Sinking City. https://unfccc.int/news/sinking-city Accessed 20 April 2025

UNICEF (2023). The climate-changed child: A children's climate risk index supplement. https://www.unicef.org/lac/en/reports/climate-changed-child

UNICEF (2020) The Toxic Truth: Children's Exposure to Lead Pollution Undermines a Generation of Future Potential. https://www.unicef.org/media/73246/file/The-toxic-truth-children%E2%80%99s-exposure-to-lead-pollution-2020.pdf

United Nations Convention to Combat Desertification (2022). The Global Land Outlook. https://www.unccd.int/resources/global-land-outlook/global-land-outlook-2nd-edition

Wan, Z., Wang, L., Chen, J. and Sperling, D. (2021). Ship scrappage records reveal disturbing environmental injustice. Marine Policy 130, 104542. https://doi.org/10.1016/j.marpol.2021.104542

Wairiu, M. (2017). Land degradation and sustainable land management practices in Pacific Island Countries. Regional Environmental Change 17(4), 1053-1064. https://doi.org/10.1007/s10113-016-1041-0

World Economic Forum (2022). Air pollution: The invisible effects on productivity, health and economic output. https://www.weforum.org/agenda/2022/07/damage-from-air-pollutants-you-won-t-hear-about-from-your-doctor/

Vakulchuk, R., Daloz, A. S., Overland, I., Sagbakken, H. F. and Standal, K. (2022). A void in Central Asia research: climate change. Central Asian Survey, 42(1), 1–20. https://doi.org/10.1080/02634937.2022.2059447

Wilder, B., Pinedo, A., Abusin, S., Ansell, D., Bacong, A.M., Calvin, J. et al. (2024). A Global Perspective on Socioeconomic Determinants of Cardiovascular Health. Canadian Journal of Cardiology 41(1), 45-59. https://doi.org/10.1016/j.cjca.2024.07.024

World Bank (2022). Key Highlights: Country Climate and Development Report for Bangladesh. https://www.worldbank.org/en/news/feature/2022/10/31/key-highlights-country-climate-and-development-report-for-bangladesh

World Bank (2023a). Climate and Development in East Asia and Pacific Region. https://www.worldbank.org/en/region/eap/brief/climate-and-development-in-east-asia-and-pacific-region

World Bank (2023b). Implementation, completion and results report. https://documents1.worldbank.org/curated/en/099090623164024392/pdf/BOSIB09b411a4601c0ade60192236aea608.pdf.

World Meteorological Organization (2023a). State of Climate in Asia 2022. https://library.wmo.int/records/item/66314-state-of-the-climate-in-asia-2022

World Meteorological Organization (2023b). Climate change and extreme weather impacts hit Asia hard. https://wmo.int/news/media-centre/climate-change-and-extreme-weather-impacts-hit-asia-hard

World Wide Fund for Nature (2019). WWF's river dolphin initiative. https://wwfint.awsassets.panda.org/downloads/river_dolphin_rivers_initiative_summary.pdf

Worldwide Fund for Nature (2023). Deforestation and forest degradation. https://www.worldwildlife.org/threats/deforestation-and-forest-degradation

Xu, W., Fan, X., Ma, J., Pimm, S.L., Kong, L., Zeng, Y. et al. (2019). Hidden Loss of Wetlands in China. Current Biology 29(18), 3065-3071. https://doi.org/10.1016/j.cub.2019.07.053

Zhang, Y., Zhang, S., Xin, J., Wang, S., He, X., Zheng, C. and Li, S. (2023). Short-term joint effects of ambient $PM_{2.5}$ and O3 on mortality in Beijing, China. Front. Public Health 11, 1232715. https://doi.org/10.3389/fpubh.2023.1232715

Zhang, F. and Lu, F. (2024). Handbook on China's Urban Environmental Governance. http://dx.doi.org/10.4337/9781803922041.00006

Zhao, H., Geng, G., Zhang, Q., Davis, S.J., Li, X., Liu, Y. et al. (2019). Inequality of household consumption and air pollution-related deaths in China. Nature Communications 10(1), 4337. https://doi.org/10.1038/s41467-019-12254-x

Zheng, C. and Guo, Z. (2022). Plans to protect China's depleted groundwater. Science 375(6583), 827-827. https://doi.org/doi:10.1126/science.abn8377

Eastern Europe

Agency for Statistics of Bosnia and Herzegovina-BHAS (1991). Population Census Data 1991. Sarajevo. http://www.statistika.ba/#link22

Alfthan, B., Krilasevic, E., Venturini, S., Bajrovic, S., Jurek, M., Schoolmeester, T. et al. (2015). Outlook on climate change adaptation in the Western Balkan Mountains. Vienna, Arendal and Sarajevo: United Nations Environment Programme, GRIDArendal and Environmental Innovations Association. https://www.grida.no/publications/162

Ali, S., Akter, S., Ymeri, P. and Fogarassy, C. (2022). How the Use of Biomass for Green Energy and Waste Incineration Practice Will Affect GDP Growth in the Less Developed Countries of the EU (A Case Study with Visegrad and Balkan Countries). Energies 15(7), 2308. https://www.mdpi.com/1996-1073/15/7/2308

Alikadić, S., Dautbašić, M., Mujezinović, O. and Zahirović, K. (2016). Analiza šumskih požara na području općine Konjic u periodu 2009 – 2013 godine. Radovi Šumarskog fakulteta Univerziteta u Sarajevu 46(1), 42-57. https://doi.org/10.54652/rsf.2016.v46.i1.78

Álvarez Fernández, A. (2021). Ecological Feedback Effects Affecting Arctic Biodiversity in Response to Glacial Melt. Nordicum-Mediterraneum 16(3), A1. https://doi.org/https://doi.org/10.33112/nm.16.3.1

Andersen, Z.J., Badyda, A., Tzivian, L., Dzhambov, A.M., Paunovic, K., Savic, S. et al. (2025). Air pollution inequalities in Europe: A deeper understanding of challenges in Eastern Europe and pathways forward towards closing the gap between East and West. Environmental Epidemiology 9(3), e383. https://doi.org/10.1097/EE9.0000000000000383

Aziz, M.A., Mattalia, G., Sulaiman, N., Ali Shah, A., Polesny, Z., Kalle, R. et al. (2022). The nexus between traditional foraging and its sustainability: a qualitative assessment among a few selected Eurasian case studies. Environment, Development and Sustainability 26, 29813-29838. https://doi.org/10.1007/s10668-022-02568-0

Babai, D., Szépligeti, M., Tóth, A. and Ulicsni, V. (2020). Traditional Ecological Knowledge and the Cultural Significance of Plants in Hungarian Communities in Slovenia. Acta Ethnographica Hungarica 65, 481-512. https://doi.org/10.1556/022.2020.00021

Batáry, P., Dicks, L.V., Kleijn, D. and Sutherland, W.J. (2015). The role of agri-environment schemes in conservation and environmental management. Conservation Biology 29(4), 1006-1016. https://doi.org/10.1111/cobi.12536

Bejan, I., Sochircă, V., Nagacevschi, T. and Tîtu, P. (2022). Spatial study of soil erosion in the Republic of Moldova. Present Environment and Sustainable Development 16(2), 259-271. https://doi.org/10.47743/pesd2022162021

Berishaj, V. (2021). Western Balkans Greenhouse Gas Emission Reduction Targets 2030. Brussels: CAN Europe. https://caneurope.org/content/uploads/2021/07/WB-GHG2030-policy-and-recommendations_final_July-22021-1.pdf Accessed 23 May 2025

Berlin Process Summit (2022). Clean energy transition in the Western Balkans. Berlin: OECD. https://t4.oecd.org/south-east-europe/programme/OECD-BN-Clean-Energy-Transition-Oct2022.pdf

Boughattas, I., Zitouni, N., Hattab, S., Mkhinini, M., Missawi, O., Helaoui, S. et al. (2022). Interactive effects of environmental microplastics and 2,4-dichlorophenoxyacetic acid (2,4-D) on the earthworm Eisenia andrei. Journal of Hazardous Materials 424, 127578. https://doi.org/10.1016/j.jhazmat.2021.127578

Breitburg, D., Levin, L.A., Oschlies, A., Grégoire, M., Chavez, F.P., Conley, D.J. et al. (2018). Declining oxygen in the global ocean and coastal waters. Science 359(6371), eaam7240. https://www.science.org/doi/abs/10.1126/science.aam7240

Bridge, G. (2004). CONTESTED TERRAIN: Mining and the Environment. Annual Review of Environment and Resources 29, 205-259. https://doi.org/10.1146/annurev.energy.28.011503.163434

Brochet, A.-L., Van Den Bossche, W., Jones, V.R., Arnardottir, H., Damoc, D., Demko, M. et al. (2019). Illegal killing and taking of birds in Europe outside the Mediterranean: assessing the scope and scale of a complex issue. Bird Conservation International 29(1), 10-40. https://doi.org/10.1017/S0959270917000533/.

Camia, A., Giuntoli, J., Jonsson, K., Robert, N., Cazzaniga, N., Jasinevicius, G. et al. (2021). The use of woody biomass for energy production in the EU. Luxembourg: Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC122719/

Carolli, M., Garcia de Leaniz, C., Jones, J., Belletti, B., Huđek, H., Pusch, M. et al. (2023). Impacts of existing and planned hydropower dams on river fragmentation in the Balkan Region. Science of the Total Environment 871, 161940. https://doi.org/10.1016/j.scitotenv.2023.161940

Castan, S., Henkel, C., Hüffer, T., Hofmann, T. (2021). Microplastics and nanoplastics barely enhance contaminant mobility in agricultural soils. Communications Earth & Environment 2, 193. https://doi.org/10.1038/s43247-021-00267-8

Cazzolla Gatti, R., Velichevksaya, A. and Simeone, L. (2021). Clarifying the Smokescreen of Russian Protected Areas. Sustainability 13(24), 13774. https://doi.org/10.3390/su132413774

CEEweb for Biodiversity (2021). Soil Biodiversity Research and Policy in the EU. Budapest: CEEweb for Biodiversity. https://www.ceeweb.org/publication.php?id=725

Chen, ZY., Petetin, H., Méndez Turrubiates, R.F., Achebak, H., Garcìa-Pando, C.P. and Ballester, J. (2024). Population exposure to multiple air pollutants and its compound episodes in Europe. Nature Communications 15, 2094. https://doi.org/10.1038/s41467-024-46103-3

Czaplicka-Kotas, A., Kulczycka, J. and Iwaszczuk, N. (2020). Energy Clusters as a New Urban Symbiosis Concept for Increasing Renewable Energy Production—A Case Study of Zakopane City. Sustainability 12(14), 5634. https://doi.org/10.3390/su12145634

Daněk, P., Sovová, L., Jehlička, P., Vávra, J. and Lapka, M. (2022). From coping strategy to hopeful everyday practice: Changing interpretations of food self-provisioning. Sociologia Ruralis, 62(3), 651-671. https://doi.org/https://doi.org/10.1111/soru.12395

Dembicka-Niemiec, A., Szafranek-Stefaniuk, E. and Kalinichenko, A. (2023). Structural and Investment Funds of the European Union as an Instrument for Creating a Low-Carbon Economy by Selected Companies of the Energy Sector in Poland. Energies 16(4), 2031. https://doi.org/10.3390/en16042031

Dengler, J., Biurrun, I., Boch, S., Dembicz, I. and Török, P. (2020). Grasslands of the Palaearctic Biogeographic Realm: Introduction and synthesis. In: Encyclopedia of the world's biomes. Goldstein, M.I. and DellaSala, D.A. (eds.). Oxford: Elsevier. 617–637. https://doi.org/10.1016/B978-0-12-409548-9.12488-2

Dobrzycka-Krahel, A. and Bogalecka, M. (2022). The Baltic Sea under Anthropopressure—The Sea of Paradoxes. Water 14(22), 3772. https://doi.org/10.3390/w14223772

Dong, Y., Gao, M., Qiu, W. and Song, Z. (2021). Effect of microplastics and arsenic on nutrients and microorganisms in rice rhizosphere soil. Ecotoxicology and Environmental Safety 211, 111899. https://doi.org/10.1016/j.ecoenv.2021.111899

European Court of Auditors (2020). Biodiversity on farmland: CAP contribution has not halted the decline. Luxembourg: European Court of Auditors. https://www.eca.europa.eu/en/publications?did=53699 Accessed 5 August 2025

European Commission, n.d. Energy poverty. Energy — Markets and Consumers. Directorate-General for Energy. European Commission. https://energy.ec.europa.eu/topics/markets-and-consumers/energy-consumers-and-prosumers/energy-poverty_en Accessed 7 August 2025

European Commission (2023). European Green Capital Award Good Practices - Kraków - Air protection. https://environment.ec.europa.eu/topics/urban-environment/european-green-capital-award/inspiration/krakow-air-protection_en Accessed 19 March 2024

European Commission Directorate-General for Environment (2016). European red list of habitats. Part 2, Terrestrial and freshwater habitats. Publications Office. https://op.europa.eu/en/publication-detail/-/publication/22542b64-c501-11e7-9b01-01aa75ed71a1/language-en

Eurostat (2025). Living conditions in Europe — housing. Statistics Explained. Data extracted: December 2024. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Living_conditions_in_Europe_-_housing Accessed 13 August 2025

Energy Community Secretariat (2021). WB6 Energy Transition Tracker: second edition. Vienna: Energy Community Secretariat. https://www.energy-community.org/dam/jcr:fe09c4f2-9151-4a48-b5c4-8eba920b4554/EnC_WB6_ETT2_22021.pdf

European Environment Agency (2015). The European environment — state and outlook 2015: synthesis report. Copenhagen: European Environment Agency. https://www.eea.europa.eu/soer/2015

European Environment Agency (2019). Land and soil in Europe – Why we need to use these vital and finite resources sustainably. Luxembourg: Publications Office of the European Union. https://doi.org/10.2800/779710

European Environment Agency (2020a). Protected areas in the Eastern Partnership countries EEA. Copenhagen: European Environment Agency. https://www.eea.europa.eu/en/analysis/publications/protected-areas-in-the-eastern/.

European Environment Agency (2020b). Land and soil. In: The European environment — state and outlook 2020. Luxembourg: Publications Office of the European Union. Chapter 5. 115-131. https://www.eea.europa.eu/ds_resolveuid/06f72c2fbf98420f982312b619aa0668

European Environment Agency (2023a). Europe's air quality status 2023, 24 April. https://www.eea.europa.eu/publications/europes-air-quality-status-2023 Accessed 12 February 2024

European Environment Agency (2023b). Greenhouse gas emissions from land use, land use change and forestry in Europe, 31 October. https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-land Accessed 23 January 2024

European Environment Agency (2023c). Soil monitoring in Europe — indicators and thresholds for soil health assessments. Copenhagen: European Environment Agency. https://www.eea.europa.eu/en/analysis/publications/soil-monitoring-in-europe

European Environment Agency (2023d). The European biomass puzzle: Challenges, opportunities and trade-offs around biomass production and use in the EU. Luxembourg: European Environment Agency. https://www.eea.europa.eu/en/analysis/publications/the-european-biomass-puzzle

European Environment Agency (2024). European Climate Risk Assessment. Luxembourg: European Environment Agency. https://www.eea.europa.eu/en/analysis/publications/european-climate-risk-assessment

Food and Agriculture Organization of the United Nations (2020). Overview of soil conditions of arable land in Ukraine – Study case for steppe and forest-steppe zones. Budapest: FAO. https://doi.org/10.4060/ca7761en

Food and Agriculture Organization of the United Nations (2021). The State of Food and Agriculture 2021. Making agrifood systems more resilient to shocks and stresses. Rome: FAO. https://www.fao.org/3/cb4476en/cb4476en.pdf

Food and Agriculture Organization of the United Nations (2023). FAOSTAT: Fertilizers by Nutrient, 2024. https://www.fao.org/faostat/en/#data/RFN

Food and Agriculture Organization of the United Nations (2024). Food Outlook – Biannual report on global food markets, June 2024. Rome: FAO. https://doi.org/10.4060/cd1158en

Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils (2015). Status of the World's Soil Resources: Main Report. Rome: Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils. https://openknowledge.fao.org/server/api/core/bitstreams/6ec24d75-19bd-4f1f-b1c5-5becf50d0871/content

Food and Agriculture Organization of the United Nations and United Nations Environment Programme (2021). Global assessment of soil pollution: Report. Rome: FAO and UNEP. https://openknowledge.fao.org/handle/20.500.14283/cb4894en

FiBL (2025). The World of Organic Agriculture: Statistics and Emerging Trends 2024. Frick and Bonn: FiBL and IFOAM. https://www.fibl.org/fileadmin/documents/shop/1797-organic-world-2025.pdf

Gális, M. (2020). Na poliach pusto-o škodlivosti rozľahlých monokultúr na ornej pôde a možných riešeniach. Bratislava: Inštitút environmentálnej politiky, Ministerstvo životného prostredia SR. https://www.minzp.sk/files/iep/2020_5_na_poliach_pusto.pdf

Geotermálna Energia (2024). Čo priniesol rok 2023 pre geotermálnu energiu na Slovensku. https://geotermalnaenergia.sk/slovensko/co-priniesol-rok-2023-pre-geotermalnu-energiu-na-slovensku/ Accessed 7 January 2024

Geotermia Podhalańska S.A., n.d. Ekologia. Geotermia Podhalańska S.A. https://www.geotermia.pl/ekologia.html Accessed on 5 August 2025

Ghoddousi, A., Pratzer, M., Lewinska, K.E., Eggers, J., Bleyhl, B., Ambarli, H. et al. (2024). Effectiveness of protected areas in the Caucasus Mountains in preventing rangeland degradation. Conservation Biology 39, e14415. https://doi.org/10.1111/cobi.14415

Golosov, V.N., Collins, A.L., Dobrovolskaya, N.G., Bazhenova, O.I., Ryzhov, Y.V. and Sidorchuk, A.Y. (2021). Soil loss on the arable lands of the forest-steppe and steppe zones of European Russia and Siberia during the period of intensive agriculture. Geoderma 381, 114678. https://doi.org/10.1016/j.geoderma.2020.114678

Gorgan, M. and Hartvigsen, M. (2022). Development of agricultural land markets in countries in Eastern Europe and Central Asia. Land Use Policy 120, 106257. https://doi.org/10.1016/j.landusepol.2022.106257

Graubner, M., Ostapchuk, I. and Gagalyuk, T. (2020). Agroholdings and land rental markets: a spatial competition perspective. European Review of Agricultural Economics 48(1), 158-206. https://doi.org/10.1093/eurrag/jbaa018

Guan, Y., Yan, J., Shan, Y., Zhou, Y., Hang, Y., Li, R. et al. (2023). Burden of the global energy price crisis on households. Nature Energy 8, 304–316. https://doi.org/10.1038/s41560-023-01209-8

Hanzelka, J., Horká, P. and Reif, J. (2019). Spatial gradients in country-level population trends of European birds. Diversity and Distributions 25(10), 1527-1536. https://doi.org/10.1111/ddi.12945

Harfst, J. and Wirth, P. (2011). Structural change in former mining regions: problems, potentials and capacities in multi-level-governance systems. Procedia - Social and Behavioral Sciences 14, 167-176. https://doi.org/10.1016/j.sbspro.2011.03.033

Hartvigsen, M. (2014). Land reform and land fragmentation in Central and Eastern Europe. Land Use Policy 36, 330-341. https://doi.org/10.1016/j.landusepol.2013.08.016

Health Effects Institute (2020). State of Global Air 2020. Special Report. Boston: Health Effects Institute. https://www.stateofglobalair.org/sites/default/files/documents/2022-09/soga-2020-report.pdf

Health Effects Institute (2022). Trends in Air Quality and Health in Southeast Europe: A State of Global Air Special Report. Boston: Health Effects Institute. https://www.stateofglobalair.org/resources/report/trends-air-quality-and-health-southeast-europe

HELCOM (2023). State of the Baltic Sea. Third HELCOM holistic assessment 2016-2021. Helsinki: Helsinki Commission – HELCOM. https://helcom.fi/wp-content/uploads/2023/10/State-of-the-Baltic-Sea-2023.pdf

Hering, D., Schürings, C., Wenskus, F., Blackstock, K., Borja, A., Birk, S. et al. (2023). Securing success for the Nature Restoration Law. Science 382(6676), 1248-1250. https://doi.org/doi:10.1126/science.adk1658

Hölzel, N., Haub, C., Ingelfinger, M.P., Otte, A. and Pilipenko, V.N. (2002). The return of the steppe large-scale restoration of degraded land in southern Russia during the post-Soviet era. Journal for Nature Conservation 10(2), 75-85. https://doi.org/10.1078/1617-1381-00009

Hrelja, E. (2019). Identification of Negative Factors Affecting Sustainable Development in Sutjeska National Park. Geografski pregled 40, 89-99. http://geografskipregled.pmf.unsa.ba/pregledi/gp40/6Hrelja.pdf

International Energy Agency (2025). Europe – Countries & Regions. https://www.iea.org/regions/europe Accessed 14 August 2025

International Monetary Fund (2024). World Economic Outlook (WEO) Database, October 2024: GDP per capita, current prices (NGDPDPC). Washington: IMF. https://www.imf.org/en/Publications/WEO/weo-database/2024/October Accessed 7 August 2025

Institute for Statistics of the Federation of BiH- FZS FBiH (2024). Kanton 10 u brojkama 2024. Sarajevo. https://fzs.ba/wp-content/uploads/2024/07/kanton-10.pdf

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2018). The IPBES assessment report on land degradation and restoration. Bonn: Zenodo. https://zenodo.org/records/3237393

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Brondizio, E. S., Settele, J., Díaz, S. and Ngo H. T. (eds.). Bonn: IPBES Secretariat. https://doi.org/10.5281/zenodo.3831673

Ivanov, A.L., Savin, I.Y., Stolbovoy, V.S., Avetyan, S.A., Shishkonakova, E.A. and Kashtanov, A.N. (2020). Map of Anthropogenic Soil Erosion of Russia. Doklady Earth Sciences 493(2), 654-657. https://doi.org/10.1134/S1028334X20080097

Jehlička, P. (2021). Eastern Europe and the geography of knowledge production: The case of the invisible gardener. Progress in Human Geography, 45(5), 1218-1236. https://doi.org/10.1177/0309132520987305

Jones, R.J.A., Houšková, B., Bullock, P. and Montanarella, L. (2005). Soil Resources of Europe. European Soil Bureau Research Report No.9. 2nd edition. Luxembourg: Office for Official Publications of the European Communities. https://esdac.jrc.ec.europa.eu/ESDB_Archive/eusoils_docs/esb_rr/n09_EUR20559.pdf

Karapinar, B. (2021). Global Land Outlook, Central and Eastern Europe Thematic Report: Ecosystem restoration for green recovery and a sustainable future. Bonn: UNCCD. https://www.unccd.int/sites/default/files/2023-01/GLO2%20CEE%20thematic%20report.pdf

Kharuk, V.I., Ponomarev, E.I., Ivanova, G.A., Dvinskaya, M.L., Coogan, S.C.P. and Flannigan, M.D. (2021). Wildfires in the Siberian taiga. Ambio. A Journal of Environment and Society 50, 1953–1974. https://doi.org/10.1007/s13280-020-01490-x

Kharuk, V.I., Dvinskaya, M.L., Im, S.T., Golyukov, A.S. and Smith, K.T. (2022). Wildfires in the Siberian Arctic. Fire 5, 106. https://doi.org/10.3390/fire5040106

Khodakivska, O. (2023). How competitive are Ukrainian agricultural holdings? International Journal of Environmental Studies 80(2), 372-379. https://doi.org/10.1080/00207233.2023.2179759

Kirdyanov, A.V., Saurer, M., Siegwolf, R., Knorre, A.A., Prokushkin, A.S., Churakova, O.V. et al. (2020). Long-term ecological consequences of forest fires in the continuous permafrost zone of Siberia. Environmental Research Letters 15(3), 034061. https://dx.doi.org/10.1088/1748-9326/ab7469

Kivinen, S., Kotilainen, J. and Kumpula, T. (2020). Mining conflicts in the European Union: environmental and political perspectives. Fennia - International Journal of Geography 198(1-2), 163-179. https://fennia.journal.fi/article/view/87223

Kjucukov, P., Hofmeister, J., Bace, R., Vitkova, L. and Svoboda, M. (2022). The effects of forest management on biodiversity in the Czech Republic: an overview of biologists' opinions. iForest - Biogeosciences and Forestry 15(3), 187-196. https://iforest.sisef.org/contents/?id=ifor3953-015

Koyamparambath, A., Sonnemann, G. and Young, S.B. (2025). Quantifying conflict risks in raw material supply using the INFORM risk index. Resources Policy 105, 105605. https://doi.org/10.1016/j.resourpol.2025.105605

Kudeyarov, V.N. (2019). Soil-Biogeochemical Aspects of Arable Farming in the Russian Federation. Eurasian Soil Science 52(1), 94-104. https://elibrary.ru/item.asp?id=38766688

Kulczycka, J. and Dziobek, E. (2021). Challenges in Managing Waste from Extractive Industries during the Transition to a Circular Economy Model in Poland. Materials Proceedings 5(1), 42. https://doi.org/10.3390/materproc2021005042/

Kuresoo, S., Kuresoo, L. and Lilleväli, U. (2020). Hidden inside a wood pellet. Intensive logging impacts in Estonian and Latvian forests. Tartu: Estonian Fund for Nature. https://media.voog.com/0000/0037/1265/files/Biomass_report_ENG%20_2020.pdf

Lechner, A., Keckeis, H., Lumesberger-Loisl, F., Zens, B., Krusch, R., Tritthart, M. et al. (2014). The Danube so colourful: A potpourri of plastic litter outnumbers fish larvae in Europe's second largest river. Environmental Pollution 188, 177-181. https://doi.org/10.1016/j.envpol.2014.02.006

Lesiv, M., Laso Bayas, J.C., See, L., Duerauer, M., Dahlia, D., Durando, N. et al. (2019). Estimating the global distribution of field size using crowdsourcing. Global Change Biology 25(1), 174-186. https://doi.org/10.1111/gcb.14492

Li, R., Hu, W., Jia, Z., Liu, H., Zhang, C., Huang, B. et al. (2025). Soil degradation: A global threat to sustainable use of black soils. Pedosphere 35(1), 264-279. https://doi.org/10.1016/j.pedsph.2024.06.011

Liao, C. and Agrawal, A. (2024). Towards a science of 'land grabbing'. Land Use Policy 137, 107002. https://doi.org/10.1016/j.landusepol.2023.107002

Lis, A. and Savchenko, O. (2022). Possibilities of using the energy potential of geothermal waters in the case of Poland and Ukraine. Construction of Optimized Energy Potential 11(1), 181-194. https://doi.org/10.1016/j.pedsph.2024.06.011

Ljusa M. and Custovic H. (2025). Land cover/land use changes in the Sarajevo Canton-study. University of Sarajevo.

Łuczaj, Ł., Jug-Dujaković, M., Dolina, K., Jeričević, M., Vitasović-Kosić, I. (2019). The ethnobotany and biogeography of wild vegetables in the Adriatic islands. Journal of Ethnobiology and Ethnomedicine 15, 18. https://doi.org/10.1186/s13002-019-0297-0

Luković, M., Kostić, M. and Darjić Stevanović, Z. (2024). Food tourism challenges in the pandemic period: getting back to traditional and natural-based products. Current Issues in Tourism 27(3), 428-444. https://doi.org/10.1080/13683500.2023.2165481

Luo, M., Daigneault, A., Zhao, X., Hao, D. and Chen, M. (2024). Impacts of forest management-induced productivity changes on future land use and land cover change. Earth's Future 12, e2024EF004878. https://doi.org/10.1029/2024EF004878

Marot, N. and Harfst, J. (2021). Post-mining landscapes and their endogenous development potential for small- and medium-sized towns: Examples from Central Europe. The Extractive Industries and Society 8(1), 168-175. https://doi.org/10.1016/j.exis.2020.07.002

Mataković, H., Beljan, K. and Posavec, S. (2024). Perception of the causes and consequences of forest fires in the Republic of Croatia. Sumarski list 148(7-8), 327-340. https://doi.org/10.31298/sl.148.7-8.1

Meštrović, A. (2007). Natural spreading of the Whitebark Pine and forming of pioneer stands on the mountain Cvrsnica in Hercegovina. Sumarski list 131(9-10), 435-452. https://hrcak.srce.hr/23957

MNRERF (2022). О состоянии и об охране окружающей среды Российской Федерации в 2021 году. Государственный доклад. Moscow: Ministry of Environment of Russia. https://2021.ecology-gosdoklad.ru/

Modabberi, A., Noori, R., Madani, K., Ehsani, A.H., Danandeh Mehr, A., Hooshyaripor, F. et al. (2020). Caspian Sea is eutrophying: the alarming message of satellite data. Environmental Research Letters 15(12), 124047. https://dx.doi.org/10.1088/1748-9326/abc6d3

Mozafari, Z., Noori, R., Siadatmousavi, S. M., Afzalimehr, H. and Azizpour, J. (2023). Satellite-based monitoring of eutrophication in the Earth's largest transboundary lake. GeoHealth, 7, e2022GH000770. https://doi.org/10.1029/2022GH000770

National Association of Oil & Gas Service (2022). Паужетская геотермальная электростанция — первая в России [Pauzhetskaya Geothermal Power Station — the First in Russia]. NANGS news, 31 March. https://nangs.org/news/renewables/pauzhetskaya-geotermalnaya-elektrostantsiya-pervaya-v-rossii Accessed 5 August 2025

Natole, M., Ying, Y., Buyantuev, A., Stessin, M., Buyantuev, V. and Lapenis, A. (2021). Patterns of mega-forest fires in east Siberia will become less predictable with climate warming. Environmental Advances 4, 100041. https://doi.org/https://doi.org/10.1016/j.envadv.2021.100041

Novikau, A. (2021). The evolution of the natural protected areas system in Belarus: From communism to authoritarianism. Global Ecology and Conservation 26, e01486. https://doi.org/10.1016/j.gecco.2021.e01486

Novoselov, A., Potravny, I., Novoselova, I. and Gassiy, V. (2021). Compensation fund as a tool for sustainable development of the Arctic indigenous communities. Polar Science 28, 100609. https://doi.org/10.1016/j.polar.2020.100609

Nowaczek, A., Kulczycka, J., Dziobek, E. and Kalnina, D. (2021). Transparency in extractive industry as a driver for circular economy implementation – case of Poland. Gospodarka Surowcami Mineralnymi - Mineral Resources Management 37(2), 145-162. https://doi.org/10.24425/gsm.2021.136298

Nowak-Olejnik, A. and Mocior, E. (2022). Provisioning Ecosystem Services of Wild Plants Collected From Seminatural Habitats: A Basis for Sustainable Livelihood and Multifunctional Landscape Conservation. Mountain Research and Development 42(1), R11-R19. https://doi.org/10.1659/MRD-JOURNAL-D-21-00036.1

Pactwa, K., Konieczna-Fuławka, M., Fuławka, K., Aro, P., Jaśkiewicz-Proć, I. and Kozłowska-Woszczycka, A. (2021). Second Life of Post-Mining Infrastructure in Light of the Circular Economy and Sustainable Development—Recent Advances and Perspectives. Energies 14(22), 7551. https://www.mdpi.com/1996-1073/14/22/7551

Panagos, P., Ballabio, C., Himics, M., Scarpa, S., Matthews, F., Bogonos, M. et al. (2021). Projections of soil loss by water erosion in Europe by 2050. Environmental Science & Policy 124, 380-392. https://doi.org/10.1016/j.envsci.2021.07.012

Pe'er, G., Bonn, A., Bruelheide, H., Dieker, P., Eisenhauer, N., Feindt, P.H. et al. (2020). Action needed for the EU Common Agricultural Policy to address sustainability challenges. People and Nature 2, 305–316. https://doi.org/10.1002/pan3.10080

Pe'er, G., Finn, J.A., Díaz, M., Birkenstock, M., Lakner, S., Röder, N. et al. (2022). How can the European Common Agricultural Policy help halt biodiversity loss? Recommendations by over 300 experts. Conservation Letters 15(6), e12901. https://doi.org/10.1111/conl.12901

Pereira, P., Bašić, F., Bogunovic, I. and Barcelo, D. (2022). Russian-Ukrainian war impacts the total environment. Science of The Total Environment 837, 155865. https://doi.org/10.1016/j.scitotenv.2022.155865

Petrescu-Mag, R.M., Petrescu, D.C. and Azadi, H. (2020). A social perspective on soil functions and quality improvement: Romanian farmers' perceptions. Geoderma 380, 114573. https://doi.org/10.1016/j.geoderma.2020.114573

Ponomarev, E.I., Zabrodin, A.N., Shvetsov, E.G. and Ponomareva, T.V. (2023). Wildfire Intensity and Fire Emissions in Siberia. Fire 6(7), 246. https://www.mdpi.com/2571-6255/6/7/246

Pozniak, S., Havrysh, N. and Yamelynets, T. (2021). Chernozems of Ukraine and its evolution under the influence of anthropogenic factors. Scientific Papers. Series A. Agronomy LXIV(2), 156–161. https://agronomyjournal.usamv.ro/pdf/2021/issue_2/Art22.pdf

Prangel, E., Reitalu, T., Neuenkamp, L., Kasari-Toussaint, L., Karise, R., Tiitsaar, A. et al. (2024). Restoration of semi-natural grasslands boosts biodiversity and re-creates hotspots for ecosystem services. Agriculture, Ecosystems & Environment 374, 109139. https://doi.org/10.1016/j.agee.2024.109139

Prūse, B., Kalle, R., Buffa, G., Simanova, A., Mežaka, I., Sõukand, R. (2021). We need to appreciate common synanthropic plants before they become rare: Case study in Latgale (Latvia). Ethnobiology and Conservation 10, 11. https://doi.org/10.15451/ec2020-12-10.11-1-26

Puljic, V.M., Jones, D., Moore, C., Myllyvirta, L., Gierens, R., Kalaba, I. et al. (2019). Chronic coal pollution - EU action on the Western Balkans will improve health and economies across Europe. Brussels: HEAL, CAN Europe, Sandbag and CEE Bankwatch Network, and Europe Beyond Coal. https://www.env-health.org/wp-content/uploads/2019/02/Chronic-Coal-Pollution-report.pdf

Pulleman, M.M., de Boer, W., Giller, K.E. and Kuyper, T.W. (2022). Soil biodiversity and nature-mimicry in agriculture; the power of metaphor? Outlook on Agriculture 51(1), 75-90. https://doi.org/10.1177/003072702210801/

Raputa, V.F., Simonenkov, D.V., Belan, B.D. and Yaroslavtseva, T.V. (2019). Estimation of SO_2 Emission into the Air of the Norilsk Industrial Region. Atmospheric and Oceanic Optics 32(6), 650-654. https://doi.org/10.1134/S1024856019060125

Ratknic, T., Ratknic, M., Ćirković-Mitrović, T. and Brasanac-Bosanac, L. (2018). The impact of climate factors on the wildfire occurrence in Serbia. Fresenius Environmental Bulletin 27, 4014-4022. https://www.prt-parlar.de/download_feb_2018/

Řehoř, J., Trnka, M., Brázdil, R., Fischer, M., Balek, J., van der Schrier, G. et al. (2024). Global hotspots in soil moisture-based drought trends. Environmental Research Letters 19(1), 014021. https://dx.doi.org/10.1088/1748-9326/ad0f01

Reif, J. and Hanzelka, J. (2020). Continent-wide gradients in open-habitat insectivorous bird declines track spatial patterns in agricultural intensity across Europe. Global Ecology and Biogeography 29(11), 1988-2013. https://doi.org/10.1111/geb.13170

Rigal, S., Dakos, V., Alonso, H., Auniņš, A., Benkő, Z., Brotons, L. et al. (2023). Farmland practices are driving bird population decline across Europe. Proceedings of the National Academy of Sciences 120(21), e2216573120. https://www.pnas.org/doi/abs/10.1073/pnas.2216573120/

Robb, G.A. (1994). Environmental Consequences of Coal Mine Closure. The Geographical Journal 160(1), 33-40. https://doi.org/10.2307/3060139

Roleček, J., Dřevojan, P., Hájková, P., Willner, W., Janišová, M., Lengyel, A., Chorney, I. et al. (2025). Peri-Carpathian forest-steppe grasslands: distribution, indicator species and extreme species richness. Journal of Biogeography 52, 712-721. https://doi.org/10.1111/jbi.15069

https://2021.ecology-gosdoklad.ru/

Russian Association of Indigenous Peoples of the North (2021). Indigenous Peoples of the North, Siberia and the Far East.https://2021.ecology-gosdoklad.ru/ Accessed on 23 May 2025

Sabatini, F.M., Keeton, W.S., Lindner, M., Svoboda, M., Verkerk, P.J., Bauhus, J. et al. (2020). Protection gaps and restoration opportunities for primary forests in Europe. Diversity and Distributions 26(12), 1646-1662. https://doi.org/10.1111/ddi.13158

Savuca, A., Nicoara, M. N. and Faggio, C. (2022). Comprehensive Review regarding the Profile of the Microplastic Pollution in the Coastal Area of the Black Sea. Sustainability 14(21), 14376. https://doi.org/10.3390/su142114376

Sharapova, A., Seck, S., MacLeod, S. and Koubrak, O. (2022). Indigenous rights and interests in a changing Arctic Ocean: Canadian and Russian experiences and challenges. Arctic Review on Law and Politics 13, 286–311. https://doi.org/10.23865/arctic.v13.3264

Shivanna, K.R. (2022). Climate change and its impact on biodiversity and human welfare. Proceedings of the Indian National Science Academy 88(2), 160-171. https://doi.org/10.1007/s43538-022-00073-6

Shytov, A. (2023). Law as an instrument of forest destruction in Russia. Trees, Forests and People 12, 100399. https://doi.org/10.1016/j.tfp.2023.100399

Shytov, A. and Shytov, A. (2022). 'The Calf Fighting The Oak': A Fight Against Illegal Logging In Russia. Journal of International Wildlife Law & Policy 25(4), 329-344. https://doi.org/10.1080/13880292.2022.2151140

Sklenicka, P., Molnarova, K.J., Salek, M., Simova, P., Vlasak, J., Sekac, P. et al. (2015). Owner or tenant: Who adopts better soil conservation practices? Land Use Policy 47, 253-261. https://doi.org/10.1016/j.landusepol.2015.04.017

Smelansky, I.E. and Tishkov, A.A. (2012). The Steppe Biome in Russia: Ecosystem Services, Conservation Status, and Actual Challenges. In: Eurasian Steppes. Ecological Problems and Livelihoods in a Changing World. Werger, M.J.A. and van Staalduinen, M.A. (eds.). Dordrecht: Springer Netherlands. 45-101. https://doi.org/10.1007/978-94-007-3886-7_2

Solokha, M., Pereira, P., Symochko, L., Vynokurova, N., Demyanyuk, O., Sementsova, K. et al. (2023). Russian-Ukrainian war impacts on the environment. Evidence from the field on soil properties and remote sensing. Science of The Total Environment 902, 166122. https://doi.org/10.1016/j.scitotenv.2023.166122

Sõukand, R., Stryamets, N., Fontefrancesco, M. F. and Pieroni, A. (2020). The importance of tolerating interstices: Babushka markets in Ukraine and Eastern Europe and their role in maintaining local food knowledge and diversity. Heliyon 6, e03222. https://doi.org/10.1016/j.heliyon.2020.e03222

Sutcliffe, L.M.E., Batáry, P., Kormann, U., Báldi, A., Dicks, L.V., Herzon, I. et al. (2015). Harnessing the biodiversity value of Central and Eastern European farmland. Diversity and Distributions 21(6), 722-730. https://doi.org/10.1111/ddi.12288

Tang, F.H.M., Lenzen, M., McBratney, A. and Maggi, F. (2021). Risk of pesticide pollution at the global scale. Nature Geoscience 14(4), 206-210. https://doi.org/10.1038/s41561-021-00712-5

Thorn, S., Seibold, S., Leverkus, A.B., Michler, T., Müller, J., Noss, R.F. et al. (2020). The living dead: acknowledging life after tree death to stop forest degradation. Frontiers in Ecology and the Environment 18(9), 505-512. https://doi.org/10.1002/fee.2252

Thurner, T., Kuzminov, I. and Lobanova, P. (2022). The Russian forest industry: declining wood production and emerging opportunities in bioenergy. Baltic Forestry 28(2). https://doi.org/10.46490/BF623

Tleubayev, A., Bobojonov, I., Gagalyuk, T., Meca, E.G. and Glauben, T. (2021). Corporate governance and firm performance within the Russian agri-food sector: does ownership structure matter? International Food and Agribusiness Management Review 24(4), 649-668. https://doi.org/10.22434/IFAMR2019.0184

Török, P., Janišová, M., Kuzemko, A., Rūsiņa, S. and Dajić-Stevanović, Z. (2018). Grasslands, their threats and management in Eastern Europe. In: Grasslands of the World: Diversity, Management and Conservation. Squires, V.R., Dengler, J., Hua, L. and Feng., H. (eds.). Boca Raton: CRC Press. 64-88

Török, P., Dembicz, I., Dajić-Stevanović, Z. and Kuzemko, A. (2020). Grasslands of Eastern Europe. In Encyclopedia of the World's Biomes. Goldstein, M.I.

and DellaSala, D.A. (eds.). Oxford: Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.12042-1

Tryjanowski, P., Hartel, T., Báldi, A., Szymański, P., Tobolka, M., Herzon, I. et al. (2011). Conservation of Farmland Birds Faces Different Challenges in Western and Central-Eastern Europe. Acta Ornithologica 46(1), 1-12. https://doi.org/10.3161/000164511X589857/

Tsymbarovich, P., Kust, G., Kumani, M., Golosov, V. and Andreeva, O. (2020). Soil erosion: An important indicator for the assessment of land degradation neutrality in Russia. International Soil and Water Conservation Research 8(4), 418-429. https://doi.org/10.1016/j.iswcr.2020.06.002

United Nations Economic Commission for Europe (2023). UNECE Annual Report 2022. Geneva: UNECE. https://unece.org/annual-report/publications/unece-annual-report-2022 Accessed 13 August 2025

United Nations Environment Programme (2019). Air Pollution and Human Health: The Case of the Western Balkans. Nairobi: UNEP. https://api.developmentaid.org/api/frontend/cms/file/2019/06/Air-Quality-and-Human-Health-Report_Case-of-Western-Balkans_preliminary_results.pdf

United Nations Environment Programme (2021). Air Pollution in the Western Balkans: Key messages for policymakers and the public. Nairobi: UNEP. https://aqmx.org/sites/default/files/resources/Pollution-Balkans-EN2.pdf

United Nations Environment Programme (2023). Rapid Environmental Assessment of Kakhovka Dam Breach Ukraine, 2023. Nairobi: UNEP. https://wedocs.unep.org/20.500.11822/43696

United Nations Environment Programme (2024). Global Resources Outlook 2024: Bend the Trend – Pathways to a liveable planet as resource use spikes. Nairobi: International Resource Panel. http://unep.org/resources/Global-Resource-Outlook-2024

United Nations Environment Programme and Plan Bleu (2020). State of the Environment and Development in the Mediterranean. https://planbleu.org/wp-content/uploads/2020/11/SoED-Full-Report.pdf/

UNEP-WCMC and IUCN (2025). Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM), August 2025. Cambridge: UNEP-WCMC and IUCN. https://www.protectedplanet.net/en Accessed 13 August 2025

United Nations High Commissioner for Refugees (2025). Operational Data Portal: Ukraine situation. https://data.unhcr.org/en/situations/ukraine Accessed 5 August 2025

Uzun, V., Shagaida, N. and Lerman, Z. (2019). Russian agriculture: Growth and institutional challenges. Land Use Policy 83, 475-487. https://doi.org/10.1016/j.landusepol.2019.02.018

Vafeas, N.A., Slezak, P. and Hitzman, M.W. (2024). Analysis of critical raw materials policy for electrical and electronic equipment: Planning for a truly circular economy. Resources Policy 99, 105380. https://doi.org/10.1016/j.resourpol.2024.105380

Varga, F., Šolić, I., Jug Dujaković, M., Łuczaj, Ł., Grdiša, M. (2019). The first contribution to the ethnobotany of inland Dalmatia: medicinal and wild food plants of the Knin area, Croatia. Acta Societatis Botanicorum Poloniae 88, 3622. https://doi.org/10.5586/asbp.3622

Vári, Á., Arany, I., Kalóczkai, Á., Kelemen, K., Papp, J. and Czúcz, B. (2020). Berries, greens, and medicinal herbs—mapping and assessing wild plants as an ecosystem service in Transylvania (Romania). Journal of Ethnobiology and Ethnomedicine 16(1), 13. https://doi.org/10.1186/s13002-020-0360-x

Veiga, J., Winterstetter, A., Murray, C., Šubelj, G., Birk, S., Lusher, A. et al. (2022). Marine Litter in Europe—An integrated assessment from source to sea. Magdeburg: European Topic Centre on Inland, Coastal and Marine Waters. https://www.eionet.europa.eu/etcs/etc-icm/products/etc-icm-reports/etc-icm-report-5-2022/

Visser, O., Kurakin, A. and Nikulin, A. (2019). Corporate social responsibility, coexistence and contestation: large farms' changing responsibilities vis-à-vis rural households in Russia. Canadian Journal of Development Studies 40(4), 588-599. https://doi.org/10.1080/02255189.2019.1688648

Wirth, P., Chang, J., Syrbe, R.-U., Wende, W. and Hu, T. (2018). Green infrastructure: a planning concept for the urban transformation of former coal-mining cities. International Journal of Coal Science & Technology 5(1), 78-91. https://doi.org/10.1007/s40789-018-0200-y

Yakusheva, N. (2019). Managing protected areas in Central Eastern Europe: Between path-dependence and Europeanisation. Land Use Policy 87, 104036. https://doi.org/10.1016/j.landusepol.2019.104036

Yang, L., Zhang, Y., Kang, S., Wang, Z. and Wu, C. (2021). Microplastics in soil: A review on methods, occurrence, sources, and potential risk. Science of The Total Environment 780, 146546. https://doi.org/10.1016/j.scitotenv.2021.146546

Zazanashvili, N., Sanadiradze, G., Garforth, M., Bitsadze, M., Manvelyan, K., Askerov, E. et al. (2020). Ecoregional Conservation Plan for the Caucausus: 2020 Edition. Tbilisi: WWF and KfW. https://wwfeu.awsassets.panda.org/downloads/ecp_2020_part_1_1.pdf

Zgłobicki, W. and Baran-Zgłobicka, B. (2024). Air pollution in major Polish cities in the period 2005–2021: Intensity, effects and attempts to reduce it. Environmental Research 240(2), 117497. https://doi.org/10.1016/j.envres.2023.117497

Živanović, V., Joksimović, M., Golić, R., Malinić, V., Krstić, F., Sedlak, M. et al. (2022). Depopulated and Abandoned Areas in Serbia in the 21st Century—From a Local to a National Problem. Sustainability 14(17), 10765. https://doi.org/10.3390/su141710765

Latin America and the Caribbean

Anbleyth-Evans, J. (2023). Port developments and marine democracy in Latin America. Marine Policy 157, 105767. https://doi.org/10.1016/j.marpol.2023.105767

Aoki-Inoue, C.Y., and Moreira, P.F. (2016). Many worlds, many nature(s), one planet: indigenous knowledge in the Anthropocene. Revista Brasileira de Política Internacional 59, 1-19. https://doi.org/10.1590/0034-7329201600209

Armenteras, D., Dávalos, Liliana M., Barreto, Joan S., Miranda et al. (2021). Fire-induced loss of the world's most biodiverse forests in Latin America. Science Advances 7(33), eabd3357. https://doi.org/10.1126/sciadv.abd3357

Baldassini, P., and Paruelo, J.M. (2020). Deforestation and current management practices reduce soil organic carbon in the semi-arid Chaco, Argentina. Agricultural Systems 178, 102749. https://doi.org/10.1016/j.agsy.2019.102749

Ballesteros-González, K. and Sullivan, A.P. and Morales-Betancourt, R. (2020). Estimating the air quality and health impacts of biomass burning in northern South America using a chemical transport model. Science of The Total Environment 739, 139755. https://doi.org/10.1016/j.scitotenv.2020.139755

Barbosa, F.D., and Ribeiro, W. C. (2024). Transboundary conflicts and water governance in the Paraguay River Basin – South America. Sustainability in Debate 15(1). https://doi.org/10.18472/SustDeb.v15n1.2024.52302

Bonnesoeur, V., Locatelli, B., Guariguata, M.R., Ochoa-Tocachi, B.F., Vanacker, V., Mao, Z. et al. (2019). Impacts of forests and forestation on hydrological services in the Andes: A systematic review. Forest Ecology and Management 433, 569-584. https://10.1016/j.foreco.2018.11.033

Botero, C.M., Palacios, M. A., Souza Filho, J. R. and Milanes, C. B. (2023). Beach litter in three South American countries: A baseline for restarting monitoring and cleaning after COVID-19 closure. Marine Pollution Bulletin 191, 114915. https://doi.org/10.1016/j.marpolbul.2023.114915

Braun, M.H., Malz, P., Sommer, C., Farías-Barahona, D., Sauter, T., Casassa, G. et al. (2019). Constraining glacier elevation and mass changes in South America. Nature Climate Change 9, 130–136. https://doi.org/10.1038/s41558-018-0375-7

Burrell, A.L., Evans, J. P., and De Kauwe, M.G. (2020). Anthropogenic climate change has driven over 5 million km2 of drylands towards desertification. Nature Communications 11(1). 1-11. https://10.1038/s41467-020-17710-7

Butt, E.W., Conibear, L., Reddington, C.L., Darbyshire, E., Morgan, W.T., Coe, H. et al. (2020). Large air quality and human health impacts due to Amazon forest and vegetation fires. Environmental Research Communications 2, 095001 https://10.1088/2515-7620/abb0db

Cadena, F., Aldás, M.B., Aguilar, A.D., Inga, A. and Cando, D. (2021). Technical possibilities for recycling plastics from agribusiness. Progress

in Rubber, Plastics and Recycling Technology 37(4), 378-393. https://doi.org/10.1177/14777606211019420

Caldas, B., Thieme, M.L., Shahbol, N., Coelho, M.E., Grill, G., Van Damme, P.A. et al. (2023). Identifying the current and future status of freshwater connectivity corridors in the Amazon Basin. Conservation Science and Practice 5(1), e12853. https://doi.org/10.1111/csp2.12853

Caribbean Community (2020). Climate Change Statistics 2020. The Regional Statistics Programme, CARICOM, Secretariat. https://drupal.caricom.org/taxonomy/term/401

Carroll, G., Eurich, J.G., Sherman, K.D., Glazer, R., Braynen, M.T., Callwood, K.A. et al. (2023). A participatory climate vulnerability assessment for recreational tidal flats fisheries in Belize and The Bahamas. Frontiers in Marine Science 10. https://doi.org/10.3389/fmars.2023.1177715

Carvalho, L.M.V. (2020). Assessing precipitation trends in the Americas with historical data: A review. WIREs Climate Change 11(2), e627. https://doi.org/10.1002/wcc.627

Castellanos, E., Lemos, M. F., Astigarraga, L., Chacón, N., Cuvi, N., Huggel, C. et al. (2022). Central and South America. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A. et al. (eds.). Cambridge and New York: Cambridge University Press. 1689–1816. https://doi.org/10.1017/9781009325844.014

Chen, C., Chaudhary, A. and Mathys, A. (2020). Nutritional and environmental losses embedded in global food waste. Resources, Conservation and Recycling 160, 104912. https://doi.org/10.1016/j.resconrec.2020.104912.

Climate Studies Group Mona (2020). The State of the Caribbean Climate. https://www.caribank.org/sites/default/files/publication-resources/The%20State%20of%20the%20Caribbean%20Climate%20Report.pdf

Confederación Nacional Agraria (2020). Historia de la Confederación Nacional Agraria. https://www.cna.org.pe/historia/

Cortes, J., Villamizar, A., Nagy, G.J., Girot, P.O, Miglioranza, K. and Villasante, S. (2020). Ecosistemas marino-costeros. In: Adaptación frente a los riesgos del cambio climático en los países RIOCC – Informe RIOCCADAPT. Moreno, J.M., Laguna-Defior, C., Barros, V., Calvo Buendía, E., Marengo, J.A. and Oswald Spring, U. (eds.). Madrid: McGraw Hill. 132-160. https://www.researchgate.net/publication/341380846_Ecosistemas_marino-costeros

Cruise Line International Association (2024). 2023 State of the Cruise Industry Report. https://cruising.org/en/news-and-research/research/2023/march/2023-state-of-the-cruise-industry-report

Dagwar, P.P. and Dutta, D. (2024). Landfill leachate a potential challenge towards sustainable environmental management. Science of The Total Environment 926, 171668. https://doi.org/10.1016/j.scitotenv.2024.171668

Dahl, M.H. (2024). The Panama Canal Is Running Dry. Climate extremes are wreaking havoc on global shipping. https://foreignpolicy.com/2024/01/15/panama-suez-canal-global-shipping-crisis-climate-change-drought/

de Oliveira Lima, S.A., Andrade, H.A. and Sousa, R.G.C. (2024). Effects of hydrological and spatial seasonality on taxonomic and functional diversity of fish assemblages in an Amazonian floodplain lake. Ecology of Freshwater Fish 33(3), e12770. https://doi.org/10.1111/eff.12770

Del Valle, A., Eriksson, M., Ishizawa, O.A. and Miranda, J.J. (2019). Mangroves for Coastal Protection: Evidence from Hurricanes in Central America. https://hdl.handle.net/10986/31454.

Diaz, R. (2013). Interactive Map of Eutrophication & Hypoxia. https://www.wri.org/data/interactive-map-eutrophication-hypoxia

Dupar, M. (2019). IPCC's special report on the ocean and cryosphere in a changing climate: what's in it for Latin America? http://hdl.handle.net/10625/58421

Fagundes, H.O., Fan, F.M., Paiva, R.C.D., Siqueira, V.A., Buarque, D.C., Kornowski, L.W. et al. (2021). Sediment Flows in South America Supported by Daily Hydrologic-Hydrodynamic Modeling Water Resources Research. https://doi.org/10.1029/2020WR027884

Fernández, A.G., Figueroa, M., Medina, A.R., and Pacheco, M.Y. (2020). Internal Migration and Labor Dynamics in the Tourist Industry of the Riviera Maya, Quintana Roo, Mexico. Revista ABRA 40(60), 77-98. https://10.15359/abra.40-60.3

Ferreira, A.C., Borges, R. and de Lacerda, L.D. (2022). Can Sustainable Development Save Mangroves? Sustainability 3. https://doi.org/10.3390/su14031263

Ferrer-Paris, J.R., Zager, I., Keith, D.A., Oliveira-Miranda, M.A., Rodríguez, J.P., Josse, C., et al. (2019). An ecosystem risk assessment of temperate and tropical forests of the Americas with an outlook on future conservation strategies. Conservation Letters 12 (2). https://doi.org/10.1111/conl.12623021). Chapter 13 - Ocean acidification and climate change. In: Climate Change. Letcher, T.M. (eds.). 3rd edition. Elsevier. 251-279. https://www.sciencedirect.com/science/article/pii/B978012821575300013X

Food and Agriculture Organization of the United Nations (2020). Global Forest Resources Assessment 2020: Main Report. Rome: FAO. https://www.sprep.org/sites/default/files/documents/publications/forest-resources-assessment-main-report.pdf

Food and Agriculture Organization of the United Nations (2022). The State of the World's Forests 2022. Forest pathways for green recovery and building inclusive, resilient and sustainable economies. Rome: FAO. https://doi.org/10.4060/cb9360en

Food and Agriculture Organization of the United Nations (2023a). FAOSTAT. https://www.fao.org/faostat/en/#home

Food and Agriculture Organization of the United Nations (2023b). The World's Mangrove 2000-2020. Rome: FAO. https://www.fao.org/3/cc7044en/cc7044en.pdf

Foucher, A., Tassano, M., Chaboche, P.A., Chalar, G., Cabrera, M., Gonzalez, J. et al. (2023). Inexorable land degradation due to agriculture expansion in South American Pampa. Nature Sustainability 6, 662–670. https://doi.org/10.1038/s41893-023-01074-z

França, F. M., Benkwitt, C. E., Peralta, G., Robinson, J.P.W., Graham, N.A.J., Tylianakis, J.M. et al. (2020). Climatic and local stressor interactions threaten tropical forests and coral reefs. Philosophical transactions of the Royal Society of London. Series B, Biological sciences 375(1794), 20190116. https://doi.org/10.1098/rstb.2019.0116

Gómez Peláez, L.M., Santos, J.M., de Almeida Albuquerque, T.T., Reis, N.C., Andreão, W.L. and de Fátima Andrade, M.(2020). Air quality status and trends over large cities in South America. Environmental Science & Policy 114, 422-435. https://doi.org/10.1016/J.ENVSCI.2020.09.009

Gouveia, N., Kephart, J.L., Dronova, I., McClure, L., Granados, J.T., Betancourt, R.M. et al. (2021). Ambient fine particulate matter in Latin American cities: Levels, population exposure, and associated urban factors. Science of The Total Environment 772, 145035. https://doi.org/10.1016/j.scitotenv.2021.145035

Guerra, C.A., Rosa, I.M.D., Valentini, E., Wolf, F., Filipponi, F., Karger, D.N. et al. (2020). Global vulnerability of soil ecosystems to erosion. Landscape Ecology 35. https://doi.org/10.1007/s10980-020-00984-z

Hagen, I., Huggel, C., Ramajo, L., Chacón, N., Ometto, J.P., Postigo, J.C. et al. (2022). Climate change-related risks and adaptation potential in Central and South America during the 21st century. Environmental Research Letters 17, 033002. https://iopscience.iop.org/article/10.1088/1748-9326/ac5271/pdf

Halpern, B.S., Longo, C., Hardy, D., McLeod, K.L., Samhouri, J.F., Katona, S. et al. (2012). An index to assess the health and benefits of the global ocean. Nature 488(7413), 615-620. https://doi.org/10.1038/nature11397

Hartinger, S.M., Yglesias-González, M., Blanco-Villafuerte, L., Palmeiro-Silva, Y.K., Lescano, A.G., Stewart-Ibarra, A. et al. (2023). The 2022 South America report of The Lancet Countdown on health and climate change: trust the science. Now that we know, we must act. Lancet Regional Health - Americas, 100470. https://www.thelancet.com/action/showPdf?pii=S2667-193X%2823%2900044-3

Helmer, E.H., Gerson, E.A., Scott Baggett, L., Bird, B.J., Ruzycki, T.S. and Voggesser, S.M. (2019). Neotropical cloud forests and páramo to contract and dry from declines in cloud immersion and frost PLOS ONE. Public Library of Science 14. https://10.1371/journal.pone.0213155

Hendges, C., Schiller, A.P., Manfrin, J., Macedo, E.K., Gonçalves, A.C. and Stangarlin, J.R. (2019). Human intoxication by agrochemicals in the region of South Brazil between 1999 and 2014. Journal of Environmental Science and Health, Part B 54(4), 219–225. https://doi.org/10.1080/03601234.2018.1550300

Hermans, K. and McLeman, R. (2021). Climate change, drought, land degradation and migration: exploring the linkages. Current Opinion in

Environmental Sustainability 50, 236-244. https://doi.org/10.1016/j.cosust.2021.04.013

IDB Invest and Finance Earth (2023) Business Trends in Marine Conservation: Unlocking a Sustainable Blue Economy in Latin America and the Caribbean. https://www.idbinvest.org/en/publications/business-trends-marine-conservation-unlocking-sustainable-blue-economy-latin-america

Instituto de Hidrología, Meteorología y Estudios Ambientales (2023). Reports on glacier retreat and water resources in Colombia. https://www.ideam.gov.co/

Intergovernmental Panel on Climate Change (2019). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/srccl/

Intergovernmental Panel on Climate Change (2022). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press. https://report.ipcc.ch/ar6/wg2/IPCC_AR6_WGII_FullReport.pdf

Intergovernmental Panel on Climate Change (2023). Central and South America. In: Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press. 1689-1816. https://www.cambridge.org/core/product/A9FC9F29685A35A7BF8C6D832E7B2A2A

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2018). Summary for policymakers of the regional assessment report on biodiversity and ecosystem services for the Americas of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn: IPBES. https://files.ipbes.net/ipbes-web-prod-public-files/spm_americas_2018_digital.pdf

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). The IPBES regional assessment report on biodiversity and ecosystem services for the Americas. Bonn: IPBES. https://doi.org/10.5281/zenodo.3831673

Jones, M.W., Abatzoglou, J.T., Veraverbeke, S., Andela, N., Lasslop, G., Forkel, M. et al. (2022). Global and Regional Trends and Drivers of Fire Under Climate Change. Reviews of Geophysics 60(3), e2020RG000726. https://doi.org/10.1029/2020RG000726

Jorquera, H., Montoya, L.D. and Rojas, N.Y. (2019). Urban Air Pollution. In: Urban Climates in Latin America. Henríquez, C. and Romero, H. (eds.). Cham: Springer International Publishing. 137-165. https://doi.org/10.1007/978-3-319-97013-4_7

Kanhai, L.D.K., Asmath, H. and Gobin, J, F., (2022). The status of marine debris/litter and plastic pollution in the Caribbean Large Marine Ecosystem (CLME): 1980–2020. Environmental Pollution 300, 118919. https://doi.org/10.1016/j.envpol.2022.118919

Kaza, S., Yao, L.C., Bhada-Tata, P. and Van Woerden, F. (2018). What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. https://hdl.handle.net/10986/30317

Kotrikla, A.M., Zavantias, A. and Kaloupi, M. (2021). Waste generation and management onboard a cruise ship: A case study. Ocean and Coastal Management 212, 105850. https://doi.org/10.1016/j.ocecoaman.2021.105850

Lam, V.W.Y., Allison, E.H., Bell, J.D., Blythe, J., Cheung, W.W.L., Frölicher, T.L. et al. (2020). Climate change, tropical fisheries and prospects for sustainable development. Nature Reviews Earth & Environment 1(9), 440-454. https://doi.org/10.1038/s43017-020-0071-9

Laterra, P., Nahuelhual, L., Vallejos, M., Berrouet, L., Arroyo Pérez, E., Enrico, L. et al. (2019). Linking inequalities and ecosystem services in Latin America. Ecosystem Services 36, 100875. https://doi.org/10.1016/j.ecoser.2018.12.001

Lentini, E. (2022). Building a water security agenda for Latin America and the Caribbean 2030. https://scioteca.caf.com/handle/123456789/1882?locale-attribute=en

Le Billon, P. and Lujala, P. (2020). Environmental and land defenders: Global patterns and determinants of repression. Global Environmental Change 65, 102163. https://doi.org/10.1016/j.gloenvcha.2020.102163

Levin, P. S., Howe, E., and Robertson, J. (2020). Impacts of stormwater on coastal ecosystems: the need to match the scales of management objectives and solutions. Philosophical Transactions of the Royal Society B. Biological Sciences 375, 20190460. https://doi.org/10.1098/rstb.2019.0460

Loukos, P. and Arathoon, L. (2021). Landscaping the Agritech Ecosystem for Smallholder Farmers in Latin America and the Caribbean. http://dx.doi.org/10.18235/0003027

Maberly, S.C., O'Donnell, R.A., Woolway, R.I., Cutler, M. E., Gong, M., Jones, I. D. et al. (2020). Global lake thermal regions shift under climate change. Nature Communications 11, 1232 (2020). https://doi.org/10.1038/s41467-020-15108-z

Magnússon, R., Cammeraat, E., Lücke, A., Jansen, B., Zimmer, A. and Recharte, J. (2020). Influence of glacial sediments on the chemical quality of surface water in the Ulta valley, Cordillera Blanca, Peru. Journal of Hydrology 587, 125027. https://doi.org/10.1016/j.jhydrol.2020.125027.

Malone, T.C. and Newton, A. (2020). The Globalization of Cultural Eutrophication in the Coastal Ocean: Causes and Consequences. Frontiers in Marine Science 7. https://doi.org/10.3389/fmars.2020.00670

Manes, S., Costello, M.J., Beckett, H., Debnath, A., Devenish-Nelson, E., Grey, K.A. et al. (2021). Endemism increases species' climate change risk in areas of global biodiversity importance. Biological Conservation 257, 109070. https://doi.org/10.1016/J.BIOCON.2021.109070

Manzano, F.A., Abeldaño Zuñiga, R.A. and de Lima, G.N. (2022). Use of Biomass Fuels for Cooking and Improved Biomass Stoves in Mexico. In: Sustainable Policies and Practices in Energy, Environment and Health Research: Addressing Cross-cutting Issues. Leal Filho, W., Vidal, D.G., Dinis, M.A.P. and Dias, R.C. (eds.). Cham: Springer International Publishing. 625-639. https://doi.org/10.1007/978-3-030-86304-3_37

Margallo, M., Ziegler-Rodriguez, K., Vázquez-Rowe, I., Aldaco, R., Irabien, Á. and Kahhat, R. (2019). Enhancing waste management strategies in Latin America under a holistic environmental assessment perspective: A review for policy support. Science of The Total Environment 689, 1255-1275. https://doi.org/10.1016/J.SCITOTENV.2019.06.393

Marine Regions and UN Official Land Area (2023). Marine Area in Latin America and the Caribbean. https://www.marineregions.org/

Mello, F.V., Cunha, S.C., Fogaça, F.H.S., Alonso, M.B., Torres, J.P.M. and Fernandes, J.O. (2022). Occurrence of pharmaceuticals in seafood from two Brazilian coastal areas: Implication for human risk assessment. Science of The Total Environment 803, 149744. https://doi.org/10.1016/j.scitotenv.2021.149744

Mendez-Espinosa, J.F., Belalcazar, L.C. and Morales Betancourt, R. (2019). Regional air quality impact of northern South America biomass burning emissions. Atmospheric Environment 203, 131-140. https://doi.org/10.1016/j.atmosenv.2019.01.042

Mena Vasconez, P. and Hofstede, R. (2006). Los paramos ecuatorianos. Botanica Economica de los Andes Centrales. 91-109. https://beisa.dk/Publications/BEISA%20Book%20pdfer/Capitulo%2006.pdf

Mendenhall, E., Hendrix, C., Nyman, E., Roberts, P.M., Hoopes, J.R., Watson, J.R. et al. (2020). Climate change increases the risk of fisheries conflict. Marine Policy 117, 103954. https://doi.org/10.1016/j.marpol.2020.103954

Méndez, V.E., Bacon, C.M., Olson, M., Petchers, S., Herrador, D., Carranza, C. et al. (2010). Effects of fair trade and organic certifications on small-scale coffee farmer households in Central America and Mexico. Renewable Agriculture and Food Systems 25, 236-251. https://www.cambridge.org/core/journals/renewable-agriculture-and-food-systems/article/abs/effects-of-fair-trade-and-organic-certifications-on-smallscale-coffee-farmer-households-in-central-america-and-mexico/FD4FB2E6A77A23543DFA9CA0C4F70523

Mesquita, P., Gong, L. and Lin, Y. (2022). Low-cost microfluidics: Towards affordable environmental monitoring and assessment. Frontiers in Lab on a Chip Technologies 1. https://doi.org/10.3389/frlct.2022.1074009

Mosquera, G.M., Hofstede, R., Bremer, L.L., Asbjornsen, H., Carabajo-Hidalgo, A., Célleri, R. et al. (2023). Frontiers in páramo water resources research: A multidisciplinary assessment. Science of The Total Environment 892, 164373. https://doi.org/10.1016/j.scitotenv.2023.164373

Mosquera-Vallejo (2022). Afro-Latin American Geography. Routledge. https://www.routledge.com/Afro-Latin-American-Geography/Mosquera-Vallejo/p/book/9780367675938

Münzel, T., Hahad, O., Lelieveld, J., Aschner, M., Nieuwenhuijsen, M. J., Landrigan, P. J. et al. (2025). Soil and water pollution and cardiovascular disease. Nature Reviews Cardiology 22, 71–89. https://doi.org/10.1038/s41569-024-01068-0

Mycoo, M.A. and Roopnarine, R.R. (2024). Water resource sustainability: Challenges, opportunities and research gaps in the English-speaking Caribbean Small Island Developing States. https://journals.plos.org/water/article?id=10.1371/journal.pwat.0000222

Olivatto, G., Martins, M., Montagner, C., Henry, T. and Carreira, R. (2019). Microplastic contamination in surface waters in Guanabara Bay, Rio de Janeiro, Brazil. Marine Pollution Bulletin 139, 157-162. https://10.1016/j.marpolbul.2018.12.042

Organization for Economic Cooperation and Development (2023). Environment at a Glance in Latin America and the Caribbean. https://www.oecd-ilibrary.org/content/publication/2431bd6c-en

Organisation for Economic Cooperation and Development (2024). Exposure to air pollution. https://data-explorer.oecd.org/vis?df%5Bds%5D=DisseminateFinalDMZ&df%5Bid%5D=DSD_AIR_POL@DF_AIR_POLL&df%5Bag%5D=OECD.ENV.EPI&utm Accessed 30 October 2025

Oswald-Spring, Ú. (2022). The Impact of Climate Change on the Gender Security of Indigenous Women in Latin America. In: Environment, Climate and Social Justice. Madhanagopal, D., Beer, C.T., Nikku, B.R. and Pelser, A.J. (eds.). Singapore: Springer. 117-142. http://dx.doi.org/10.1007/978-981-19-1987-9_7

Our World in Data. (2023). Red List Index, 2023. https://ourworldindata.org/grapher/red-list-index. Accessed 14 August 2025.

Palme, M. and Carrasco, C. (2022). Urban heat island in Latin American cities. Global Urban Heat Island Mitigation. Elsevier. 251-267. https://doi.org/10.1016/B978-0-323-85539-6.00014-7

Paiva, B.P., Schettini, C.A.F. and Siegle, E. (2024). Effect of hydropower dam flow regulation on salt-water intrusion: São Francisco River, Brazil. Journal of Marine Systems 241, 103904. https://doi.org/10.1016/j.jmarsys.2023.103904

Pan American Health Organization (2023). New UN report: 43.2 million people suffer from hunger in Latin America and the Caribbean, and the region has higher levels of overweight and obesity than the global estimate. https://www.paho.org/en/news/9-11-2023-new-report-432-million-people-suffer-hunger-latin-america-and-caribbean-and-region

Parra-Romero, A. and Castillo, C.C. (2023). Do we inhabit the same mountain? Towards ontological openings in páramo conservation. Ambiente & Sociedade 26, e0133. https://doi.org/10.1590/1809-4422asoc20210133r1vu2023L1OA

Picq, M.L. (2020). Resistance to extractivism and megaprojects in Latin America. Oxford University Press. https://oxfordre.com/politics/view/10.1093/acrefore/9780190228637.001.0001/acrefore-9780190228637-e-1742.

Pemberthy M.D., Padilla, Y., Echeverri, A. and Peñuela, G.A. (2020). Monitoring pharmaceuticals and personal care products in water and fish from the Gulf of Urabá, Colombia. Heliyon 6(6). https://doi.org/10.1016/j.heliyon.2020.e04215

Penafiel, D., Cevallos-Valdiviezo, H., Espinel, R. and Van Damme, P. (2019). Local traditional foods contribute to diversity and species richness of rural women's diet in Ecuador. Public Health Nutrition 22(16), 2962-2971. https://www.cambridge.org/core/product/F4A5B7A00B8F530464EF50F8EDCFE8DC

Potapov, P.. Turubanova, S., Hansen, M.C., Tyukavina, A., Zalles, V., Khan, A. et al. (2022). Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. Nature Food 3(1), 19–28. https://doi.org/10.1038/s43016-021-00429-z

Powers, R.P. and Jetz, W. (2019). Global habitat loss and extinction risk of terrestrial vertebrates under future land-use-change scenarios. Nature Climate Change 9(4), 323-329. https://doi.org/10.1038/s41558-019-0406-z

Prăvălie, R., Patriche, C., Borrelli, P., Panagos, P., Roșca, B., Dumitraşcu, M. et al. (2021). Arable lands under the pressure of multiple land degradation processes. A global perspective. Environmental Research 194, 110697. https://doi.org/10.1016/J.ENVRES.2020.110697

Quintanilla, M., León, A.G. and Josse, C. (2022). Amazonia against the clock: A Regional Assessment on where And how to protect 80% By 2025. https://amazonia80x2025.earth/

Rastogi, R.P., Phulwaria, M. and Gupta, D.K. (2021). Mangroves: Ecology, Biodiversity and Management. https://doi.org/10.1007/978-981-16-2494-0

Riquetti, N.B., Mello, C.R., Leandro, D. and Guzman, J.A. (2023). Climate change projections of soil erosion in South America in the XXI century. Geoderma Regional 33, e00657. https://doi.org/10.1016/j.geodrs.2023.e00657.

Rivera, J. (2024). Characterization of the recent (2019–2022) La Plata Basin hydrological drought from a centennial-scale perspective. HydroResearch 7, 140-153. https://www.researchgate.net/publication/378522923_Characterization_of_the_recent_2019-2022_La_Plata_Basin_hydrological_drought_from_a_centennial-scale_perspective

Rodríguez, C., García, B., Pinto, C., Sánchez, R., Serrano, J. and Leiva, E. (2022). Water Context in Latin America and the Caribbean: Distribution, Regulations and Prospects for Water Reuse and Reclamation. Water 14(21), 3589. https://doi.org/10.3390/w14213589

Salazar, O., Chinchilla-Soto, C., de los Santos-Villalobos, S., Ayala Zepeda, M., Benavides, L., Berriel, V. et al. (2022). Water consumption by agriculture in Latin America and the Caribbean: impact of climate change and applications of nuclear and isotopic techniques. Natural Resource Modelling 49, 1-21. http://dx.doi.org/10.7764/ijanr.v49i1.234

Santofimia, E., López-Pamo, E., Palomino, E.J., González-Toril, E. and Aguilera, Á. (2017). Acid rock drainage in Nevado Pastoruri glacier area (Huascarán National Park, Perú): hydrochemical and mineralogical characterization and associated environmental implications. Environmental Science and Pollution Research 24(32), 25243-25259. https://doi.org/10.1007/s11356-017-0093-0

Santos, L., Aquino, E., Fernandes, S., Ternes, Y. and Feres, V. (2023). Dengue, chikungunya, and Zika virus infections in Latin America and the Caribbean: a systematic review. Revista Panamericana de Salud Pública 47, 1. http://dx.doi.org/10.26633/RPSP.2023.34

Santos, T., and Colgan, C.S. (2023). Regionalism Beyond Land Borders: Strengthening regional integration in Latin America and the Caribbean through blue economy policies. Revista Brasileira de Política Internacional 66 (2). https://doi.org/10.1590/0034-7329202300218

Schilmann, A., Ruiz-García, V., Serrano-Medrano, M., De La Sierra De La Vega, L.A., Olaya-García, B., Estevez-García, J.A. et al. (2021). Just and fair household energy transition in rural Latin American households: Are we moving forward? Environmental Research Letters. https://10.1088/1748-9326/ac28b2

Ocean Health Index (2023). Ocean Health Index. https://oceanhealthindex.org/global-scores/

Ocean Health Index (2025). Ocean Health Index. https://oceanhealthindex.org/global-scores/

Sharma, A., Kumar, V., Shahzad, B., Tanveer, M., Sidhu, G.P.S., Handa, N. et al. (2019). Worldwide pesticide usage and its impacts on ecosystem. SN Applied Sciences 1(11), 1446. https://doi.org/10.1007/s42452-019-1485-1

Sheldon, K.S. (2019). Climate Change in the Tropics: Ecological and Evolutionary Responses at Low Latitudes. Annual Review of Ecology, Evolution, and Systematics 50, 303-333. https://doi.org/10.1146/annurev-ecolsys-110218-025005

Silva, J., Cruz-Neto, O., Peres, C.A., Tabarelli, M. and Lopes, A.V. (2019). Climate change will reduce suitable Caatinga dry forest habitat for endemic plants with disproportionate impacts on specialized reproductive strategies. PLOS ONE 14(5), e0217028. https://doi.org/10.1371/journal.pone.0217028

Soares, M.O., Bezerra, L.E.A., Copertino, M., Lopes, B.D., Barros, K.V.d.S., Rocha-Barreira, C.A. et al. (2022). Blue Carbon Ecosystems in Brazil: Overview and an Urgent Call for Conservation and Restoration. Frontiers in Marine Science 9. https://doi.org/10.3389/fmars.2022.797411

Son, R., Wang, S.Y.S., Tseng, W.L. et al. (2020). Climate diagnostics of the extreme floods in Peru during early 2017. Climate Dynamics 54, 935–945. https://doi.org/10.1007/s00382-019-05038-y

Song, X.-P., Hansen, M.C., Potapov, P., Adusei, B., Pickering, J., Adami, M. et al. (2021). Massive soybean expansion in South America since 2000 and implications for conservation. Nature Sustainability 4(9), 784-792. https://doi.org/10.1038/s41893-021-00729-z

Sweetman, B.M., Cissell, J.R., Rhine, S. and Steinberg, M.K. (2019). Land cover changes on Ambergris Caye, Belize: A case study of unregulated tourism development. The Professional Geographer 71(3), 403–415. https://doi.org/10.1080/00330124.2018.1531031

Taleisnik, E., and Lavado, R.S. (2021). Saline and Alkaline Soils in Latin America. https://link.springer.com/book/10.1007/978-3-030-52592-7

Tambutti, M. and Gómez, J.J. (2020). The outlook for oceans, seas and marine resources in Latin America and the Caribbean: conservation, sustainable development and climate change mitigation. Project Documents (LC/TS.2020/167). Santiago: Economic Commission for Latin America and the Caribbean (ECLAC). https://repositorio.cepal.org/server/api/core/bitstreams/f7194ce4-f318-47d0-a4a1-b3a1b47673c5/content

Thielen, D.R., Ramoni-Perazzi, P., Zamora-Ledezma, E., Puche, M.L., Marquez, M., Quintero, J.I. et al. (2023). Effect of extreme El Niño events on the precipitation of Ecuador. Natural Hazards and Earth System Sciences 23(4), 1507-1527. https://doi.org/10.5194/nhess-23-1507-2023

Timmermann, C. (2019). A Latin American Perspective to Agricultural Ethics. In: Controversies in Latin American Bioethics. Rivera-López, E., Hevia, M. (eds.). Volume 79. Springer, Cham. 203-217. http://dx.doi.org/10.1007/978-3-030-17963-2_11

Tovar, C., Carril, A.F., Gutiérrez, A.G., Ahrends, A., Fita, L., Zaninelli, P. et al. (2022). Understanding climate change impacts on biome and plant distributions in the Andes: Challenges and opportunities. Journal of Biogeography 49(8), 1420-1442. https://doi.org/10.1111/jbi.14389

United Nations Educational, Scientific and Cultural Organization and United Nations Water (2020). The United Nations World Water Development Report 2020: Water and Climate Change. Paris. https://unesdoc.unesco.org/ark:/48223/pf0000372985.locale=en.

United Nations Educational Scientific and Cultural Organization (2021). Progress on transboundary water cooperation: global status of SDG indicator 6.5.2 and acceleration needs, 2021. https://unesdoc.unesco.org/ark:/48223/pf0000378914

United Nations Convention to Combat Desertification (2019). The Global Land Outlook, Latin America and the Caribbean Thematic Report. Sustainable land management and climate change adaptation. Bonn: United Nations Convention to Combat Desertification. https://www.unccd.int/resources/publications/global-land-outlook-latin-america-and-caribbean-thematic-report-sustainable

United Nations Convention to Combat Desertification (2022). Global Land Outlook 2nd edition. Land Restoration for Recovery and Resilience. https://www.unccd.int/resources/global-land-outlook/global-land-outlook-2nd-edition

United Nations Development Programme (2019). Human Development Report 2019. https://hdr.undp.org/content/human-development-report-2019

United Nations Development Programme Latin America and the Caribbean (2023). Climate change's impact on coastal flooding to increase 5-times over this century, putting over 70 million people in the path of expanding floodplains, according to new UNDP and CIL data. https://www.undp.org/latin-america/press-releases/climate-changes-impact-coastal-flooding-increase-5-times-over-century-putting-over-70-million-people-path-expanding

United Nations Economic Commission for Latin America and the Caribbean (2021). Social Panorama of Latin America and the Caribbean. https://www.cepal.org/en/publications/46688-social-panorama-latin-america-2020#:~:text=pdfepubmobi-,Description,about%20profound%20changes%20in%20societies.

United Nations Economic Commission for Latin America and the Caribbean (2023a). Urban and Cities Platform of Latin America and the Caribbean. https://plataformaurbana.cepal.org/en

United Nations Economic Commission for Latin America and the Caribbean (2023b). Lithium extraction and industrialization: Opportunities and challenges for Latin America and the Caribbean. https://repositorio.cepal.org/items/8894db33-cdd4-41ce-b1ec-37d34f0e288b

United Nations Educational Scientific and Cultural Organization (2021). Progress on transboundary water cooperation: global status of SDG indicator 6.5.2 and acceleration needs, 2021. https://unesdoc.unesco.org/ark:/48223/pf0000378914.

United Nations Environment Programme (2018). Waste Management Outlook for Latin America and the Caribbean. Panama. https://www.cepal.org/en/publications/46688-social-panorama-latin-america-2020#

United Nations Environment Programme (2020). Marine and coastal ecosystems and human wellbeing: A synthesis report based on the findings of the Millennium Ecosystem Assessment. https://www.unep.org/resources/report/marine-and-coastal-ecosystems-and-human-well-being-synthesis-report-based-findings

United Nations Environmental Programme World Conservation Monitoring Centre (2020). Annual Review 2019-2020. https://www.unep-wcmc.org/en/news/unep-wcmc-publishes-annual-review-2019-2020

United Nations Water and United Nations Educational Scientific and Cultural Organization (2022). Groundwater. Making the invisible visible. https://unesdoc.unesco.org/ark:/48223/pf0000380721

Vallarino Castillo, R., Negro Valdecantos, V. and del Campo, M.J. (2023). Understanding the impact of hydrodynamics on coastal erosion in Latin America: a systematic review. Frontiers in Environmental Science 11. https://doi.org/10.3389/fenvs.2023.1267402

Vergara, I., Garreaud, R., Delaney, I. and Ayala, Á. (2024). Deglaciation in the subtropical Andes has led to a peak in sediment delivery. Communications Earth & Environment 5(1), 630. https://doi.org/10.1038/s43247-024-01815-8

Viglizzo, E.F., and Ricard, F. (2020). Climate Change and Salinity-Vulnerable Ecosystems in Latin America. In: Saline and Alkaline Soils in Latin America. Taleisnik, E. and Lavado, R.S. (eds.). Springer, Cham. https://doi.org/10.1007/978-3-030-52592-7_23

Villate Daza, D.A., Sánchez Moreno, H., Portz, L., Portantiolo Manzolli, R., Bolívar-Anillo, H. J. and Anfuso, G. (2020). Mangrove Forests Evolution and Threats in the Caribbean Sea of Colombia. Water, 12(4), 1113. https://doi.org/10.3390/w12041113.

Vincent, S., Jennerjahn, T. and Kumarasamy, R. (2021). Chapter 4 - Biogeocycling of nutrients (C, N, P, S, and Fe) and implications on greenhouse gas emissions. In: Microbial Communities in Coastal Sediments. Vincent, S.G.T., Jennerjahn, T. and Ramasamy, K. (eds.). https://www.sciencedirect.com/science/article/pii/B9780128151655000042

Vousdoukas, M.I., Ranasinghe, R., Mentaschi, L., Plomaritis, T. A., Athanasiou, P., Luijendijk, A. et al. (2020) Sandy coastlines under threat of erosion. Nature Climate Change 10, 260–263. https://doi.org/10.1038/s41558-020-0697-0

Warren-Vega, W.M., Campos-Rodríguez, A., Zárate-Guzmán, A.I. and Romero-Cano, L.A. (2023). A Current Review of Water Pollutants in American Continent: Trends and Perspectives in Detection, Health Risks, and Treatment Technologies. International Journal of Environmental Research and Public Health 20(5), 4499. https://pmc.ncbi.nlm.nih.gov/articles/PMC10001968/

Wong, T. and Geuns, L. (2019). The discovery of a major hydrocarbon occurrence in the Guiana Basin, offshore Suriname: A blessing or a curse? Geology Today 35(3), 98–103. https://doi.org/10.1111/gto.12288.

World Bank (2022). The Fight against Food Insecurity in the Caribbean. https://www.worldbank.org/en/news/feature/2022/06/28/food-insecurity-caribbean.

World Bank (2023). Population, total - Latin America & Caribbean. https://data.worldbank.org/indicator/SP.POP.TOTL?locations=ZJ

World Meteorological Organization (2022). State of Global Water Resources 2022 Report. https://library.wmo.int/viewer/68473/download?file=1333_en.pdf&type=pdf&navigator=1

World Meteorological Organization (2023). State of the Climate in Latin America and the Caribbean 2022. https://doi.org/10.18356/9789263113221.

World Resources Institute (2011). Eutrophication & Hypoxia Map Data Set. http://www.wri.org/resources/data-sets/eutrophication-hypoxia-map-data-set Accessed 15 October 2025

World Wide Fund for Nature (2024). Living Planet Report 2024 – A System in Peril. https://livingplanet.panda.org/

Xi, Y., Peng, S., Ciais, P. and Chen, Y. (2020). Future impacts of climate change on inland Ramsar wetlands. Nature Climate Change 11(1), 45-51. https://doi.org/10.1038/s41558-020-00942-2

Zhong, H., Feng, K., Sun, L., Tian, Z., Fischer, G., Cheng, L. et al. (2021). Water-land tradeoffs to meet future demands for sugar crops in Latin

America and the Caribbean: A bio-physical and socio-economic nexus perspective. Resources, Conservation and Recycling 169, 105510. https://doi.org/10.1016/j.resconrec.2021.105510

Zhou, Q., Wang, S., Liu, J., Hu, X., Liu, Y., He, Y. et al. (2022). Geological evolution of offshore pollution and its long-term potential impacts on marine ecosystems. Geoscience Frontiers 13(5). https://doi.org/10.1016/j.gsf.2022.101427

Western Europe and Others Group

Abram, N.J., Henley, B.J., Sen Gupta, A., Lippmann, T.J.R., Clarke, H., Dowdy, A.J. et al. (2021). Connections of climate change and variability to large and extreme forest fires in southeast Australia. Communications Earth & Environment 2(1), 8. https://doi.org/10.1038/s43247-020-00065-8

Adewumi, A.J. and Ogundele, O.D. (2024). Hidden hazards in urban soils: A meta-analysis review of global heavy metal contamination (2010-2022), sources and its Ecological and health consequences. Sustainable Environment 10(1). https://doi.org/10.1080/27658511.2023.2293239

Adger, W.N., Barnett, J., Heath, S. and Jarillo, S. (2022). Climate change affects multiple dimensions of well-being through impacts, information and policy responses. Nature Human Behaviour 6(11), 1465-1473. https://doi.org/10.1038/s41562-022-01467-8

Anderson, M.A., Fisk, A.T., Laing, R., Noël, M., Angnatok, J., Kirk, J. et al. (2023). Changing environmental conditions have altered the feeding ecology of two keystone Arctic marine predators. Scientific Reports 13(1), 14056. https://doi.org/10.1038/s41598-023-39091-9

Arango, T. (2023). After Devastating Wildfires, Maui Pushes for Honoring Its Past. The New York Times 23 October 2023. https://www.nytimes.com/2023/10/20/us/maui-lahaina-fires-rebuilding.html Accessed 2 April 2025

Arctic Monitoring and Assessment Programme (2018). Adaptation Actions for a Changing Arctic: Perspectives from the Baffin Bay/Davis Strait Region. Oslo, Norway: Arctic Monitoring and Assessment Programme (AMAP). https://www.amap.no/documents/doc/Adaptation-Actions-for-a-Changing-Arctic-Perspectives-from-the-Baffin-BayDavis-Strait-Region/1630 Accessed 2 April 2025

Arimitsu, M.L., Piatt, J.F., Hatch, S., Suryan, R.M., Batten, S., Bishop, M.A. et al. (2021). Heatwave-induced synchrony within forage fish portfolio disrupts energy flow to top pelagic predators. Global Change Biology 27(9), 1859-1878. https://doi.org/10.1111/gcb.15556

Arnaiz-Schmitz, C., Herrero-Jáuregui, C. and Schmitz, M.F. (2018). Losing a heritage hedgerow landscape. Biocultural diversity conservation in a changing social-ecological Mediterranean system. Science of The Total Environment 637-638, 374-384. https://doi.org/10.1016/j.scitotenv.2018.04.413

Assembly of First Nations (2019). Declaring a First Nations Climate Emergency. Resolution no. 05/2019. Ottawa, Canada. https://www.afn.ca/wp-content/uploads/2019/08/19-05-Declaring-a-First-Nations-Climate-Emergency.pdf Accessed 2nd April 2025

Assis, J., Fragkopoulou, E., Serrão, E.A., Horta e Costa, B., Gandra, M. and Abecasis, D. (2021). Weak biodiversity connectivity in the European network of no-take marine protected areas. Science of The Total Environment 773, 145664. https://doi.org/10.1016/j.scitotenv.2021.145664

Australia Department of Climate Change, Energy, the Environment and Water (2024). Australia's Circular Economy Framework. Canberra, December: Australia Department of Climate Change, Energy, the Environment and Water. https://www.dcceew.gov.au/environment/protection/circular-economy Accessed 2 April 2025

Baker, J.M. (2021). Do Berries Listen? Berries as Indicators, Ancestors, and Agents in Canada's Oil Sands Region. Ethnos 86(2), 273-294. https://doi.org/10.1080/00141844.2020.1765829

Baker, R.E., Mahmud, A.S., Miller, I.F., Rajeev, M., Rasambainarivo, F., Rice, B.L. et al. (2022). Infectious disease in an era of global change. Nature Reviews Microbiology 20(4), 193-205. https://doi.org/10.1038/s41579-021-00639-z.

Balasooriya, B.M.J.K., Rajapakse, J. and Gallage, C. (2023). A review of drinking water quality issues in remote and indigenous communities in rich nations with special emphasis on Australia. Science of The Total Environment 903, 166559. https://doi.org/10.1016/j.scitotenv.2023.166559

Ballester, J., Quijal-Zamorano, M., Méndez Turrubiates, R.F., Pegenaute, F., Herrmann, F.R., Robine, J.M. et al. (2023). Heat-related mortality in Europe during the summer of 2022. Nature Medicine 29(7), 1857-1866. https://doi.org/10.1038/s41591-023-02419-z

Baron, J.S., Barber, M., Adams, M., Agboola, J.I., Allen, E.B., Bealey, W.J. et al. (2014). The Effects of Atmospheric Nitrogen Deposition on Terrestrial and Freshwater Biodiversity. In: Nitrogen Deposition, Critical Loads and Biodiversity. Sutton, M.A., Mason, K.E., Sheppard, L.J., Sverdrup, H., Haeuber, R. and Hicks, W.K. (eds.). Dordrecht: Springer Netherlands. 465-480. https://doi.org/10.1007/978-94-007-7939-6_49

Bassler, H. (2024). Turkish wildfires threaten historic sites, ancient city of Assos. Wildfire Today 28 June 2024. https://wildfiretoday.com/2024/06/28/turkish-wildfires-threaten-historic-sites-ancient-city-of-assos/ Accessed 2 April 2025

Berberian, A.G., Gonzalez, D.J.X. and Cushing, L.J. (2022). Racial Disparities in Climate Change-Related Health Effects in the United States. Current Environmental Health Reports 9(3), 451-464. https://doi.org/10.1007/s40572-022-00360-w

Bidadian, B., Strager, M.P., Butler, P. and Ghadimi, H. (2024). Flood Risk Impacts from an Unlikely Source: Redlining Efforts of the 1930s in Houston, Texas. Environmental Justice 18(1). https://doi.org/10.1089/env.2023.0027

BirdLife International (2024). Fire on Madeira Threatens Endangered Zino's Petrel. BirdLife International. https://www.birdlife.org/news/2024/09/03/fire-on-madeira-threatens-endangered-zinos-petrel/ Accessed 1 October 2024

Blavier, C.L.S., Huerto-Cardenas, H.E., Aste, N., Del Pero, C., Leonforte, F. and Della Torre, S. (2023). Adaptive measures for preserving heritage buildings in the face of climate change: A review. Building and Environment 245, 110832. https://doi.org/10.1016/j.buildenv.2023.110832

Boldt, J.L., Javorski, A. and Chandler, P.C. (2022). State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2021. Canadian Technical Report of Fisheries and Aquatic Sciences. Sidney, B.C.: Fisheries and Oceans Canada. https://www.dfo-mpo.gc.ca/oceans/publications/soto-rceo/2021/technical-report-rapport-technique-eng.html Accessed 2 April 2025

Bolster, C.H., Mitchell, R., Kitts, A., Campbell, A., Cosh, M., Farrigan, T.L. et al. (2023). Ch. 11. Agriculture, food systems, and rural communities. In: Fifth National Climate Assessment. Crimmins, A.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Stewart, B.C. and Maycock, T.K. (eds.). Washington: U.S. Global Change Research Program. https://doi.org/10.7930/NCA5.2023.CH11

Bouchama, A., Mündel, T. and Laitano, O. (2024). Beyond heatwaves: A nuanced view of temperature-related mortality. Temperature 11(3), 190-202. https://doi.org/10.1080/23328940.2024.2310459

Brennan, M., Brown, D. and Pope, L. (2023). Recent Trends in Tropical Cyclone Fatalities in the United States. https://blog.ametsoc.org/2023/08/08/recent-trends-in-tropical-cyclone-fatalities-in-the-united-states/ Accessed 10 October 2024

Brugueras, S., Fernández-Martínez, B., Martínez-de la Puente, J., Figuerola, J., Porro, T.M., Rius, C. et al. (2020). Environmental drivers, climate change and emergent diseases transmitted by mosquitoes and their vectors in southern Europe: A systematic review. Environmental Research 191, 110038. https://doi.org/10.1016/j.envres.2020.110038

Bruno, A., Dovizio, M., Milillo, C., Aruffo, E., Pesce, M., Gatta, M. et al. (2024). Orally Ingested Micro- and Nano-Plastics: A Hidden Driver of Inflammatory Bowel Disease and Colorectal Cancer. Cancers 16(17), 3079. https://doi.org/10.3390/cancers16173079

Burns, A.M., Chandler, G., Dunham, K.J. and Carlton, A.G. (2023). Data Gap: Air Quality Networks Miss Air Pollution from Concentrated Animal Feeding Operations. Environmental Science & Technology 57(49), 20718-20725. https://doi.org/10.1021/acs.est.3c06947

Buttle, E., Sharp, E.L. and Fisher, K. (2023). Managing ubiquitous 'forever chemicals': More-than-human possibilities for the problem of PFAS. New Zealand Geographer 79(2), 97-106. https://doi.org/10.1111/nzg.12365

Byrne, B., Liu, J., Bowman, K.W., Pascolini-Campbell, M., Chatterjee, A., Pandey, S. et al. (2024). Carbon emissions from the 2023 Canadian wildfires. Nature 633(8031), 835-839. https://doi.org/10.1038/s41586-024-07878-z

Caminade, C., McIntyre, K.M. and Jones, A.E. (2019). Impact of recent and future climate change on vector-borne diseases. Annals of the New

York Academy of Sciences 1436(1), 157-173. https://doi.org/10.1111/nyas.13950

Camp, A.A. and Lehmann, D.M. (2021). Impacts of Neonicotinoids on the Bumble Bees Bombus terrestris and Bombus impatiens Examined through the Lens of an Adverse Outcome Pathway Framework. Environmental Toxicology and Chemistry 40(2), 309-322. https://doi.org/10.1002/etc.4939

Canadell, J.G., Monteiro, P.M.S., Costa, M.H., Cotrim da Cunha, L., Cox, P.M., Eliseev, A.V. et al. (2021). Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (eds.). Cambridge and New York: Cambridge University Press. 673–816. https://doi.org/10.1017/9781009157896.007

Ceballos, G., Ehrlich, P.R. and Raven, P.H. (2020). Vertebrates on the brink as indicators of biological annihilation and the sixth mass extinction. Proceedings of the National Academy of Sciences 117(24), 13596-13602. https://doi.org/10.1073/pnas.1922686117

Chan, F.T., Stanislawczyk, K., Sneekes, A.C., Dvoretsky, A., Gollasch, S., Minchin, D. et al. (2019). Climate change opens new frontiers for marine species in the Arctic: Current trends and future invasion risks. Global Change Biology 25(1), 25-38. https://doi.org/10.1111/gcb.14469

Chancel, L., Bothe, P. and Voituriez, T. (2023). Climate Inequality Report 2023. World Inequality Lab Study 2023(1), 149. https://wid.world/news-article/climate-inequality-report-2023-fair-taxes-for-a-sustainable-future-in-the-global-south/ Accessed 2 April 2025

Chen, C., Xiao, W. and Chen, H.Y.H. (2023). Mapping global soil acidification under N deposition. Global Change Biology 29(16), 4652-4661. https://doi.org/10.1111/gcb.16813

Chen, K., Ma, Y., Bell, M.L. and Yang, W. (2023). Canadian Wildfire Smoke and Asthma Syndrome Emergency Department Visits in New York City. JAMA 330(14), 1385-1387. https://doi.org/10.1001/jama.2023.18768

Chen, Y., Lara, M.J., Jones, B.M., Frost, G.V. and Hu, F.S. (2021). Thermokarst acceleration in Arctic tundra driven by climate change and fire disturbance. One Earth 4(12), 1718-1729. https://doi.org/10.1016/j.oneear.2021.11.011

Cheng, I., Zhang, L., He, Z., Cathcart, H., Houle, D., Cole, A. et al. (2022). Long-term declines in atmospheric nitrogen and sulfur deposition reduce critical loads exceedances at multiple Canadian rural sites, 2000–2018. Atmospheric Chemistry and Physics 22(22), 14631-14656. https://doi.org/10.5194/acp-22-14631-2022

Chowdhury, S., Hänninen, R., Sofiev, M. and Aunan, K. (2024). Fires as a source of annual ambient $PM_{2.5}$ exposure and chronic health impacts in Europe. Science of The Total Environment 922, 171314. https://doi.org/10.1016/j.scitotenv.2024.171314

Clarke, B., Barnes, C., Sparks, N., Toumi, R., Yang, W., Giguere, J. et al. (2024). Climate change key driver of catastrophic impacts of Hurricane Helene that devastated both coastal and inland communities. London: Imperial College London. https://doi.org/10.25561/115024

Clarke, B., Otto, F., Stuart-Smith, R. and Harrington, L. (2022). Extreme weather impacts of climate change: an attribution perspective. Environmental Research: Climate 1(1), 012001. https://doi.org/10.1088/2752-5295/ac6e7d

Clarke, J., Haour, A., Morel, H., Forster, J., Orlove, B., Holtorf, C. et al. (2025). Curating transformation can strengthen adaptation and minimize losses and damages. Climate Action 4(1), 4. https://doi.org/10.1038/s44168-025-00210-z

Coakley, J., Bridgen, P., Mueller, J., Douwes, J. and Mannetje, A. (2018). Polybrominated diphenyl ethers and perfluorinated alkyl substances in blood serum of New Zealand adults, 2011–2013. Chemosphere 208, 382-389. https://doi.org/10.1016/j.chemosphere.2018.05.191

Coastwise (2023). Coastwise - Coastal Transition Accelerator Programme (CTAP). North Norfolk District Council. https://www.north-norfolk.gov.uk/media/9247/nndc-coastwise-presentation-july-2023.pdf Accessed 1 October 2024

Convention on Biological Diversity (2022). The Kunming-Montreal Global Biodiversity Framework. Convention on Biological Diversity CBD/COP/DEC/15/4. Montreal, Canada. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf

Copernicus Climate Change Service (C3S) (2024). European State of the Climate 2023: Flooding. https://climate.copernicus.eu/esotc/2023/flooding. Accessed 22 October 2024.

Costello, M.J., Tsai, P., Wong, P.S., Cheung, A.K.L., Basher, Z. and Chaudhary, C. (2017). Marine biogeographic realms and species endemicity. Nature Communications 8(1), https://doi.org/10.1038/s41467-017-01121-2 Accessed 2 April 2025

Cresswell, I.D., Janke, T. and Johnston, E. (2021). Australia state of the environment 2021: overview. Independent report to the Australian Government Minister for the Environment. Canberra, Commonwealth of Australia. https://doi.org/10.26194/f1rh-7r05

Cunningham, C.X., Williamson, G.J. and Bowman, D.M.J.S. (2024). Increasing frequency and intensity of the most extreme wildfires on Earth. Nature Ecology & Evolution 8(8), 1420-1425. https://doi.org/10.1038/s41559-024-02452-2

Cushing, L.J., Li, S., Steiger, B.B. and Casey, J.A. (2023). Historical red-lining is associated with fossil fuel power plant siting and present-day inequalities in air pollutant emissions. Nature Energy 8(1), 52-61. https://doi.org/10.1038/s41560-022-01162-y

Day, J.C., Heron, S.F. and Markham, A. (2020). Assessing the climate vulnerability of the world's natural and cultural heritage. Parks Stewardship Forum 36(1). https://doi.org/10.5070/p536146384

Department of Conservation (2020). Towards a Predator Free New Zealand: Predator Free 2050 Strategy. Wellington, New Zealand: New Zealand Department of Conservation. https://www.doc.govt.nz/nature/pests-and-threats/predator-free-2050/our-work/predator-free-2050-strategic-documents Accessed 2 April 2025

de Souza, P., Anenberg, S., Makarewicz, C., Shirgaokar, M., Duarte, F., Ratti, C. et al. (2024). Quantifying Disparities in Air Pollution Exposures across the United States Using Home and Work Addresses. Environmental Science & Technology 58(1), 280-290. https://doi.org/10.1021/acs.est.3c07926

de Vries, W., Posch, M., Simpson, D., de Leeuw, F.A.A.M., van Grinsven, H.J.M., Schulte-Uebbing, L.F. et al. (2024). Trends and geographic variation in adverse impacts of nitrogen use in Europe on human health, climate, and ecosystems: A review. Earth-Science Reviews 253, 104789. https://doi.org/10.1016/j.earscirev.2024.104789

de Vries, W., Schulte-Uebbing, L., Kros, H., Voogd, J.C. and Louwagie, G. (2021). Spatially explicit boundaries for agricultural nitrogen inputs in the European Union to meet air and water quality targets. Science of The Total Environment 786, 147283. https://doi.org/10.1016/j.scitotenv.2021.147283

DeWitt, J.C., Glüge, J., Cousins, I.T., Goldenman, G., Herzke, D., Lohmann, R. et al. (2024). Zürich II Statement on Per- and Polyfluoroalkyl Substances (PFASs): Scientific and Regulatory Needs. Environmental Science & Technology Letters 11(8), 786-797. https://doi.org/10.1021/acs.estlett.4c00147

Dicks, L.V., Breeze, T.D., Ngo, H.T., Senapathi, D., An, J., Aizen, M.A. et al. (2021). A global-scale expert assessment of drivers and risks associated with pollinator decline. Nature Ecology & Evolution 5(10), 1453-1461. https://doi.org/10.1038/s41559-021-01534-9

Domke, G.M., Fettig, C.J., Marsh, A.S., Baumflek, M., Gould, W.A., Halofsky, J.E. et al. (2023). Ch. 7. Forests. In: Fifth National Climate Assessment. Crimmins, A.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Stewart, B.C. and Maycock, T.K. (eds.). Washington: U.S. Global Change Research Program. https://doi.org/10.7930/NCA5.2023.CH7

Donatti, C.I., Nicholas, K., Fedele, G., Delforge, D., Speybroeck, N., Moraga, P. et al. (2024). Global hotspots of climate-related disasters. International journal of disaster risk reduction: IJDRR. 108, 104488. https://doi.org/10.1016/j.ijdrr.2024.104488

Donley, N., Bullard, R.D., Economos, J., Figueroa, I., Lee, J., Liebman, A.K. et al. (2022). Pesticides and environmental injustice in the USA: root causes, current regulatory reinforcement and a path forward. BMC Public Health 22(1), 708. https://doi.org/10.1186/s12889-022-13057-4

Donnelly, A. and Rodríguez-Rodríguez, D. (2022). Effectiveness of protected areas against land development in coastal areas of the Mediterranean global biodiversity hotspot. Global Ecology and Conservation 38, e02223. https://doi.org/10.1016/j.gecco.2022.e02223

Dziedzic, R., Pondicherry, P. and Dziedzic, M. (2025). Review of national policy instruments motivating circular construction. Resources, Conservation and Recycling 215, 108053. https://doi.org/10.1016/j.resconrec.2024.108053

Ebi, K.L., Capon, A., Berry, P., Broderick, C., de Dear, R., Havenith, G. et al. (2021). Hot weather and heat extremes: health risks. The Lancet 398(10301), 698-708. https://doi.org/10.1016/S0140-6736(21)01208-3

Ebi, K.L. and Hess, J.J. (2020). Health Risks Due To Climate Change: Inequity. In: Causes And Consequences. Health Affairs 39(12), 2056-2062. https://doi.org/10.1377/hlthaff.2020.01125

Eby, P., Peel, A.J., Hoegh, A., Madden, W., Giles, J.R., Hudson, P.J. et al. (2023). Pathogen spillover driven by rapid changes in bat ecology. Nature 613(7943), 340-344. https://doi.org/10.1038/s41586-022-05506-2

Environment and Climate Change Canada (2024). Canada's 2030 Nature Strategy: Halting and Reversing Biodiversity Loss in Canada. Gatineau Quebec: Government of Canada. https://www.canada.ca/en/environment-climate-change/services/biodiversity/canada-2030-nature-strategy.html Accessed 2 April 2025

Environmental Protection Agency (2024). Climate Change Indicators: Heat Waves. https://www.epa.gov/climate-indicators/climate-change-indicators-heat-waves Accessed 22 September 2024

European Academies' Science Advisory Council (2019). The imperative of climate action to protect human health in Europe. Halle, Germany: European Academies' Science Advisory Council. https://easac.eu/publications/details/the-imperative-of-climate-action-to-protect-human-health-in-europe

European Commission (2023). State of Health in the EU: Synthesis Report 2023. Luxembourg: European Union. https://doi.org/10.2875/458883

European Commission (2024). Neonicotinoids. Directorate-General for Health and Food Safety. https://food.ec.europa.eu/plants/pesticides/approval-active-substances-safeners-and-synergists/renewal-approval/neonicotinoids_en Accessed 1 October 2024

European Commission (2025). Renovation Wave: The Renovation Wave aims to improve energy efficiency, boost the economy and deliver better living-standards for Europeans. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en Accessed 1 April 2025

European Commission: Joint Research Centre, San-Miguel-Ayanz, J., Durrant, T., Boca, R., Maianti, P., Libertà, G. et al. (2023). Forest fires in Europe, Middle East and North Africa 2022. Publications Office of the European Union. https://doi.org/10.2760/348120

European Environment Agency (2018). Unequal exposure and unequal impacts: social vulnerability to air pollution, noise and extreme temperatures in Europe. Luxembourg: Publications Office of the European Union. https://doi.org/10.2800/324183

European Environment Agency (2022a). Who benefits from nature in cities? Social inequalities in access to urban green and blue spaces across Europe. https://www.eea.europa.eu/publications/who-benefits-from-nature-in/who-benefits-from-nature-in Accessed 4 October 2024

European Environment Agency (2022b). Chemicals signals. Zero pollution monitoring assessment. European Environment Agency. https://www.eea.europa.eu/publications/zero-pollution/health/signals/chemicals Accessed 2 April 2025

European Environment Agency (2022c). Waste management Zero pollution monitoring assessment. European Environment Agency. https://doi.org/10.2800/515047

European Environment Agency (2022d). Textiles and the environment – The role of design in Europe's circular economy. Publications Office of the European Union. https://doi.org/10.2800/578806

European Environment Agency (2023a). Designated terrestrial protected areas in Europe. https://www.eea.europa.eu/en/analysis/indicators/terrestrial-protected-areas-in-europe?activeAccordion=309c5ef9-de09-4759-bc02-802370dfa366 Accessed 26th November 2025

European Environment Agency (2023b). Nitrate in groundwater. https://www.eea.europa.eu/en/analysis/indicators/nitrate-in-groundwater-8th-eap. Accessed 1 October 2024.

European Environment Agency (2023c). How pesticides impact human health and ecosystems in Europe. European Environment Agency. https://doi.org/10.2800/760240

European Environment Agency (2023d). Harm to human health from air pollution in Europe: burden of disease 2023. European Environment Agency. https://www.eea.europa.eu/publications/harm-to-human-health-from-air-pollution Accessed 2 April 2025

European Environment Agency (2023e). Waste generation in Europe. European Environment Agency. https://www.eea.europa.eu/en/analysis/indicators/waste-generation-and-decoupling-in-europe Accessed 2 April 2025

European Environment Agency (2024a). European Climate Risk Assessment. Copenhagen: European Environment Agency https://doi.org/10.2800/8671471

European Environment Agency (2024b). Nutrients in transitional, coastal and marine waters in Europe. https://www.eea.europa.eu/en/analysis/indicators/nutrients-in-transitional-coastal-and. Accessed 30 January 2024.

European Environment Agency (2024c). Emissions of the main air pollutants in Europe. European Environment Agency. https://www.eea.europa.eu/en/analysis/indicators/emissions-of-the-main-air Accessed 1 October 2024

European Environment Agency (2024d). Accelerating the circular economy in Europe: State and outlook 2024. Copenhagen: European Environment Agency. https://doi.org/10.2800/055236

European Parliament (2024). Urgent activation of the EU Solidarity Fund for Madeira Pedro, A.M. Priority question for written answer. P-001692/2024. European Parliament. https://www.europarl.europa.eu/doceo/document/P-10-2024-001692_EN.html Accessed 21 October 2024

European Union (2014). Consolidated text: Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species, 2014 (European Union). http://data.europa.eu/eli/reg/2014/1143/2019-12-14 Accessed 2 April 2025

European Union (2022). Commission Implementing Regulation (EU) 2022/1203 of 12 July 2022 amending Implementing Regulation (EU) 2016/1141 to update the list of invasive alien species of Union concern, 2022. http://data.europa.eu/eli/reg_impl/2022/1203/oj Accessed 2 April 2025

Facey, J.A., Michie, L.E., King, J.J., Hitchcock, J.N., Apte, S.C. and Mitrovic, S.M. (2022). Severe cyanobacterial blooms in an Australian lake; causes and factors controlling succession patterns. Harmful Algae 117, 102284. https://doi.org/10.1016/j.hal.2022.102284

Fantle-Lepczyk, J.E., Haubrock, P.J., Kramer, A.M., Cuthbert, R.N., Turbelin, A.J., Crystal-Ornelas, R. et al. (2022). Economic costs of biological invasions in the United States. Science of The Total Environment 806, 151318. https://doi.org/10.1016/j.scitotenv.2021.151318

Fernández-Llamazares, Á., Garteizgogeascoa, M., Basu, N., Brondizio, E.S., Cabeza, M., Martínez-Alier, J. et al. (2020). A State-of-the-Art Review of Indigenous Peoples and Environmental Pollution. Integrated Environmental Assessment and Management 16(3), 324-341. https://doi.org/10.1002/ieam.4239

Fong, K.C. and Bell, M.L. (2021). Do fine particulate air pollution ($PM_{2.5}$) exposure and its attributable premature mortality differ for immigrants compared to those born in the United States? Environmental Research 196, 110387. https://doi.org/10.1016/j.envres.2020.110387

Food and Agriculture Organization and United Nations Environment Programme (2021). Global assessment of soil pollution - Summary for policy makers. Rome: FAO and UNEP. https://doi.org/10.4060/cb4827en

Galappaththi, E.K., Ford, J.D., Bennett, E.M. and Berkes, F. (2019). Climate change and community fisheries in the arctic: A case study from Pangnirtung, Canada. Journal of Environmental Management 250, 109534. https://doi.org/10.1016/j.jenvman.2019.109534

Gallo, E., Quijal-Zamorano, M., Méndez Turrubiates, R.F., Tonne, C., Basagaña, X., Achebak, H. et al. (2024). Heat-related mortality in Europe during 2023 and the role of adaptation in protecting health. Nature Medicine 30, 3101-3105. https://doi.org/10.1038/s41591-024-03186-1

Galvez-Hernandez, P., Dai, Y. and Muntaner, C. (2025). The DANA disaster: unraveling the political and economic determinants for Valencia's floods devastation. International Journal for Equity in Health 24(1), 64. https://doi.org/10.1186/s12939-025-02435-0

Gewurtz, S.B., Auyeung, A.S., De Silva, A.O., Teslic, S. and Smyth, S.A. (2024). Per- and polyfluoroalkyl substances (PFAS) in Canadian municipal wastewater and biosolids: Recent patterns and time trends 2009 to 2021.

Science of The Total Environment 912, 168638. https://doi.org/10.1016/j.scitotenv.2023.168638

Ghahramani, L., McArdle, K. and Fatorić, S. (2020). Minority Community Resilience and Cultural Heritage Preservation: A Case Study of the Gullah Geechee Community. Sustainability 12(6), 2266. https://doi.org/10.3390/su12062266

Gibson, J.C. (2020). Emerging persistent chemicals in human biomonitoring for populations in the Arctic: A Canadian perspective. Science of The Total Environment 708, 134538. https://doi.org/10.1016/j.scitotenv.2019.134538

Gignoux-Wolfsohn, S.A., Dunn, D.C., Cleary, J., Halpin, P.N., Anderson, C.R., Bax, N.J. et al. (2024). New framework reveals gaps in US ocean biodiversity protection. One Earth 7(1), 31-43. https://doi.org/10.1016/j.oneear.2023.12.014

Gillett, Z.E., Taschetto, A.S., Holgate, C.M. and Santoso, A. (2023). Linking ENSO to Synoptic Weather Systems in Eastern Australia. Geophysical Research Letters 50(15), e2023GL104814. https://doi.org/10.1029/2023GL104814

Golzadeh, N., Barst, B.D., Baker, J.M., Auger, J.C. and McKinney, M.A. (2021). Alkylated polycyclic aromatic hydrocarbons are the largest contributor to polycyclic aromatic compound concentrations in traditional foods of the Bigstone Cree Nation in Alberta, Canada. Environmental Pollution 275, 116625. https://doi.org/10.1016/j.envpol.2021.116625

Gomes, D.G.E., Ruzicka, J.J., Crozier, L.G., Huff, D.D., Brodeur, R.D. and Stewart, J.D. (2024). Marine heatwaves disrupt ecosystem structure and function via altered food webs and energy flux. Nature Communications 15(1), 1988. https://doi.org/10.1038/s41467-024-46263-2

Gonzalez, D.J.X., Nardone, A., Nguyen, A.V., Morello-Frosch, R. and Casey, J.A. (2023). Historic redlining and the siting of oil and gas wells in the United States. Journal of Exposure Science & Environmental Epidemiology 33(1), 76-83. https://doi.org/10.1038/s41370-022-00434-9

Goodling, E. (2019). Intersecting hazards, intersectional identities: A baseline Critical Environmental Justice analysis of US homelessness. Environment and Planning E: Nature and Space 3(3), 833-856. https://doi.org/10.1177/2514848619892433

Goulson, D. (2019). The insect apocalypse, and why it matters. Current Biology 29(19), R967-R971. https://doi.org/10.1016/j.cub.2019.06.069

Government of Canada (2025). Explore circular economy initiatives. https://www.canada.ca/en/services/environment/conservation/sustainability/circular-economy/circular-economy-initiatives.html Accessed 1 April 2025

Guimond, J.A., Mohammed, A.A., Walvoord, M.A., Bense, V.F. and Kurylyk, B.L. (2021). Saltwater Intrusion Intensifies Coastal Permafrost Thaw. Geophysical Research Letters 48(19), e2021GL094776. https://doi.org/10.1029/2021GL094776

Hall, R.J., Pragert, H., Phiri, B.J., Fan, Q.-H., Li, X., Parnell, A. et al. (2021). Apicultural practice and disease prevalence in Apis mellifera, New Zealand: a longitudinal study. Journal of Apicultural Research 60(5), 644-658. https://doi.org/10.1080/00218839.2021.1936422

Hantson, S., Andela, N., Goulden, M.L. and Randerson, J.T. (2022). Human-ignited fires result in more extreme fire behavior and ecosystem impacts. Nature Communications 13(1), 2717. https://doi.org/10.1038/s41467-022-30030-2

Harrison, S. and Noss, R. (2017). Endemism hotspots are linked to stable climatic refugia. Annals of Botany 119(2), 207-214. https://doi.org/10.1093/aob/mcw248

Hauser, D.D.W., Whiting, A.V., Mahoney, A.R., Goodwin, J., Harris, C., Schaeffer, R.J. et al. (2021). Co-production of knowledge reveals loss of Indigenous hunting opportunities in the face of accelerating Arctic climate change. Environmental Research Letters 16(9), 095003. https://doi.org/10.1088/1748-9326/ac1a36

Hausman, C. and Stolper, S. (2021). Inequality, information failures, and air pollution. Journal of Environmental Economics and Management 110, 102552. https://doi.org/10.1016/j.jeem.2021.102552

He, K., Yang, Q., Shen, X., Dimitriou, E., Mentzafou, A., Papadaki, C. et al. (2024). Brief communication: Storm Daniel flood impact in Greece in 2023: mapping crop and livestock exposure from synthetic-aperture radar (SAR). Natural Hazards and Earth System Sciences 24(7), 2375-2382. https://doi.org/10.5194/nhess-24-2375-2024

Heide-Jørgensen, M.P., Chambault, P., Jansen, T., Gjelstrup, C.V.B., Rosing-Asvid, A., Macrander, A. et al. (2023). A regime shift in the Southeast Greenland marine ecosystem. Global Change Biology 29(3), 668-685. https://doi.org/10.1111/gcb.16494

Henke, M., Miesse, T., de Lima, A.d.S., Ferreira, C.M. and Ravens, T.M. (2024). Increasing coastal exposure to extreme wave events in the Alaskan Arctic as the open water season expands. Communications Earth & Environment 5(1), 165. https://doi.org/10.1038/s43247-024-01323-9

Henley, B.J., McGregor, H.V., King, A.D., Hoegh-Guldberg, O., Arzey, A.K., Karoly, D.J. et al. (2024). Highest ocean heat in four centuries places Great Barrier Reef in danger. Nature 632(8024), 320-326. https://doi.org/10.1038/s41586-024-07672-x

Hetzer, J., Forrest, M., Ribalaygua, J., Prado-López, C. and Hickler, T. (2024). The fire weather in Europe: large-scale trends towards higher danger. Environmental Research Letters 19(8), 084017. https://doi.org/10.1088/1748-9326/ad5b09

Hilty, J., Worboys, G.L., Keeley, A., Woodley, S., Lausche, B.J., Locke, H. et al. (2020). Guidelines for conserving connectivity through ecological networks and corridors. Best Practice Protected Area Guidelines Series. Groves, C. (eds.). Gland: IUCN. https://doi.org/10.2305/IUCN.CH.2020.PAG.30.en

Hošeková, L., Eidam, E., Panteleev, G., Rainville, L., Rogers, W.E. and Thomson, J. (2021). Landfast Ice and Coastal Wave Exposure in Northern Alaska. Geophysical Research Letters 48(22), e2021GL095103. https://doi.org/10.1029/2021GL095103

Hsiang, S., Greenhill, S., Martinich, J., Grasso, M., Schster, R.M., Barrage, L. et al. (2023). Chapter 19: Economics. In: Fifth National Climate Assessment. Crimmins, A.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Stewart, B.C. and Maycock, T.K. (eds.). Washington: U.S. Global Change Research Program. https://doi.org/10.7930/NCA5.2023.CH19

Huang, W., Xu, H., Wu, J., Ren, M., Ke, Y. and Qiao, J. (2024). Toward cleaner air and better health: Current state, challenges, and priorities. Science 385(6707), 386-390. https://doi.org/10.1126/science.adp7832

Huntington, H.P., Strawhacker, C., Falke, J., Ward, E.M., Behnken, L., Curry, T.N. et al. (2023). Chapter 29: Alaska. In: Fifth National Climate Assessment. Crimmins, A.R., Avery, C.W., D.R. Easterling, Kunkel, K.E., Stewart, B.C. and Maycock, T.K. (eds.). Washington: U.S. Global Change Research Program. https://doi.org/10.7930/NCA5.2023.CH29

Ingvaldsen, R.B., Assmann, K.M., Primicerio, R., Fossheim, M., Polyakov, I.V. and Dolgov, A.V. (2021). Physical manifestations and ecological implications of Arctic Atlantification. Nature Reviews Earth & Environment 2(12), 874-889. https://doi.org/10.1038/s43017-021-00228-x

Intergovernmental Panel on Climate Change (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press. https://doi.org/10.1017/9781009325844

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Brondizio, E.S., Settele, J., Díaz, S. and Ngo, H.T. (eds.). Bonn: IPBES Secretariat. https://doi.org/10.1017/9781009325844

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2023). Summary for Policymakers of the Thematic Assessment Report on Invasive Alien Species and their Control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Roy, H. E., Pauchard, A., Stoett, P., Renard Truong, T., Bacher, S., Galil, B.S. et al. (eds.). Bonn: IPBES Secretariat. https://doi.org/10.5281/zenodo.7430692

International Labour Office (2019). Working on a warmer planet: The impact of heat stress on labour productivity and decent work. Geneva: International Labour Organization. https://www.ilo.org/publications/major-publications/working-warmer-planet-effect-heat-stress-productivity-and-decent-work Accessed 2 April 2025

International Union for Conservation of Nature - World Commission on Protected Areas (2024). IUCN World Commission on Protected Areas: impact report 2023. Gland: IUCN. https://portals.iucn.org/library/node/51455 Accessed 2 April 2025

International Union for Conservation of Nature (2024). Agriculture and conservation. IUCN Flagship Report Series. Gland: IUCN. https://doi.org/10.2305/AMHX3737

Inuit Tapiriit Kanatami (2019). National Inuit Climary Change Strategy. Ottawa: Inuit Tapiriit Kanatami. https://doi.org/10.25607/OBP-1758.

Ives, A.M., Brenn-White, M., Buckley, J.Y., Kendall, C.J., Wilton, S. and Deem, S.L. (2022). A Global Review of Causes of Morbidity and Mortality in Free-Living Vultures. EcoHealth 19(1), 40-54. https://doi.org/10.1007/s10393-021-01573-5

Jain, P., Barber, Q.E., Taylor, S.W., Whitman, E., Castellanos Acuna, D., Boulanger, Y. et al. (2024). Drivers and Impacts of the Record-Breaking 2023 Wildfire Season in Canada. Nature Communications 15(1), 6764. https://doi.org/10.1038/s41467-024-51154-7

Jansson, J.K. and Hofmockel, K.S. (2020). Soil microbiomes and climate change. Nature Reviews Microbiology 18(1), 35-46. https://doi.org/10.1038/s41579-019-0265-7.

Jay, A.K., Crimmins, A.R., Avery, C.W., Dahl, T.A., Dodder, R.S., Hamlington, B.D. et al. (2023). Overview: Understanding risks, impacts, and responses. In: Fifth National Climate Assessment. Crimmins, A.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Stewart, B.C. and Maycock, T.K. (eds.). Washington: U.S. Global Change Research Program. Chapter 1. https://nca2023.globalchange.gov/ Accessed 2 April 2025

Jones, M.W., Abatzoglou, J.T., Veraverbeke, S., Andela, N., Lasslop, G., Forkel, M. et al. (2022). Global and Regional Trends and Drivers of Fire Under Climate Change. Reviews of Geophysics 60(3), e2020RG000726. https://doi.org/10.1029/2020RG000726

Jones, T., Parrish, J.K., Peterson, W.T., Bjorkstedt, E.P., Bond, N.A., Ballance, L.T. et al. (2018). Massive Mortality of a Planktivorous Seabird in Response to a Marine Heatwave. Geophysical Research Letters 45(7), 3193-3202. https://doi.org/10.1002/2017GL076164

Jørgensen, L.L. (2024). Ecosystem Based Management in a Rapidly Warming Arctic. The 3rd International Conference on The Ecosystem Approach to Management in Arctic Large Marine Ecosystems - Conference report. PAME conference report. https://hdl.handle.net/11374/3296. Accessed 2 April 2025.

Kabisch, N., Remahne, F., Ilsemann, C. and Fricke, L. (2023). The urban heat island under extreme heat conditions: a case study of Hannover, Germany. Scientific Reports 13(1), 23017. https://doi.org/10.1038/s41598-023-49058-5

Kovacs, K.M., Belikov, S., Boveng, P., Desportes, G., Ferguson, S., Hansen, R. et al. (2021). 2021 State of the Arctic Marine Biodiversity Report (SAMBR) Update: 2021 State of the Arctic Marine Biodiversity Report (SAMBR) Update: Marine Mammals. Technical Report. Akureyri: Conservation of Arctic Flora and Fauna International Secretariat. https://hdl.handle.net/11374/3284

Krause-Jensen, D., Archambault, P., Assis, J., Bartsch, I., Bischof, K., Filbee-Dexter, K. et al. (2020). Imprint of Climate Change on Pan-Arctic Marine Vegetation. Frontiers in Marine Science 7. https://doi.org/10.3389/fmars.2020.617324

Kurwadkar, S., Dane, J., Kanel, S.R., Nadagouda, M.N., Cawdrey, R.W., Ambade, B. et al. (2022). Per- and polyfluoroalkyl substances in water and wastewater: A critical review of their global occurrence and distribution. Science of The Total Environment 809, 151003. https://doi.org/10.1016/j.scitotenv.2021.151003

La, V. (2024). Hot days or heat waves: A split over how to count heat deaths. Science 385, 922–922. https://doi.org/10.1126/science.ads7687

Lamb, C.T., Willson, R., Richter, C., Owens-Beek, N., Napoleon, J., Muir, B. et al. (2022). Indigenous-led conservation: Pathways to recovery for the nearly extirpated Klinse-Za mountain caribou. Ecological Applications 32(5), e2581. https://doi.org/10.1002/eap.2581

Lane, H.M., Morello-Frosch, R., Marshall, J.D. and Apte, J.S. (2022). Historical Redlining Is Associated with Present-Day Air Pollution Disparities in U.S. Cities. Environmental Science & Technology Letters 9(4), 345-350. https://doi.org/10.1021/acs.estlett.1c01012

Lansbury Hall, N. and Crosby, L. (2022). Climate Change Impacts on Health in Remote Indigenous Communities in Australia. International Journal of Environmental Health Research 32(3), 487-502. https://doi.org/10.1080/09603123.2020.1777948

Leemans, M., Couderq, S., Demeneix, B. and Fini, J.-B. (2019). Pesticides With Potential Thyroid Hormone-Disrupting Effects: A Review of Recent Data. Frontiers in Endocrinology 10. https://doi.org/10.3389/fendo.2019.00743

Leggat, W.P., Camp, E.F., Suggett, D.J., Heron, S.F., Fordyce, A.J., Gardner, S. et al. (2019). Rapid Coral Decay Is Associated with Marine Heatwave Mortality Events on Reefs. Current Biology 29(16), 2723-2730. https://doi.org/10.1016/j.cub.2019.06.077

Lenka, S.P., Kah, M. and Padhye, L.P. (2022). Occurrence and fate of poly- and perfluoroalkyl substances (PFAS) in urban waters of New Zealand. Journal of Hazardous Materials 428, 128257. https://doi.org/10.1016/j.jhazmat.2022.128257

Leung, M.R., Sun, C., Zeng, J. et al. (2025). Structural diversity of axonemes across mammalian motile cilia. Nature 637, 1170–1177. https://doi.org/10.1038/s41586-024-08337-5

Li, G., Fang, C., Watson, J.E.M., Sun, S., Qi, W., Wang, Z. et al. (2024). Mixed effectiveness of global protected areas in resisting habitat loss. Nature Communications 15(1), 8389. https://doi.org/10.1038/s41467-024-52693-9

Li, X., Ma, X., Lyu, F. and Song, Y. (2023). Examine the environmental inequity impact of urban heat mitigation on redlining legacy: case study of Charlotte's retrofitting, 2001–2020. Frontiers in Environmental Science 11. https://doi.org/10.3389/fenvs.2023.1218819

Lindholm, K.-J. and Ekblom, A. (2019). A framework for exploring and managing biocultural heritage. Anthropocene 25, 100195. https://doi.org/10.1016/j.ancene.2019.100195

Liu, J., Clark Lara, P., Bechle Matthew, J., Hajat, A., Kim, S.-Y., Robinson Allen, L. et al. (2021). Disparities in Air Pollution Exposure in the United States by Race/Ethnicity and Income, 1990–2010. Environmental Health Perspectives 129(12), 127005. https://doi.org/10.1289/EHP8584

Liu, X., Lara, R., Dufresne, M., Wu, L., Zhang, X., Wang, T. et al. (2024). Variability of ambient air ammonia in urban Europe (Finland, France, Italy, Spain, and the UK). Environment International 185, 108519. https://doi.org/10.1016/j.envint.2024.108519

London Assembly (2022). Shocking inequality in children with asthma admitted to hospital in London. Mayor of London & London Assembly. https://www.london.gov.uk/increaseinasthmaadmissions Accessed 1 October 2024

Lulham, N., Warren, F.J., Walsh, K.A. and Szwarc, J. (2023). Canada in a Changing Climate: Synthesis Report. Ottawa: Government of Canada. https://changingclimate.ca/synthesis Accessed 2 April 2025

Malan, N., Roughan, M., Hemming, M. and Ingleton, T. (2024). Quantifying coastal freshwater extremes during unprecedented rainfall using long timeseries multi-platform salinity observations. Nature Communications 15(1), 424. https://doi.org/10.1038/s41467-023-44398-2

Mamy, L., Pesce, S., Sanchez, W., Amichot, M., Artigas, J., Aviron, S. et al. (2022). Impacts des produits phytopharmaceutiques sur la biodiversité et les services écosystémiques. Rapport de l'expertise scientifique collective. INRAE and IFREMER. https://doi.org/10.17180/0gp2-cd65

Markkula, I., Turunen, M., Rikkonen, T., Rasmus, S., Koski, V. and Welker, J.M. (2024). Climate change, cultural continuity and ecological grief: Insights from the Sámi Homeland. Ambio 53(8), 1203-1217. https://doi.org/10.1007/s13280-024-02012-9

Mata, L., Knapp, R.A., McDougall, R., Overton, K., Hoffmann, A.A. and Umina, P.A. (2024). Acute toxicity effects of pesticides on beneficial organisms – Dispelling myths for a more sustainable use of chemicals in agricultural environments. Science of The Total Environment 930, 172521. https://doi.org/10.1016/j.scitotenv.2024.172521

Mattalia, G., McAlvay, A., Teixidor-Toneu, I., Lukawiecki, J., Moola, F., Asfaw, Z. et al. (2024). Cultural keystone species as a tool for biocultural stewardship. A global review. People and Nature 00, 1-14. https://doi.org/10.1002/pan3.10653

Matthews, V., Longman, J., Berry, H.L., Passey, M., Bennett-Levy, J., Morgan, G.G. et al. (2019). Differential Mental Health Impact Six Months After Extensive River Flooding in Rural Australia: A Cross-Sectional Analysis Through an Equity Lens. Frontiers in Public Health 7. https://doi.org/10.3389/fpubh.2019.00367

May, C.L., Osler, M.S., Stockdon, H.F., Barnard, P.L., Callahan, J.A., Collini, R.C. et al. (2023). Chapter 9: Coastal effects. In: Fifth National Climate Assessment. Crimmins, A.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Stewart, B.C. and Maycock, T.K. (eds.). Washington: U.S. Global Change Research Program. https://doi.org/10.7930/NCA5.2023.CH9

McElwee, P.D., Carter, S.L., Hyde, K.J.W., West, J.M., Akamani, K., Babson, A.L. et al. (2023). Chapter 8: Ecosystems, ecosystem services, and biodiversity. In: Fifth National Climate Assessment. Crimmins, A.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Stewart, B.C. and Maycock, T.K. (eds.). Washington: U.S. Global Change Research Program. https://doi.org/10.7930/NCA5.2023.CH14

McLauchlan, K.K., Higuera, P.E., Miesel, J., Rogers, B.M., Schweitzer, J., Shuman, J.K. et al. (2020). Fire as a fundamental ecological process: Research advances and frontiers. Journal of Ecology 108, 2047–2069. https://doi.org/10.1111/1365-2745.13403

McPherson, R.A., Wekerle, C., Kanzow, T., Ionita, M., Heukamp, F.O., Zeising, O. et al. (2024). Atmospheric blocking slows ocean-driven melting of Greenland's largest glacier tongue. Science 385(6715), 1360-1366. https://doi.org/10.2737/fs-1217

Mekonnen, Z.A., Riley, W.J., Berner, L.T., Bouskill, N.J., Torn, M.S., Iwahana, G. et al. (2021). Arctic tundra shrubification: a review of mechanisms and impacts on ecosystem carbon balance. Environmental Research Letters 16(5), 053001. https://doi.org/10.1088/1748-9326/abf28b

Méndez, M., Flores-Haro, G. and Zucker, L. (2020). The (in)visible victims of disaster: Understanding the vulnerability of undocumented Latino/a and indigenous immigrants. Geoforum 116, 50-62. https://doi.org/10.1016/j.geoforum.2020.07.007

Mondal, P., Walter, M., Miller, J., Epanchin-Niell, R., Gedan, K., Yawatkar, V. et al. (2023). The spread and cost of saltwater intrusion in the US Mid-Atlantic. Nature Sustainability 6(11), 1352-1362. https://doi.org/10.1038/s41893-023-01186-6

Mosley, L.M., Priestley, S., Brookes, J., Dittmann, S., Farkaš, J., Farrell, M. et al. (2023). Extreme eutrophication and salinisation in the Coorong estuarine-lagoon ecosystem of Australia's largest river basin (Murray-Darling). Marine Pollution Bulletin 188, 114648. https://doi.org/10.1016/j.marpolbul.2023.114648

Mucioki, M. (2024). Climate and land-use change impacts on cultural use berries: Considerations for mitigative stewardship. Plants, People, Planet 6(4), 791-802. https://doi.org/10.1002/ppp3.10500

National Academies of Sciences Engineering and Medicine, Health and Medicine Division, Division on Earth and Life Studies, Board on Population Health and Public Health Practice, Board on Environmental Studies and Toxicology and Committee on the Guidance on PFAS Testing and Health Outcomes (2022). Guidance on PFAS Exposure, Testing, and Clinical Follow-Up. In: Potential Health Effects of PFAS. Washington. https://www.ncbi.nlm.nih.gov/books/NBK584690/ Accessed 2 April 2025

National Oceanic and Atmospheric Administration (2020). Marine Protected Areas 2020: Building Effective Conservation Networks. Marine Protected Areas of the United States. https://marineprotectedareas.noaa.gov/media/docs/2020-mpa-building-effective-conservation-networks.pdf Accessed 2 April 2025

Neumann, J.T., Black, J.L., Hœrlé, S., Smith, B.W., Watkins, R., Lagos, M. et al. (2022). Artificial weathering of rock types bearing petroglyphs from Murujuga, Western Australia. Heritage Science 10(1), 77. https://doi.org/10.1186/s40494-022-00706-5

Niinimäki, K., Peters, G., Dahlbo, H., Perry, P., Rissanen, T. and Gwilt, A. (2020). The environmental price of fast fashion. Nature Reviews Earth & Environment 1(4), 189-200. https://doi.org/10.1038/s43017-020-0039-9

Nill, L., Grünberg, I., Ullmann, T., Gessner, M., Boike, J. and Hostert, P. (2022). Arctic shrub expansion revealed by Landsat-derived multitemporal vegetation cover fractions in the Western Canadian Arctic. Remote Sensing of Environment 281, 113228. https://doi.org/10.1016/j.rse.2022.113228

North American Bird Conservation Initiative (2022). The State of the Birds. United States of America: North American Bird Conservation Initiative. https://StateoftheBirds.org Accessed 2 April 2025

O'Donnell, K.L., Bernhardt, E.S., Yang, X., Emanuel, R.E., Ardón, M., Lerdau, M.T. et al. (2024). Saltwater intrusion and sea level rise threatens U.S. rural coastal landscapes and communities. Anthropocene 45, 100427. https://doi.org/10.1016/j.ancene.2024.100427

Organisation for Economic Co-operation and Development (OECD) (2024a). Exposure to air pollution. OECD Data. https://www.oecd.org/en/data/indicators/air-pollution-exposure.html Accessed 4 September 2024

Organisation for Economic Co-operation and Development (OECD) (2024b). Waste – Waste by sector: generation, recovery and recycling. OECD Data. https://data-explorer.oecd.org/vis?df[ds]=dsDisseminateFinalDMZ&df[id]=DSD_WSECTOR%40DF_WSECTOR&df[ag]=OECD.ENV.EPI&dq=.A.TOTAL.KG_PS._T&lom=LASTNPERIODS&lo=5&to[TIME_PERIOD]=false Accessed 12 November 2025

Ortmeyer, F., Hansen, B. and Banning, A. (2023). Groundwater nitrate problem and countermeasures in strongly affected EU countries—a comparison between Germany, Denmark and Ireland. Grundwasser 28(1), 3-22. https://doi.org/10.1007/s00767-022-00530-5

Osland, M.J., Stevens, P.W., Lamont, M.M., Brusca, R.C., Hart, K.M., Waddle, J.H. et al. (2021). Tropicalization of temperate ecosystems in North America: The northward range expansion of tropical organisms in response to warming winter temperatures. Global Change Biology 27(13), 3009-3034. https://doi.org/10.1111/gcb.15563

Oswald, Y., Owen, A. and Steinberger, J.K. (2020). Large inequality in international and intranational energy footprints between income groups and across consumption categories. Nature Energy 5(3), 231-239. https://doi.org/10.1038/s41560-020-0579-8

Ottenbros, I., Lebret, E., Huber, C., Lommen, A., Antignac, J.-P., Čupr, P. et al. (2023). Assessment of exposure to pesticide mixtures in five European countries by a harmonized urinary suspect screening approach. International Journal of Hygiene and Environmental Health 248, 114105. https://doi.org/10.1016/j.ijheh.2022.114105

Pagad, S., Bisset, S., Genovesi, P., Groom, Q., Hirsch, T., Jetz, W. et al. (2022). Country Compendium of the Global Register of Introduced and Invasive Species. Scientific Data 9(1), 391. https://doi.org/10.1038/s41597-022-01514-z

Page, M.L. and Williams, N.M. (2023). Honey bee introductions displace native bees and decrease pollination of a native wildflower. Ecology 104(2), e3939. https://doi.org/10.1002/ecy.3939

Parker, T.C., Thurston, A.M., Raundrup, K., Subke, J.-A., Wookey, P.A. and Hartley, I.P. (2021). Shrub expansion in the Arctic may induce large-scale carbon losses due to changes in plant-soil interactions. Plant and Soil 463(1), 643-651. https://doi.org/10.1007/s11104-021-04919-8

Parks Canada (2024). Wildfire status — Jasper Wildfire Complex. Government of Canada. https://parks.canada.ca/pn-np/ab/jasper/visit/feu-alert-fire/feudeforet-wildfire#updates Accessed 1 October 2024

Parks, R.M., Kontis, V., Anderson, G.B., Baldwin, J.W., Danaei, G., Toumi, R. et al. (2023). Short-term excess mortality following tropical cyclones in the United States. Science Advances 9(33), eadg6633. https://doi.org/10.1126/sciadv.adg6633

Perry, R.I., Nemcek, N., Hennekes, M., Sastri, A., Ross, A.R.S., Shannon, H. et al. (2023). Domoic acid in Canadian Pacific waters, from 2016 to 2021, and relationships with physical and chemical conditions. Harmful Algae 129, 102530. https://doi.org/10.1016/j.hal.2023.102530

Phillips, H.R.P., Cameron, E.K., Eisenhauer, N., Burton, V.J., Ferlian, O., Jin, Y. et al. (2024). Global changes and their environmental stressors have a significant impact on soil biodiversity: A meta-analysis. iScience 27(9). https://doi.org/10.1016/j.isci.2024.110540

Piatt, J.F., Parrish, J.K., Renner, H.M., Schoen, S.K., Jones, T.T., Arimitsu, M.L. et al. (2020). Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014-2016. PLOS ONE 15(1), e0226087. https://doi.org/10.1371/journal.pone.0226087

Pörtner, H.-O., Scholes, R.J., Arneth, A., Barnes, D.K.A., Burrows, M.T., Diamond, S.E. et al. (2023). Overcoming the coupled climate and biodiversity crises and their societal impacts. Science 380(6642), eabl4881. https://doi.org/10.1126/science.abl4881

Powell, E.B., Laurent, K.A.S. and Dubayah, R. (2022). Lidar-Imagery Fusion Reveals Rapid Coastal Forest Loss in Delaware Bay Consistent with Marsh Migration. Remote Sensing 14(18). https://doi.org/10.3390/rs14184577

Pozzebon, E.A. and Seifert, L. (2023). Emerging environmental health risks associated with the land application of biosolids: a scoping review. Environmental Health 22(1), 57. https://doi.org/10.1186/s12940-023-01008-4

Priadka, P., Suzuki, N. and Nation, L.D. (2025). Identifying indigenous knowledge components for Whudzih (Caribou) recovery planning. FACETS 10, 1-11. https://doi.org/10.1139/facets-2023-0139

Qian, Y., Chakraborty, T.C., Li, J., Li, D., He, C., Sarangi, C. et al. (2022). Urbanization Impact on Regional Climate and Extreme Weather: Current

Understanding, Uncertainties, and Future Research Directions. Advances in Atmospheric Sciences 39(6), 819-860. https://doi.org/10.1007/s00376-021-1371-9

Rabalais, N.N. and Turner, R.E. (2019). Gulf of Mexico Hypoxia: Past, Present, and Future. Limnology and Oceanography Bulletin 28(4), 117-124. https://doi.org/10.1002/lob.10351

Ramage, J., Jungsberg, L., Wang, S., Westermann, S., Lantuit, H. and Heleniak, T. (2021). Population living on permafrost in the Arctic. Population and Environment 43(1), 22-38. https://doi.org/10.1007/s11111-020-00370-6

Rana, K., Page, A., Kent, J.L. and Arora, A. (2022). Pathways Linking Housing Inequalities and Health Outcomes among Migrant and Refugee Populations in High-Income Countries: A Protocol for a Mixed-Methods Systematic Review. International Journal of Environmental Research and Public Health 19(24). https://doi.org/10.3390/ijerph192416627

Rayasam, S.D.G., Koman, P.D., Axelrad, D.A., Woodruff, T.J. and Chartres, N. (2022). Toxic Substances Control Act (TSCA) Implementation: How the Amended Law Has Failed to Protect Vulnerable Populations from Toxic Chemicals in the United States. Environmental Science & Technology 56(17), 11969-11982. https://doi.org/10.1021/acs.est.2c02079

Reed, G., Brunet, N.D., McGregor, D., Scurr, C., Sadik, T., Lavigne, J. et al. (2022). Toward Indigenous visions of nature-based solutions: an exploration into Canadian federal climate policy. Climate Policy 22(4), 514-533. https://doi.org/10.1080/14693062.2022.2047585

Reed, G., Fox, S., Littlechild, D., McGregor, D., Lewis, D., Popp, J. et al. (2024). For Our Future: Indigenous Resilience Report. Ottawa. https://doi.org/10.1080/14693062.2022.2047585

Rees, W.G., Hofgaard, A., Boudreau, S., Cairns, D.M., Harper, K., Mamet, S. et al. (2020). Is subarctic forest advance able to keep pace with climate change? Global Change Biology 26(7), 3965-3977. https://doi.org/10.1111/gcb.15113

Riggi, L.G.A., Raderschall, C.A., Fijen, T.P.M., Scheper, J., Smith, H.G., Kleijn, D. et al. (2023). Early-season mass-flowering crop cover dilutes wild bee abundance and species richness in temperate regions: A quantitative synthesis. Journal of Applied Ecology 00, 1-13. https://doi.org/10.1111/1365-2664.14566

Robin, L., Robin, K., Camerlenghi, E., Ireland, L. and Ryan-Colton, E. (2022). How Dreaming and Indigenous ancestral stories are central to nature conservation: Perspectives from Walalkara Indigenous Protected Area, Australia. Ecological Management & Restoration 23(S1), 43-52. https://doi.org/10.1111/emr.12528

Rocklöv, J. and Dubrow, R. (2020). Climate change: an enduring challenge for vector-borne disease prevention and control. Nature Immunology 21(5), 479-483. https://doi.org/10.1038/s41590-020-0648-y

Romanello, M., Napoli, C.d., Green, C., Kennard, H., Lampard, P., Scamman, D. et al. (2023). The 2023 report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. The Lancet 402(10419), 2346-2394. https://doi.org/10.1016/S0140-6736(23)01859-7

Rotherham, I.D. (2022). Challenges for the restoration of cultural values in UK woodlands. Forest Ecology and Management 503, 119756. https://doi.org/10.1016/j.foreco.2021.119756

Sabatini, F.M., Jiménez-Alfaro, B., Jandt, U., Chytrý, M., Field, R., Kessler, M. et al. (2022). Global patterns of vascular plant alpha diversity. Nature Communications 13(1), https://doi.org/10.1038/s41467-022-32063-z

Sacatelli, R., Kaplan, M., Carleton, G. and Lathrop, R.G. (2023). Coastal Forest Dieback in the Northeast USA: Potential Mechanisms and Management Responses. Sustainability 15(8). https://doi.org/10.3390/su15086346

Salazar-Miranda, A., Conzelmann, C., Phan, T. and Hoffman, J. (2024). Long-term effects of redlining on climate risk exposure. Nature Cities 1(6), 436-444. https://doi.org/10.1038/s44284-024-00076-y

Saliu, T.D. and Sauvé, S. (2024). A review of per- and polyfluoroalkyl substances in biosolids: geographical distribution and regulations. Frontiers in Environmental Chemistry 5. https://doi.org/10.3389/fenvc.2024.1383185

Sánchez-Bayo, F. and Wyckhuys, K.A.G. (2019). Worldwide decline of the entomofauna: A review of its drivers. Biological Conservation 232, 8-27. https://doi.org/10.1016/j.biocon.2019.01.020

Sandlos, J. and Keeling, A. (2017). 10. The Giant Mine's Long Shadow: Arsenic Pollution and Native People in Yellowknife, Northwest Territories. In: Mining North America. McNeill, J.R. and Vrtis, G. (eds.). University of California Press. 280-312. https://doi.org/10.1525/9780520966536-013

Santangeli, A., Buechley, E.R., Mammola, S. and Lambertucci, S.A. (2022). Priorities for research and action to prevent a New World vulture crisis. Biological Conservation 270, 109563. https://doi.org/10.1016/j.biocon.2022.109563

Schulte-Uebbing, L.F., Beusen, A.H.W., Bouwman, A.F. and de Vries, W. (2022). From planetary to regional boundaries for agricultural nitrogen pollution. Nature 610(7932), 507-512. https://doi.org/10.1038/s41586-022-05158-2

Schulz, R., Bub, S., Petschick, L.L., Stehle, S. and Wolfram, J. (2021). Applied pesticide toxicity shifts toward plants and invertebrates, even in GM crops. Science 372(6537), 81-84. https://doi.org/10.1126/science.abe1148

Schumacher, K. and Forster, A.L. (2022). Facilitating a Circular Economy for Textiles: Workshop Report. National Institute of Standards and Technology. https://doi.org/10.6028/NIST.SP.1500-207

Secretariat of the Convention on Biological Diversity (2020). Global Biodiversity Outlook 5. Montreal: Secretariat of the Convention on Biological Diversity. https://www.cbd.int/GBO5 Accessed 2 April 2025

Semenza, J.C. and Paz, S. (2021). Climate change and infectious disease in Europe: Impact, projection and adaptation. The Lancet Regional Health – Europe 9, 100230. https://doi.org/10.1016/j.lanepe.2021.100230

Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Luca, A.D. et al. (2021). Weather and Climate Extreme Events in a Changing Climate. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (eds.). Cambridge and New York: Cambridge University Press. 1513–1766. https://doi.org/10.1017/9781009157896.013

Sesana, E., Gagnon, A., Ciantelli, C., Cassar, J. and Hughes, J. (2021). Climate change impacts on cultural heritage: A literature review. WIREs Climate Change 12. https://doi.org/10.1002/wcc.710

Sicard, P., Agathokleous, E., Anenberg, S.C., De Marco, A., Paoletti, E. and Calatayud, V. (2023). Trends in urban air pollution over the last two decades: A global perspective. Science of The Total Environment 858, 160064. https://doi.org/10.1016/j.scitotenv.2022.160064

Siegel, L., Goldscheider, N., Petitta, M., Xanke, J., Andreo, B., Bakalowicz, M. et al. (2023). Distribution, threats and protection of selected karst groundwater-dependent ecosystems in the Mediterranean region. Hydrogeology Journal 31(8), 2231-2249. https://doi.org/10.1007/s10040-023-02711-9

Smart, L.S., Taillie, P.J., Poulter, B., Vukomanovic, J., Singh, K.K., Swenson, J.J. et al. (2020). Aboveground carbon loss associated with the spread of ghost forests as sea levels rise. Environmental Research Letters 15(10), 104028. https://doi.org/10.1088/1748-9326/aba136

Smith, B.W., Black, J.L., Hoerle, S., Ferland, M.A., Diffey, S.M., Neumann, J.T. et al. (2022). The impact of industrial pollution on the rock art of Murujuga, Western Australia. Rock Art Research 39(1), 3-14. https://search.informit.org/doi/10.3316/informit.393299089754403 Accessed 2 April 2025

Smith, K.E., Burrows, M.T., Hobday, A.J., King, N.G., Moore, P.J., Sen Gupta, A. et al. (2023). Biological Impacts of Marine Heatwaves. Annual Review of Marine Science 15, 119-145. https://doi.org/10.1146/annurev-marine-032122-121437

Sonne, C., Desforges, J.-P., Gustavson, K., Bossi, R., Bonefeld-Jørgensen, E.C., Long, M. et al. (2023). Assessment of exposure to perfluorinated industrial substances and risk of immune suppression in Greenland and its global context: a mixed-methods study. The Lancet Planetary Health 7(7), e570-e579. https://doi.org/10.1016/S2542-5196(23)00106-7

Spezzano, P. (2021). Mapping the susceptibility of UNESCO World Cultural Heritage sites in Europe to ambient (outdoor) air pollution. Science of The Total Environment 754, 142345. https://doi.org/10.1016/j.scitotenv.2020.142345

Stahlmann-Brown, P., Manaaki Whenua and Robertso, T. (2024). Report on the 2023 New Zealand Colony Loss Survey. Wellington: Ministry for Primary Industries. https://www.mpi.govt.nz/dmsdocument/61414-Report-on-the-2023-New-Zealand-Colony-Loss-Survey.Accessed 2 April 2025

Szymczak, S., Backendorf, F., Bott, F., Fricke, K., Junghänel, T. and Walawender, E. (2022). Impacts of Heavy and Persistent Precipitation on

Railroad Infrastructure in July 2021: A Case Study from the Ahr Valley, Rhineland-Palatinate, Germany. Atmosphere 13(7). https://doi.org/10.3390/atmos13071118

Talloni-Álvarez, N.E., Sumaila, U.R., Le Billon, P. and Cheung, W.W.L. (2019). Climate change impact on Canada's Pacific marine ecosystem: The current state of knowledge. Marine Policy 104, 163-176. https://doi.org/10.1016/j.marpol.2019.02.035

Tang, Y.S., Flechard, C.R., Dämmgen, U., Vidic, S., Djuricic, V., Mitosinkova, M. et al. (2021). Pan-European rural monitoring network shows dominance of NH3 gas and NH4NO3 aerosol in inorganic atmospheric pollution load. Atmos. Chem. Phys. 21(2), 875-914. https://doi.org10.5194/acp-21-875-2021

The Saami Council (2023). Climate Change in Sápmi. Kárášjohka: The Saami Council. https://www.saamicouncil.net/documentarchive/sami-climate-report Accessed 2 April 2025

Thurston, G., Yu, W. and Luglio, D. (2023). An Evaluation of the Asthma Impact of the June 2023 New York City Wildfire Air Pollution Episode. American Journal of Respiratory and Critical Care Medicine 208(8), 898-900. https://doi.org/10.1164/rccm.202306-1073LE

Tian, H., Bian, Z., Shi, H., Qin, X., Pan, N., Lu, C. et al. (2022). History of anthropogenic Nitrogen inputs (HaNi) to the terrestrial biosphere: a 5-arcmin resolution annual dataset from 1860 to 2019. Earth System Science Data 14(10), 4551-4568. https://doi.org/10.5194/essd-14-4551-2022

Tian, H., Xu, R., Pan, S., Yao, Y., Bian, Z., Cai, W.-J. et al. (2020). Long-Term Trajectory of Nitrogen Loading and Delivery From Mississippi River Basin to the Gulf of Mexico. Global Biogeochemical Cycles 34(5), e2019GB006475. https://doi.org/10.1029/2019GB006475

Tibbett, M., Fraser, T.D. and Duddigan, S. (2020). Identifying potential threats to soil biodiversity. PeerJ 8, e9271. https://doi.org/10.7717/peerj.9271

Tradowsky, J.S., Philip, S.Y., Kreienkamp, F., Kew, S.F., Lorenz, P., Arrighi, J. et al. (2023). Attribution of the heavy rainfall events leading to severe flooding in Western Europe during July 2021. Climatic Change 176(7), 90. https://doi.org/10.1007/s10584-023-03502-7

Tudi, M., Li, H., Li, H., Wang, L., Lyu, J., Yang, L. et al. (2022). Exposure Routes and Health Risks Associated with Pesticide Application. Toxics 10(6). https://doi.org/10.3390/toxics10060335

United Nations Environment Programme (2019). Frontiers 2018/19 Emerging Issues of Environmental Concern. Nairobi: United Nations Environment Programme. https://www.unep.org/resources/frontiers-201819-emerging-issues-environmental-concern Accessed 2 April 2025

United Nations Environment Programme (2024). Global Waste Management Outlook 2024: Beyond an age of waste – Turning rubbish into a resource. Nairobi: United Nations Environment Programme. https://wedocs.unep.org/20.500.11822/44939 Accessed 2 April 2025

United Nations Environment Programme and International Resource Panel (2024). Global Resources Outlook 2024 - Bend the trend: Pathways to a Liveable Planet as Resource Use Spikes. Nairobi: United Nations Environment Programme. https://wedocs.unep.org/20.500.11822/44901 Accessed 2 April 2025

United Nations Environment Programme and Secretariat of the Basel, Rotterdam and Stockholm Conventions (2023). Chemicals in plastics: a technical report. Geneva: United Nations Environment Programme. https://www.unep.org/resources/report/chemicals-plastics-technical-report Accessed 2 April 2025

United Nations Environment Programme World Conservation Monitoring Centre (2022). Rarity-weighted species richness. Derived from Areas of Habitat maps created from data from the IUCN Red List, BirdLife International, the Global Assessment of Reptile Distributions (GARD), the Botanical Information and Ecology Network (BIEN) database and additional vascular plant species ranges were created from point data from the IUCN Red List, Botanic Gardens Conservation International (BGCI), the Global Biodiversity Information Facility (GBIF) and iNaturalist. https://data-gis.unep-wcmc.org/portal/home/item.html?id=b849fcf6e50446238160212c8165da91 Accessed 25 October 2024

United Nations Environment Programme World Conservation Monitoring Centre and International Union for Conservation of Nature (2021). Protected Planet Report 2020. Cambridge and Gland: United Nations Environment Programme World Conservation Monitoring Centre and International Union for Conservation of Nature. https://livereport.protectedplanet.net/ Accessed 2 April 2025

United States Centers for Disease Control and Prevention (2024). About Immigrant and Refugee Health. https://www.cdc.gov/immigrant-refugee-health/about/ Accessed 3 October 2023

United States Department of the Interior (2021). U.S. Department of the Interior Invasive Species Strategic Plan, Fiscal Years 2021-2025. Washington. https://www.doi.gov/sites/doi.gov/files/doi-invasive-species-strategic-plan-2021-2025-508.pdf

United States Environmental Protection Agency (2025). What is a Circular Economy? US EPA. https://www.epa.gov/circulareconomy/what-circular-economy Accessed 1 April 2025

United States Government (2021). Infrastructure Investment and Jobs Act H.R.3684. House - Transportation and Infrastructure, United States 117-58: https://www.congress.gov/bill/117th-congress/house-bill/3684 Accessed 21 October 2024

United States of America, Government Accountability Office (2021). Disaster Recovery: Efforts to Identify and Address Barriers to Receiving Federal Recovery Assistance. Government Accountability Office. GAO-22-105488. https://www.gao.gov/assets/gao-22-105488.pdf

United States of America, Department of Labor and Occupational Safety and Health Administration (2024). Heat Injury and Illness Prevention in Outdoor and Indoor Work Settings Federal Register, 89, 169: 376 https://www.federalregister.gov/documents/2024/08/30/2024-14824/heat-injury-and-illness-prevention-in-outdoor-and-indoor-work-settings Accessed 2 April 2025

United States of America, National Oceanic and Atmospheric Administration (2024). Assessing the U.S. Climate in June 2024. https://www.ncei.noaa.gov/news/national-climate-202406 Accessed 30 September 2024

Ury, E.A., Yang, X., Wright, J.P. and Bernhardt, E.S. (2021). Rapid deforestation of a coastal landscape driven by sea-level rise and extreme events. Ecological Applications 31(5), e02339. https://doi.org/10.1002/eap.2339

Valuation Office Agency (2024). Council Tax: stock of properties statistical commentary. United Kingdom Government. https://www.gov.uk/government/statistics/council-tax-stock-of-properties-2024/council-tax-stock-of-properties-statistical-commentary Accessed 25 October 2024

van Daalen, K.R., Romanello, M., Rocklöv, J., Semenza, J.C., Tonne, C., Markandya, A. et al. (2022). The 2022 Europe report of the Lancet Countdown on health and climate change: towards a climate resilient future. The Lancet Public Health 7(11), e942-e965. https://doi.org/10.1016/S2468-2667(22)00197-9

van Damme, M., Clarisse, L., Stavrakou, T., Wichink Kruit, R., Sellekaerts, L., Viatte, C. et al. (2022). On the weekly cycle of atmospheric ammonia over European agricultural hotspots. Scientific Reports 12(1), 12327. https://doi.org/10.1038/s41598-022-15836-w

van den Brekel, L., Lenters, V., Mackenbach, J.D., Hoek, G., Wagtendonk, A., Lakerveld, J. et al. (2024). Ethnic and socioeconomic inequalities in air pollution exposure: a cross-sectional analysis of nationwide individual-level data from the Netherlands. The Lancet Planetary Health 8(1), e18-e29. https://doi.org/10.1016/S2542-5196(23)00258-9

van der Sluijs, J.P. (2020). Insect decline, an emerging global environmental risk. Current Opinion in Environmental Sustainability 46, 39-42. https://doi.org/10.1016/j.cosust.2020.08.012

Van Meter, K.J., Byrnes, D.K. and Basu, N.B. (2023). Memory and Management: Competing Controls on Long-Term Nitrate Trajectories in U.S. Rivers. Global Biogeochemical Cycles 37(4), e2022GB007651. https://doi.org/10.1029/2022GB007651

Van Meter, K.J., Schultz, V.O. and Chang, S.Y. (2023). Data-driven approaches demonstrate legacy N accumulation in Upper Mississippi River Basin groundwater. Environmental Research Letters 18(9), 094016. https://doi.org/10.1029/2022GB007651

van Weelden, C., Towers, J.R. and Bosker, T. (2021). Impacts of climate change on cetacean distribution, habitat and migration. Climate Change Ecology 1, 100009. https://doi.org/10.1016/j.ecochg.2021.100009

Venegas, R.M., Acevedo, J. and Treml, E.A. (2023). Three decades of ocean warming impacts on marine ecosystems: A review and perspective. Deep Sea Research Part II: Topical Studies in Oceanography 212, 105318. https://doi.org/10.1016/j.dsr2.2023.105318

Vienna University of Economics and Business (WU Vienna) – Institute for Ecological Economics. n.d. Country Profiles. Visualisation Centre. https://

www.materialflows.net/visualisation-centre/country-profiles/ Accessed 12 August 2025

Vitasse, Y., Ursenbacher, S., Klein, G., Bohnenstengel, T., Chittaro, Y., Delestrade, A. et al. (2021). Phenological and elevational shifts of plants, animals and fungi under climate change in the European Alps. Biological Reviews 96(5), 1816-1835. https://doi.org/10.1111/brv.12727

Vujić, A., Gilbert, F., Flinn, G., Englefield, E., Varga, Z., Ferreira, C.C. et al. (2022). European Red List of Hoverflies. Brussels: European Commission. https://data.europa.eu/doi/10.2779/359875 Accessed 2 April 2025

Waddington, K., Harrison, A., Rayner, D., Tucker, T. and Glamore, W. (2023). Estuarine Hypoxia—Identifying High Risk Catchments Now and Under Future Climate Scenarios. Water Resources Research 59(9), e2023WR035026. https://doi.org/10.1029/2023WR035026

Wang, R., Pan, D., Guo, X., Sun, K., Clarisse, L., Van Damme, M. et al. (2023). Bridging the spatial gaps of the Ammonia Monitoring Network using satellite ammonia measurements. Atmospheric Chemistry and Physics 23(20), 13217-13234. https://doi.org/10.5194/acp-23-13217-2023

Wang, Y., Faloona, I.C. and Houlton, B.Z. (2023). Satellite NO2 trends reveal pervasive impacts of wildfire and soil emissions across California landscapes. Environmental Research Letters 18(9), 094032. https://doi.org/10.1088/1748-9326/acec5f

Weissman, D.S. and Tully, K.L. (2020). Saltwater intrusion affects nutrient concentrations in soil porewater and surface waters of coastal habitats. Ecosphere 11(2), e03041. https://doi.org/10.1002/ecs2.3041

White, E.E., Ury, E.A., Bernhardt, E.S. and Yang, X. (2022). Climate Change Driving Widespread Loss of Coastal Forested Wetlands Throughout the North American Coastal Plain. Ecosystems 25(4), 812-827. https://doi.org/10.1007/s10021-021-00686-w

White, R.H., Anderson, S., Booth, J.F., Braich, G., Draeger, C., Fei, C. et al. (2023). The unprecedented Pacific Northwest heatwave of June 2021. Nature Communications 14(1), 727. https://doi.org/10.1038/s41467-023-36289-3

Wolff, N.H., Mumby, P.J., Devlin, M. and Anthony, K.R.N. (2018). Vulnerability of the Great Barrier Reef to climate change and local pressures. Global Change Biology 24(5), 1978-1991. https://doi.org/10.1111/gcb.14043

World Integrated Trade Solution -UNSD Comtrade (2024). Honey; natural exports by country in 2021. World Integrated Trade Solution. https://wits.worldbank.org/trade/comtrade/en/country/ALL/year/2021/tradeflow/Exports/partner/WLD/product/040900# Accessed 2 February 2024

World Meteorological Organization (2024). State of the Global Climate 2023. Geneva: World Meteorological Organization. https://library.wmo.int/idurl/4/68835 Accessed 2 April 2025

World Weather Attribution (2024). Yet another hurricane wetter, windier and more destructive because of climate change. https://www.worldweatherattribution.org/yet-another-hurricane-wetter-windier-and-more-destructive-because-of-climate-change/ Accessed 22 October 2024

World Wide Fund For Nature (2024). Living Planet Report 2024 – A System in Peril. Gland: WWF. https://livingplanet.panda.org/en-GB Accessed 2 April 2025

Yang, X., Wang, Y., Zhao, C., Fan, H., Yang, Y., Chi, Y. et al. (2022). Health risk and disease burden attributable to long-term global fine-mode particles. Chemosphere 287, 132435. https://doi.org/10.1016/j.chemosphere.2021.132435

Young, R. and Hsiang, S. (2024). Mortality caused by tropical cyclones in the United States. Nature 635, 121-128. https://doi.org/10.1038/s41586-024-07945-5

Zachariah, M., Philip, S., Pinto, I., Vahlberg, M., Singh, R., Otto, F. et al. (2023). Extreme heat in North America, Europe and China in July 2023 made much more likely by climate change. Grantham Institute for Climate Change. https://doi.org/10.25561/105549

Zacharias, Q. and Kaplan, D. (2023). The past, present, and potential future of phosphorus management in the Florida Everglades. Restoration Ecology 31(3), e13799. https://doi.org/10.1111/rec.13799

Zalzal, J. and Hatzopoulou, M. (2022). Fifteen Years of Community Exposure to Heavy-Duty Emissions: Capturing Disparities over Space and Time. Environmental Science & Technology 56(23), 16621-16632. https://doi.org/10.1021/acs.est.2c04320

Zamuda, C.D., Bilello, D.E., Carmack, J., Davis, X.J., Efroymson, R.A., Goff, K.M. et al. (2023). Chapter 5: Energy supply, delivery, and demand. In: Fifth National Climate Assessment. Crimmins, A.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Stewart, B.C. and Maycock, T.K. (eds.). Washington: U.S. Global Change Research Program. https://nca2023.globalchange.gov/chapter/5 Accessed 2 April 2025

Zhang, X., Li, H.-Y., Deng, Z.D., Leung, L.R., Skalski, J.R. and Cooke, S.J. (2019). On the variable effects of climate change on Pacific salmon. Ecological Modelling 397, 95-106. https://doi.org/10.1016/j.ecolmodel.2019.02.002

Zhang, C., Wang, X., Kaur, P. and Gan, J. (2023). A critical review on the accumulation of neonicotinoid insecticides in pollen and nectar: Influencing factors and implications for pollinator exposure. Science of The Total Environment 899, 165670. https://doi.org/10.1016/j.scitotenv.2023.165670

Zhou, J., Mogollón, J.M., van Bodegom, P.M., Barbarossa, V., Beusen, A.H.W. and Scherer, L. (2023). Effects of Nitrogen Emissions on Fish Species Richness across the World's Freshwater Ecoregions. Environmental Science & Technology 57(22), 8347-8354. https://doi.org/10.1021/acs.est.2c09333

Zhou, T., Li, X., Liu, H., Dong, S., Zhang, Z., Wang, Z. et al. (2024). Occurrence, fate, and remediation for per-and polyfluoroalkyl substances (PFAS) in sewage sludge: A comprehensive review. Journal of Hazardous Materials 466, 133637. https://doi.org/10.1016/j.jhazmat.2024.133637

Telecoupling

Adger, W.N., Fransen, S., Safra de Campos, R. and Clark, W.C. (2024). Migration and sustainable development. Proceedings of the National Academy of Sciences 121(3), e2206193121. https://doi.org/10.1073/pnas.2206193121

Ahmed, M.N.Q., Givens, J.E. (2025). Farmers' Climate Change Adaptation Strategies and the Role of Environmental Awareness and Education: A Review in Africa. In: Practices, Perceptions and Prospects for Climate Change Education in Africa. Mbah, M.F., Molthan-Hill, P., Molua, E.L. (eds.). Springer, Cham. https://doi.org/10.1007/978-3-031-84081-4_9

Azam, M. and Raza, A. (2022). Does foreign direct investment limit trade-adjusted carbon emissions: fresh evidence from global data. Environmental Science and Pollution Research 29(25), 37827-37841. https://doi.org/10.1007/s11356-021-18088-9

Bhardwaj, B. and Sharma, D. (2023). Migration of skilled professionals across the border: Brain drain or brain gain? European Management Journal 41(6), 1021-1033. https://doi.org/10.1016/j.emj.2022.12.011

Beine, M., Docquier, F. and Rapoport, H. (2001). Brain drain and economic growth: theory and evidence. Journal of development economics 64(1), 275-289. https://doi.org/10.1016/S0304-3878(00)00133-4

Castro, A.J., Ibarrola-Rivas, M.-J., Kastner, T., Nonhebel, S. and Turkelboom, F. (2020). Telecoupling through tomato trade: what consumers do not know about the tomato on their plate. Global Sustainability 3, e7. https://doi.org/10.1017/sus.2020.4

Chen, H., Goutte, S. (2025). Migration surge under the context of climate change: a case study of China. Environmental Economics and Policy Studies 20(2). https://doi.org/10.1007/s10018-024-00431-2

Christoforidis, T. and Katrakilidis, C. (2022). Does Foreign Direct Investment Matter for Environmental Degradation? Empirical Evidence from Central–Eastern European Countries. Journal of the Knowledge Economy 13(4), 2665-2694. https://doi.org/10.1007/s13132-021-00820-y

Coenen, J., Bager, S., Meyfroidt, P., Newig, J. and Challies, E. (2021). Environmental Governance of China's Belt and Road Initiative. Environmental Policy and Governance 31(1), 3-17. https://doi.org/10.1002/eet.1901

da Silva, R. F. B., Vina, A., Moran, E. F., Dou, Y., Batistella, M. and Liu, J. (2021). Socioeconomic and environmental effects of soybean production in metacoupled systems. Scientific reports 11, 1-12. https://doi.org/10.1038/s41598-021-98256-6

da Silva, R.F.B., Millington, J.D.A., Viña, A., Dou, Y., Moran, E., Batistella, M. et al. (2023). Balancing food production with climate change mitigation and biodiversity conservation in the Brazilian Amazon. Science of The Total Environment 904, 166681. https://doi.org/10.1016/j.scitotenv.2023.166681

Dedeoğlu, M., Koçak, E. and Uucak, Z.Ş. (2021). The impact of immigration on human capital and carbon dioxide emissions in the USA: an empirical

investigation. Air Quality, Atmosphere & Health 14(5), 705-714. https://doi.org/10.1007/s11869-020-00973-w

Delazeri, L.M.M., Da Cunha, D.A. and Oliveira, L.R. (2022). Climate change and rural–urban migration in the Brazilian Northeast region. GeoJournal 87, 2159–2179. https://doi.org/10.1007/s10708-020-10349-3

Destek, M.A. and Okumus, I. (2019). Does pollution haven hypothesis hold in newly industrialized countries? Evidence from ecological footprint. Environmental Science and Pollution Research 26(23), 23689-23695. https://doi.org/10.1007/s11356-019-05614-z

Duan, X., Zhang, J., Sun, P., Zhang, H., Wang, C., Sun, Y.-Y. et al. (2022). Carbon Emissions of the Tourism Telecoupling System: Theoretical Framework, Model Specification and Synthesis Effects. International Journal of Environmental Research and Public Health 19(10). https://doi.org/10.3390/ijerph19105984

Guo, X., Chen, R., Li, Q. and Meadows, M.E. (2021). Achieving win–win solutions in telecoupled human–land systems. Land 10(3), 272. https://doi.org/10.3390/land10030272

Hao, Y., Wu, Y., Wu, H. and Ren, S. (2020). How do FDI and technical innovation affect environmental quality? Evidence from China. Environmental Science and Pollution Research 27(8), 7835-7850. https://doi.org/10.1007/s11356-019-07411-0

Hua, X., Kono, Y., Zhang, L., Xu, E. and Luo, R. (2019). How transnational labor migration affects upland land use practices in the receiving country: Findings from the China-Myanmar borderland. Land Use Policy 84, 163-176. https://doi.org/10.1016/j.landusepol.2019.03.012

Li, Y., Zhang, Y., Tiffany, L.A., Chen, R., Cai, M. and Liu, J. (2021). Synthesizing social and environmental sensing to monitor the impact of large-scale infrastructure development. Environmental Science & Policy 124, 527-540. https://doi.org/10.1016/j.envsci.2021.07.020

Liu, J. (2020). Telecoupling. International Encyclopedia of Geography 1-8. https://doi.org/10.1002/9781118786352.wbieg2049

Liu, J. (2023). Leveraging the metacoupling framework for sustainability science and global sustainable development. National Science Review 10(7). https://doi.org/10.1093/nsr/nwad090

Liu, J., Hull, V., Batistella, M., DeFries, R., Dietz, T., Fu, F. et al. (2013). Framing Sustainability in a Telecoupled World. Ecology and Society 18(2). https://doi.org/10.5751/ES-05873-180226

Liu, J., Dou, Y., Batistella, M., Challies, E., Connor, T., Friis, C. et al. (2018). Spillover systems in a telecoupled Anthropocene: typology, methods, and governance for global sustainability. Current Opinion in Environmental Sustainability 33, 58-69. https://doi.org/10.1016/j.cosust.2018.04.009

Muradian, R., Cahyafitri, R., Ferrando, T., Grottera, C., Jardim-Wanderley, L., Krause, T. et al. (2025). Will the EU deforestation-free products regulation (EUDR) reduce tropical forest loss? Insights from three producer countries. Ecological Economics 227, 108389. https://doi.org/10.1016/j.ecolecon.2024.108389

Nabulsi, H. (2025). Migration and Its Effects on Regional Development: A Theoretical Approach. In: Unveiling Developmental Disparities in the Middle East. IGI Global. 271-286

Opoku, E.E.O. and Boachie, M.K. (2020). The environmental impact of industrialization and foreign direct investment. Energy Policy 137, 111178. https://doi.org/ https://doi.org/10.1016/j.enpol.2019.111178

Remer, M. and Liu, J. (2022). International Tourism in the Arctic under COVID-19: A Telecoupling Analysis of Iceland. Sustainability 14(22). https://doi.org/0.3390/su142215237

Sachs, J.D., Lafortune, G. and Fuller, G. (2024). The SDGs and the UN Summit of the Future. Sustainable Development Report 2024. Paris and Dublin: SDSN and Dublin University Press. https://files.unsdsn.org/sustainable-development-report-2024.pdf/

Sibhatu, K.T. (2023). Oil palm boom: its socioeconomic use and abuse. Frontiers in Sustainable Food Systems 7. https://doi.org/10.3389/fsufs.2023.1083022

Stark, O., Helmenstein, C. and Prskawetz, A. (1997). A brain gain with a brain drain. Economics letters 55(2), 227-234. https://doi.org/10.1016/S0165-1765(97)00085-2

China Power Team (2024). "How Is the Belt and Road Initiative Advancing China's Interests?" China Power. May 8, 2017. Updated October 11, 2024. Accessed 2 August 2025. https://chinapower.csis.org/china-belt-and-road-initiative/

Thives, V., Søndergaard, N. and Inoue, C.Y.A. (2022). Bringing states back into commodity-centric environmental governance: the telecoupled soy trade between Brazil and China. Third World Quarterly 43(9), 2129-2148. https://ideas.repec.org/a/taf/ctwqxx/v43y2022i9p2129-2148.html

To, A.H., Ha, D.T., Nguyen, H.M. and Vo, D.H. (2019). The Impact of Foreign Direct Investment on Environment Degradation: Evidence from Emerging Markets in Asia. International Journal of Environmental Research and Public Health 16(9). https://doi.org/10.3390/ijerph16091636

United Nations Environment Programme (2024). Environmental impact of the conflict in Gaza: Preliminary assessment of environmental impacts. Nairobi. https://wedocs.unep.org/20.500.11822/45739

Yao, G., Hertel, T.W. and Taheripour, F. (2018). Economic drivers of telecoupling and terrestrial carbon fluxes in the global soybean complex. Global Environmental Change 50, 190-200. https://doi.org/10.1016/j.gloenvcha.2018.04.005

Xiao, H., Bao, S., Ren, J., Xu, Z., Xue, S. and Liu, J. (2024). Global transboundary synergies and trade-offs among Sustainable Development Goals from an integrated sustainability perspective. Nature Communications 15(1), 500. https://www.nature.com/articles/s41467-023-44679-w

Xu, Z., Li, Y., Chau, S.N., Dietz, T., Li, C., Wan, L. et al. (2020). Impacts of international trade on global sustainable development. Nature Sustainability 3(11), 964-971. https://doi.org/10.1038/s41893-020-0572-z

Zaehringer, J.G., Schneider, F., Heinimann, A. and Messerli, P. (2019). Co-producing knowledge for sustainable development in telecoupled land systems. In: Telecoupling: Exploring land-use change in a globalised world. Springer. 357-381. https://doi.org/10.1007/978-3-030-11105-2_19

Zeng, Y., Runting, R.K., Watson, J.E. and Carrasco, L.R. (2022). Telecoupled environmental impacts are an obstacle to meeting the sustainable development goals. Sustainable Development 30(1), 76-82. https://doi.org/10.1002/sd.2229

Credit: NASA Visible Earth

PART C

Outlooks

Indigenous Knowledge and Local Knowledge Chapeau C

Chapter 9
Scenario Methodology: Current Trends and Transformation Pathways

Chapter 10
Continuation of Current Trends: Global Implications

Chapter 11
Transformation Pathways towards Achieving Global Goals: Global Implications

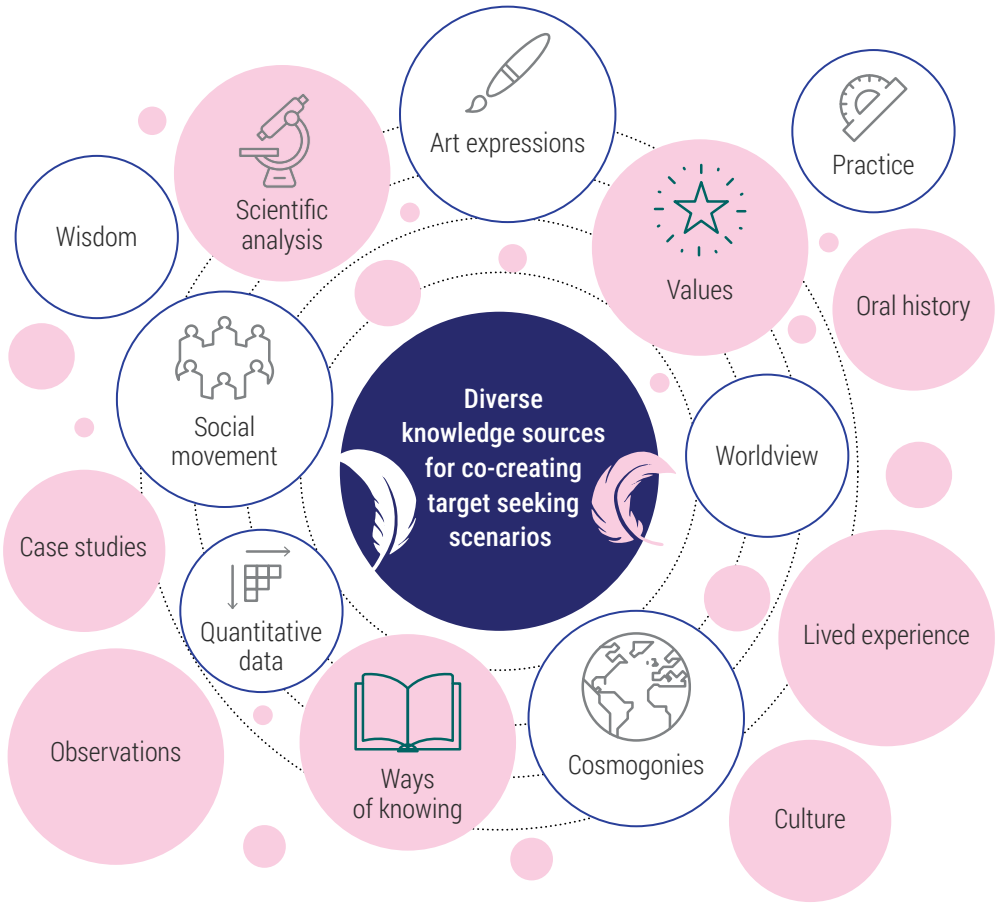
Indigenous Knowledge and Local Knowledge Chapeau C

Perspectives from Indigenous Knowledge and Local Knowledge can foster a co-creation process that is necessary for building responsible and resilient scenarios for future generations. Indigenous Knowledge and Local Knowledge play an active role in the generation of relational understanding, which often includes gender-specific experiences (Jessen 2021; Ibarra et al. 2023; IK & LK Dialogues 2025).

In addition to enabling holistic insight into ongoing environmental challenges and possible futures, need to center Indigenous Knowledge and Local Knowledge perspectives in scenario analysis. Existing scenario approaches struggle to engage the knowledge, observations, and aspirations of Indigenous Peoples (Aguiar et al. 2020; Pereira et al. 2021). Indeed, scenario analysis typically relies on quantifiable indicators, while Indigenous Knowledge and wisdom cannot be easily quantified. If not handled carefully, scenario analysis can lead to disempowerment of place-based narratives, erosion of trust-building and result in the silencing or appropriation of Indigenous Knowledge (Bates 2007; Camara-Leret et al. 2019; Carmona et al. 2023). Indigenous perspectives involve cyclic rather than linear relationships, along with unique forms of sentience between humans and non-human beings, which can be difficult or even incommensurable to capture in conventional scenario frameworks (Natcher et al. 2007; Cadman et al. 2023).

The co-creation of knowledge is an approach to intercultural collaboration that shares different types of knowledge and experiences to inform high-level policy decisions (Brock et al. 2024; IK & LK Dialogues 2025). This approach values multiple knowledge systems promoting equity between knowledge holders while expanding the scope of data in modelling exercises. By centring Indigenous Knowledge and Local Knowledge in the co-creation process, new scenario analysis can better represent changes occurring across different locations and ecological systems, capturing nuances that might be overlooked by conventional scientific approaches alone (Pearman-Gillman et al. 2020; Cadman et al. 2023). This inclusive approach supports the development of diverse and culturally relevant future scenarios, which are crucial for achieving global policy commitments, such as climate change mitigation, land and biodiversity conservation, and access to resources (Ibarra et al. 2023). These new scenarios, which employ Indigenous approaches to scenario building, can inform local actions, ensuring that global goals are translated into context-relevant strategies (Hérivaux et al. 2021; Hallberg-Sramek et al. 2023). Poor in-depth knowledge and limited willingness to engage with Indigenous Peoples knowledge systems have led to the neglect of Indigenous needs, values and observations in scenario planning (Jesse et al. 2021). During the GEO-7 Indigenous Knowledge and Local Knowledge Dialogues, participants provided

Figure C.1: Diverse knowledge sources for co-creating target seeking scenarios that sustain people and Mother Nature



Note: Worldviews refer to how humans and other entities exist and co-exist in places (e.g., communities, countries, or the planet), which can inform how different knowledge systems understand what is real. Cosmogonies are predominant among Indigenous Peoples, referring to how humans are related to their surroundings, where values like relationality and reciprocity are key to observing, respecting, and sustaining Mother Nature. In this context, multiple methodologies can be used, such as arts, quantitative data, observation, listening, scientific analysis, etc. To truly enable a co-creation space, it is necessary to intentionally balance power asymmetries and apply rights-based frameworks to ensure that Indigenous Peoples and their knowledges are equitably included in the co-creation process and are not exploited.

Source: adapted from Global Alliance for the Future of Food (2021)

key insights on desirable futures and pathways to achieve environmental and social sustainability (IK & LK Dialogues 2025).

Additionally, they stressed the urgency of addressing historical and current injustices especially those tied to colonial legacies and violations of Indigenous rights as essential for fostering reconciliation and decolonization for the next generations from the Haudenosaunee (Iroquois) Indigenous Peoples to respect and honour both ancestors and descendants. It is a way to stay connected with ones past family and show care for those yet to be born, reflecting a perspective of continuity. For scenario planning to be effective, it must recognize Indigenous Peoples inherent rights, including their customary land rights, self-determination, Indigenous data sovereignty and Free,Prior and Informed Consent (FPIC). At the same time, it must address the legacy of colonialism in science and the education system, particularly concerning cultural suppression, forced relocation and social exclusion (IK & LK Dialogues 2025). Furthermore, the involvement of Indigenous Peoples in designing, reviewing and implementing the outcomes of the co-creation process is essential to minimize the risk of unintentional harm. Their participation also ensures that the resulting practices are culturally appropriate and aligned with gender-specific roles and responsibilities, thereby reducing the risk of excluding women, girls, and elders (Mayo D'Arrigo 2019; Hallberg-Sramek et al. 2023; Jacobi et al. 2022).

References

Aguiar, A.P.D., Collste, D., Harmáčková, Z.V., Pereira, L., Selomane, O., Galafassi, D. et al. (2020). Co-designing global target-seeking scenarios: A cross-scale participatory process for capturing multiple perspectives on pathways to sustainability. Global Environmental Change 65, 102198. https://doi.org/10.1016/j.gloenvcha.2020.102198

Bates, P. (2007). Inuit and Scientific Philosophies about Planning, Prediction, and Uncertainty. Arctic Anthropology 44(2), 87. https://doi.org/10.1353/arc.2011.0065

Bélisle, A.C., Wapachee, A. and Asselin, H. (2021). From landscape practices to ecosystem services: Landscape valuation in Indigenous contexts. Ecological Economics 179, 106858. https://doi.org/10.1016/j.ecolecon.2020.106858

Bisht, P. (2017). Decolonizing futures: Exploring storytelling as a tool for inclusion in foresight. Master of Design in Strategic Foresight & Innovation, OCAD University. https://openresearch.ocadu.ca/id/eprint/2129

Brock, S.A.-O., Baker, L.A.-O., Jekums, A.A.-O., Ahmed, F., Fernandez, M., Montenegro de Wit, M.A.-O. et al. (2024). Knowledge democratization approaches for food systems transformation. Nat Food 5(5), 2662-1355. https://doi.org/10.1038/s43016-024-00966-3

Cadman, R., Snook, J., Broomfield, T., Goudie, J., Johnson, R., Watts, K. et al. (2023). Articulating Indigenous Futures: Using Target Seeking Scenario Planning in Support of Inuit-led Fisheries Governance. Journal of Participatory Research Methods 4(2). https://doi.org/10.35844/001c.77450

Cámara-Leret, R., Fortuna, M.A. and Bascompte, J. (2019). Indigenous Knowledge networks in the face of global change. Proceedings of the National Academy of Sciences 116(20), 9913-9918. https://doi.org/10.1073/pnas.1821843116

Carmona, R., Reed, G., Thorsell, S., Dorough, D.S., MacDonald, J.P., Rai, T.B. et al. (2023). Analysing engagement with Indigenous Peoples in the Intergovernmental Panel on Climate Change's Sixth Assessment Report. npj Climate Action 2(1), 29. https://doi.org/10.1038/s44168-023-00048-3

Global Alliance for the Future of Food (2021). The politics of knowledge. Understanding the evidence for Agroecology, Regenerative Approaches, and Indigenous Foodways. Global Alliance for the Future of Food. https://story.futureoffood.org/the-politics-of-knowledge/

Hallberg-Sramek, I., Nordström, E.-M., Priebe, J., Reimerson, E., Mårald, E. and Nordin, A. (2023). Combining scientific and Local Knowledge improves evaluating future scenarios of forest ecosystem services. Ecosystem Services 60, 101512. https://doi.org/10.1016/j.ecoser.2023.101512

Hérivaux, C., Vinatier, F., Sabir, M., Guillot, F. and Rinaudo, J.D. (2021). Combining narrative scenarios, Local Knowledge and land-use change modelling for integrating soil erosion in a global perspective. Land Use Policy 105, 105406. https://doi.org/10.1016/j.landusepol.2021.105406

Ibarra, J.T., Caviedes, J., Marchant, C., Mathez-Stiefel, S.L., Navarro-Manquilef, S. and Sarmiento, F.O. (2023). Mountain social-ecological resilience requires transdisciplinarity with Indigenous and local worldviews. Trends Ecol Evol 38(11), 1005-1009. https://doi.org/10.1016/j.tree.2023.07.004

IK & LK Dialogues (2025). Indigenous Knowledge and Local Knowledge Dialogues. Global Environment Outlook 7. Mexico City: CopIt-arXives https://copitarxives.fisica.unam.mx/SC0011EN/SC0011EN.php

Jacobi, J., Llanque, A., Mukhovi, S.M., Birachi, E., von Groote, P., Eschen, R. et al. (2022). Transdisciplinary co-creation increases the utilization of knowledge from sustainable development research. Environmental Science & Policy 129, 107-115. https://doi.org/10.1016/j.envsci.2021.12.017

Jessen, T.D., Ban, N.C., Claxton, N.X. and Darimont, C.T. (2021). Contributions of Indigenous Knowledge to ecological and evolutionary understanding. Frontiers in Ecology and the Environment 20(2), 93-101. https://doi.org/10.1002/fee.2435

Mayo D'Arrigo, M.J. (2019). Capacidades democráticas para la gobernanza de las áreas naturales protegidas. El caso de la Reserva Natural de Salinas y Aguada Blanca (2015 – 2017). Revista Kawsaypacha: Sociedad y Medio Ambiente(3), 11-40. https://revistas.pucp.edu.pe/index.php/Kawsaypacha/article/view/20959/20648

Nadasdy, P. (1999). The politics of TEK: Power and the" integration" of knowledge. Arctic Anthropology 36(1/2), 1-18. https://www.jstor.org/stable/40316502

Natcher, D.C., Huntington, O., Huntington, H., Chapin, F.S., Trainor, S.F. and DeWilde, L.O. (2007). Notions of Time and Sentience: Methodological Considerations for Arctic Climate Change Research. Arctic Anthropology 44(2), 113. https://doi.org/10.1353/arc.2011.0065

Pearman-Gillman, S.B., Katz, J.E., Mickey, R.M., Murdoch, J.D. and Donovan, T.M. (2020). Predicting wildlife distribution patterns in New England USA with expert elicitation techniques. Global Ecology and Conservation 21, e00853. https://doi.org/10.1016/j.gecco.2019.e00853

Pereira, L., Asrar, G.R., Bhargava, R., Fisher, L.H., Hsu, A., Jabbour, J. et al. (2021). Grounding global environmental assessments through bottom-up futures based on local practices and perspectives. Sustainability Science 16(6), 1907-1922. https://doi.org/10.1007/s11625-021-01013-x

Vizenor, G. (2008). Survivance: Narratives of native presence. Lincoln: University of Nebraska Press. https://mascriticalrace.wordpress.com/wp-content/uploads/2017/10/vizenor-2008-aesthetics.pdf

Walter, M., Kukutai, T., Carroll, S.R. and Rodriguez-Lonebear, D. (2020). Indigenous Data Sovereignty and Policy. 1 edn: Routledge. https://doi.org/10.4324/9780429273957

09 Scenario Methodology: Current Trends and Transformation Pathways

Co-ordinating Lead Authors: Paul Lucas (PBL Netherlands Environmental Assessment Agency) and Detlef van Vuuren (PBL Netherlands Environmental Assessment Agency, Utrecht University)

Lead Authors: Ana Paula Aguiar (INPE, Brazilian Institute for Space Research), Alaa Al Khourdajie (Imperial College London), Vassilis Daioglou (PBL Netherlands Environmental Assessment Agency, Utrecht University), Sibel Eker (International Institute for Applied Systems Analysis, IIASA), Yolanda López-Maldonado (Indigenous Science), Mariana Gutierres-Paz (United Nations Development Programme) and Audrone Telesiene (Kaunas University of Technology)

Fellow: Pushp Raj Tiwari (University of Hertfordshire)

Credit: KrzysztofBubel/Envato

Chapter summary

Credit: Ikunl/Envato

Scenario analysis helps envision plausible futures, which can be assessed both qualitatively using narrative and quantitatively using models (*well established*). Scenarios provide a simplified description of how the future may unfold, based on a coherent and internally consistent set of assumptions about key driving forces and their interrelationships. The qualitative narratives and quantitative models used in scenario development complement each other. Narratives provide an overall logic, while models allow the elaboration of possible trends for those parameters that can be quantified. By considering the interrelations between different systems, environmental and socioeconomic challenges, and social groups, model-based scenarios can help address synergies and trade-offs among various developments, aspirations and measures. {9.2}

The scenario analysis in GEO-7 examines the environmental and socioeconomic implications of continuing today's trends, as well as alternative routes that address the global environmental crises. The *Current Trends Scenario* is an explorative scenario and represents a continuation of current policies and practices. It is used to assess the environmental and socioeconomic implications of failing to address the global environmental crises effectively. The target-seeking scenarios are normative scenarios that describe alternative routes to achieve a set of internationally agreed goals related to the global environmental crises. The goals include limiting global warming in line with the Paris Agreement, halting and reversing biodiversity loss in line with the Kunming-Montreal Global Biodiversity Framework, and achieving land degradation neutrality in line with the United Nations Convention to Combat Desertification 2018–2030 Strategic Framework, alongside improving air quality, ending hunger, and achieving universal access to clean water and modern energy services in line with related Sustainable Development Goals. {9.2, 9.3}

Two contrasting target-seeking scenarios are developed, representing Transformation Pathways, that combine different solutions across the five systems to achieve internationally agreed goals. Multiple pathways are possible and can

coexist in different contexts. To facilitate the understanding of the core assumptions and how they affect different systems, for this 7th Global Environment Outlook (GEO-7) report, two contrasting scenarios are developed and discussed. Their narratives are based on alternative assumptions about societal values and approaches to solving global environmental crises while improving human well-being. Both affect production and consumption patterns, as well as environmental management, but with a diverging rationale, assuming different forms of structural change in society. The *Behaviour-focused Transformation Pathway* envisions a profound transformation in society's values, beliefs and norms, accompanied by a significant decrease in consumption, particularly in affluent countries. The *Technology-focused Transformation Pathway* envisions massive investments in technology development, aiming for efficiency and clean-technology gains in an economically globalized, commodified, liberal and urbanized world. Based on these general assumptions, the two scenarios combine specific solutions for each system. {9.4}

The Transformation Pathways can foster discussions about possible pathways towards a more sustainable future among multiple actors at different levels (*well established*). The pathways are neither predictions nor prescriptions, and no likelihood is attached to them. Instead, they illustrate, under a set of general and system-specific internally consistent assumptions, how different interrelated systems may dynamically evolve over time and what their environmental and socioeconomic implications are. They are archetypes of alternative transformations and act as a heuristic device to explore the solution space of possible pathways to achieve internationally agreed goals. As such, they illustrate – in general terms – the type, extent and effort required to meet the goals; the critical choices involved; related socioeconomic implications; the associated synergies and trade-offs across the goals, measures, and systems; and the possible challenges and opportunities that may arise. They are aimed at fostering discussions about possible pathways towards a more sustainable future, among multiple actors at different levels. {9.2, 9.4}

The GEO-7 scenario methodology combines unique narratives with a suite of well-established and linked models to describe diverse aspects of the future evolution of human and environmental systems in an interactive way. New narratives were constructed to illustrate alternative transformations of the five systems, and a suite of models is used to quantify these narratives. Together, these models cover key elements of the five systems, global environmental crises and their related goals, and the environmental and socioeconomic implications. The models are linked to enable cross-system interactions and thereby enhance the representation of the overall system by explicitly accounting for critical interdependencies and feedback between the component models. Results are compared with established scenario databases and existing literature to address uncertainty and consistency with the broader scenario community. While the methodology provides valuable insights, it is limited in terms of scenario scope, issue coverage and the level of aggregation. {9.4, 9.5, 9.6}

9.1 Introduction

Part B of this assessment demonstrates that most environmental systems are under severe pressure and that trends in environmental degradation are on the rise. These trends are disrupting people's lives and their livelihoods worldwide. Key questions for Part C include:

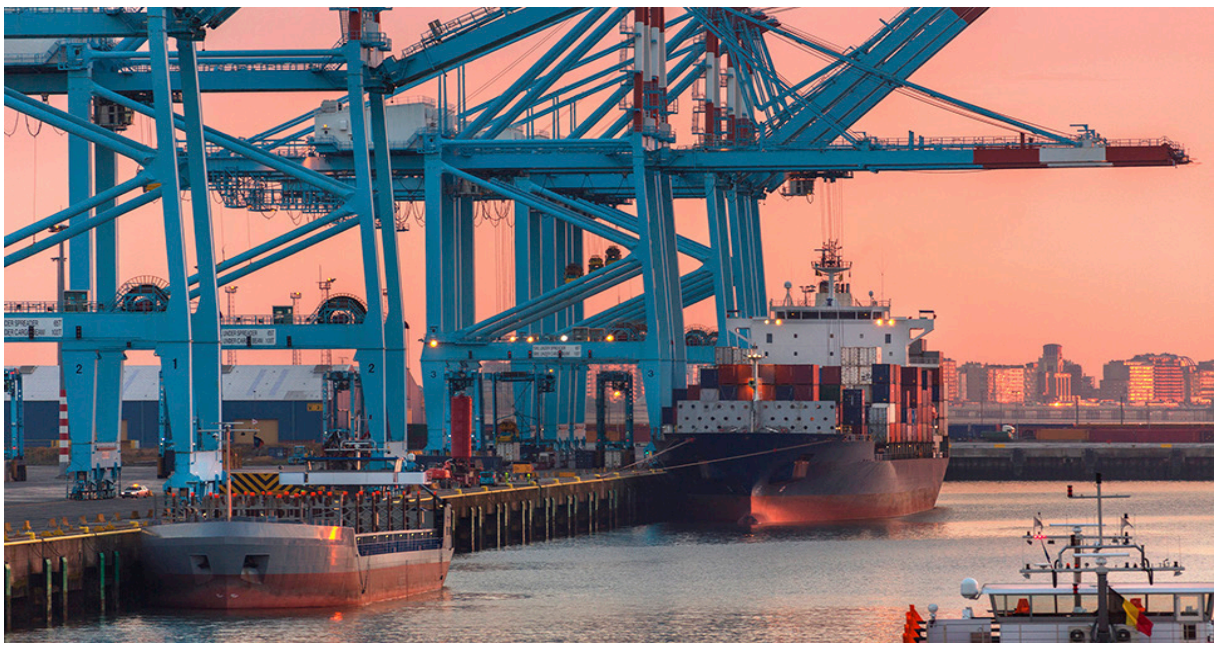
- What are the likely environmental and socioeconomic implications of a continuation of these trends? and
- What is needed to achieve internationally agreed goals related to the global environmental crises – climate change, biodiversity loss and land degradation, and pollution and waste – and to ensure this also helps achieve the Sustainable Development Goals (SDGs)?

To address these questions, three scenarios are developed, utilizing both qualitative and quantitative methods. This chapter presents the methodological approach for developing these scenarios.

9.2 Explorative and target-seeking scenarios

Scenarios provide simplified descriptions of how the future may take shape based on a coherent and internally consistent set of assumptions about key driving forces and their relationships (Raskin et al. 2005; van Vuuren et al. 2012; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem [IPBES] 2016). They can contain a combination of qualitative and quantitative elements using narratives and models (Raskin et al. 2005). These elements complement each other, as narratives can provide an overall logic while models can help elaborate possible trends for those parameters that can be quantified (**Figure 9.1**). Furthermore, where narratives can include important qualitative factors such as values, behaviour and institutions, model-based scenarios offer structure, discipline and rigour (Raskin et al. 2005). By considering the interrelations of different systems, environmental and socioeconomic challenges, and social groups, model-based scenarios can help address synergies and trade-offs among various developments, aspirations and measures.

Many scenarios have been discussed in the scientific literature (Lauer et al. 2024) and used in global environmental assessments (UNEP 2021) such as the Intergovernmental Panel on Climate Change (IPCC 2018; IPCC 2022), Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem (IPBES 2019), United Nations Convention to Combat Desertification (UNCCD 2022) and United Nations Environment Programme (UNEP 2024). In earlier Global Environmental Outlooks (GEOs), scenario analysis has played a prominent role (Bakkes et al. 2022), with the emphasis shifting from what could happen using exploratory scenarios (UNEP 2002;



Credit: image Envato

UNEP 2007) to what should happen using normative target-seeking scenarios (UNEP 2012; UNEP 2019).

Building on previous assessments, particularly GEO-6, the emphasis in GEO-7 is on systems transformation to achieve internationally agreed goals related to the global environmental crises. As the scenario literature addressing this question is limited, GEO-7's Outlook Chapters (Part C: Chapters 9, 10 and 11) provide a comprehensive and tailored analysis of new scenarios. Other new elements include a focus on the five systems of economy and finance, food, energy, materials and waste, and environment; an assessment of both environmental and socioeconomic implications of system transformation; and an accounting of plural, conditional possible futures through the development of two distinct Transformation Pathways.

To address the overarching questions of GEO-7, three scenarios are developed: one exploratory scenario called the Current Trends scenario and two alternative target-seeking scenarios, outlined as Transformation Pathways (**Figure 9.2**). The methodology is based on the Story and Simulation approach (Alcamo 2008; Elsawah et al., 2020), which combines qualitative and

Credit: image Envato

Figure 9.1: Feedback and complementary aspects between qualitative and quantitative aspects of the GEO-7 scenarios

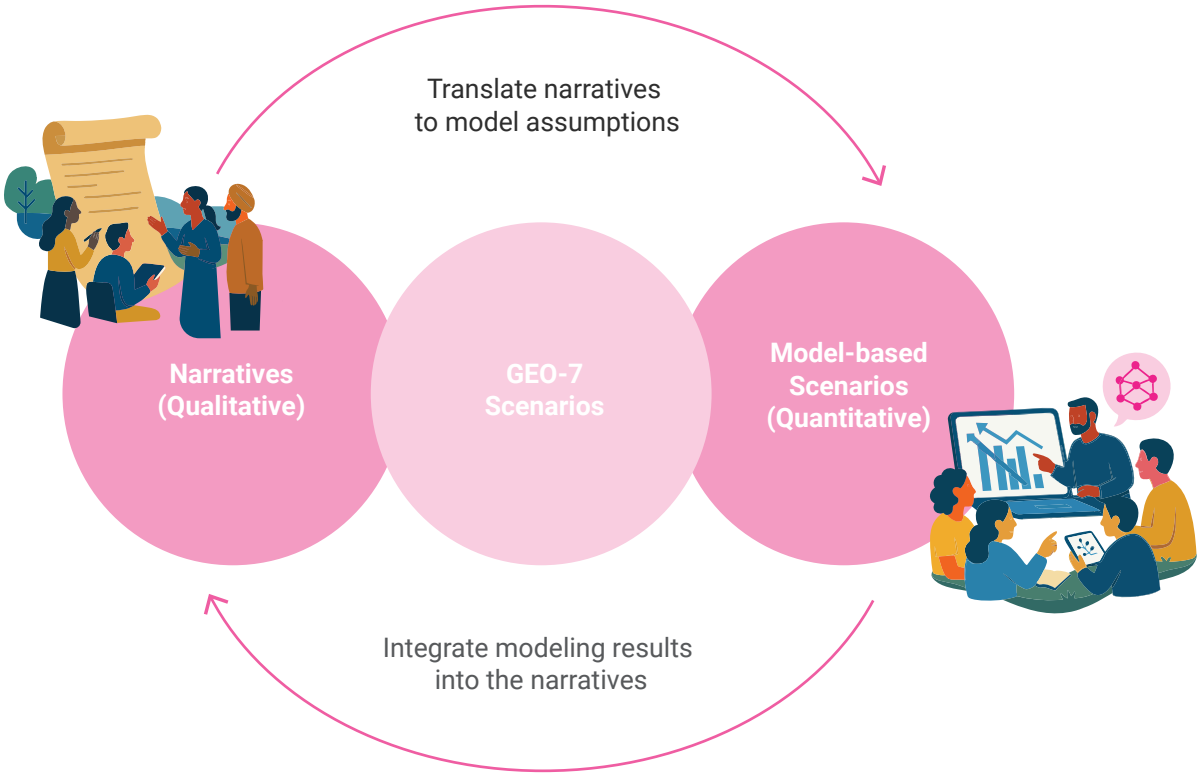
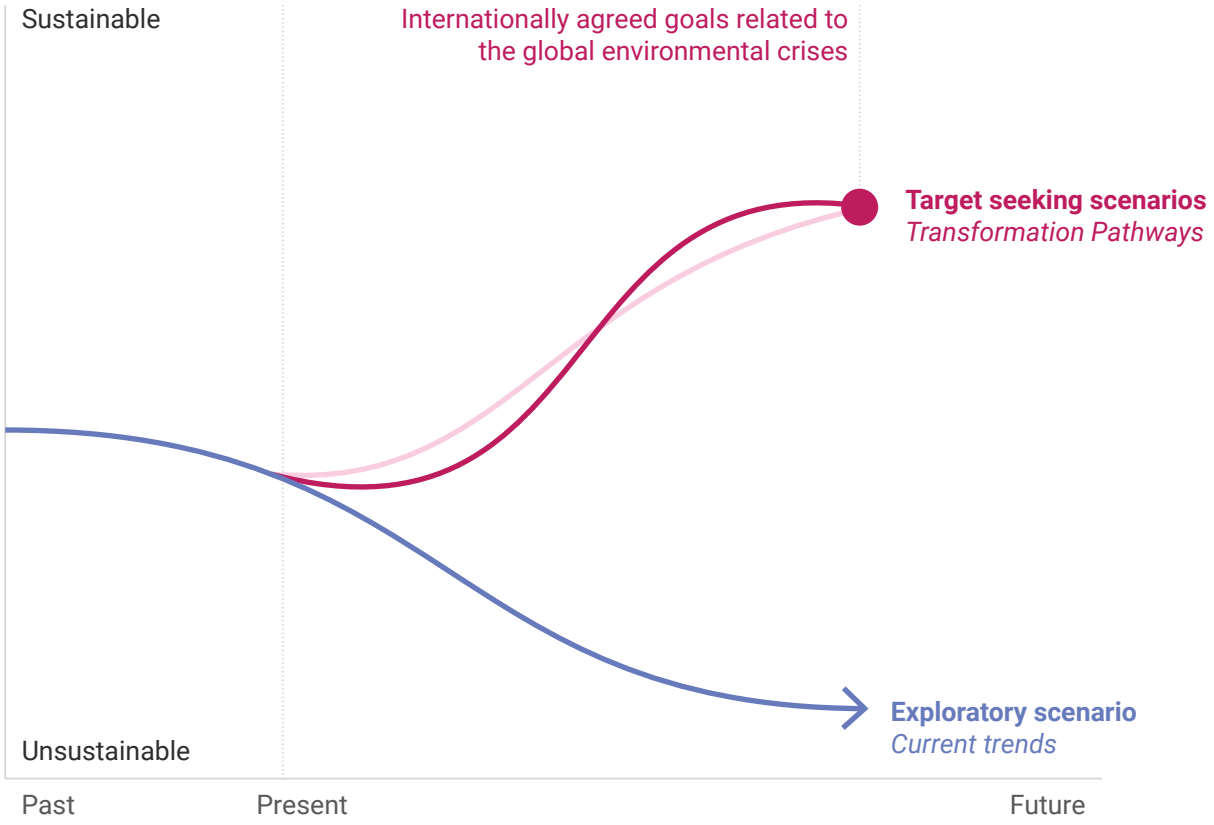


Figure 9.2: Scenarios used in the outlook chapters



quantitative elements. For the Current Trends scenario, the narrative is based on O'Neill et al. (2017), while the narratives for the two Transformation Pathways are specifically developed for GEO-7 (Section 9.4). All three scenarios are formalized using analytical models (Section 9.5). The narratives provide consistency in assumptions across the five systems to enable quantification, while they are also critical to facilitate the understanding and analysis of the quantitative results.

The Current Trends Scenario describes how the five systems develop under a continuation of current trends and efforts, and allows for an assessment of environmental and socioeconomic implications in the absence of stricter policies to address the global environmental crises. It is based on the middle-of-the-road scenario of the Shared Socioeconomic Pathways (SSPs), which describes a world that "…follows a path in which social, economic, and technological trends do not shift markedly from historical patterns…" (O'Neill et al. 2017). While the SSPs were developed principally to support climate change research (van Vuuren et al. 2014), they have also been used for other fields, including biodiversity loss (Pereira et al. 2024), land degradation (van der Esch et al. 2021) and air pollution (Rao et al. 2017). The scenario is not a simple extrapolation of recent experience but rather a development pathway that is consistent with typical patterns observed in the past. The scenario does not include policies and policy objectives that are currently being implemented. While such climate change-related policies are relatively well recognized and utilized in scenario studies (UNEP 2024), this is not the case for the other global environmental crises. Moreover, the primary objective is to examine the likely outcomes of current trends.

The two Transformation Pathways are normative. They describe alternative routes to a desired future scenario defined by a set of internationally agreed goals (Section 9.3). They allow assessment of the required extent and effort, the related socioeconomic implications, key interactions across the five systems, the critical choices involved, and the associated synergies and trade-offs across goals, as well as potential challenges and opportunities. They are driven by integrated solutions that transform the five systems based on alternative assumptions about

societal values and approaches to solving the global environmental crises while improving human well-being. It is crucial to recognize that these Transformation Pathways outline what can be achieved in each system to attain the desirable futures but do not specify how to implement these solutions. The implementation of Solution Pathways is discussed in Part D, Chapters 12–18.

The three scenarios are not predictions or prescriptions, nor is there any likelihood attached to them. Instead, they illustrate, under a set of general and system-specific internally consistent assumptions, how different interrelated systems may dynamically evolve over time and what their environmental and socioeconomic implications are. The two Transformation Pathways are archetypes of alternative possible transformations. They are not mutually exclusive but act as a heuristic device to explore the solution space of possible pathways to achieve globally agreed goals. As such, they aim to foster discussion about possible pathways towards more sustainable futures among multiple actors at different levels.

9.3 Internationally agreed goals used in the scenario analysis

The scenario analysis is guided by a selection of internationally agreed goals related to the global environmental crises (**Table 9.1**). The GEO-7 Current Trends Scenario is used to assess the extent to which these goals are being achieved without stepped-up efforts. In contrast, the two Transformation Pathways are used to illustrate different combinations of measures tailored to achieve these goals.

Given the modelling complexity, the set of goals includes one goal per global environmental crisis. The broader complexity and impacts of the global environmental crises, for example the multiple dimensions of biodiversity, aquatic systems, and the broad range of pollutants, are discussed in Part B, Chapters 3–6, although not in a forward-looking perspective. For each goal, an indicator and a target value are defined in line with international treaties and agreements. The goals for climate change, and biodiversity loss and land degradation are based on the agreed goals within their respective Rio Conventions: The United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD) and and the United Nations Convention to Combat Desertification (UNCCD). Where possible, the goals link to specific SDG targets. For pollution and waste, the goal is based on the 2030 Agenda for Sustainable Development.

- The climate change goal is based on the long-term temperature goal of the Paris Agreement: "…holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels…" (UNFCCC 2015). Global mean temperature increase is used as an indicator to assess future trends in climate change.

- The goal for biodiversity loss is based on the Kunming-Montreal Global Biodiversity Framework (GBF) of the United Nations Convention on Biological Diversity (CBD 2022). Goal A of the GBF is about protecting and restoring biodiversity to bend the trend of biodiversity loss, with increasing biodiversity again by 2050. Target 1 aims to reduce the loss of areas of high biodiversity importance to near zero by 2030. To assess trends in biodiversity loss, the Mean Species Abundance indicator is used, which measures biodiversity intactness (Schipper et al. 2020; Pereira et al. 2013). Given the modelling constraints, the analysis focuses on terrestrial systems only.

- The goal for addressing land degradation is based on the UNCCD 2018–2030 Strategic Framework (UNCCD 2018) and the GBF (CBD 2022). The overall goal of the UNCCD is to achieve land degradation neutrality. Target 2 of the GBF is to restore 30 per cent of degraded ecosystems by 2030. To assess trends in land degradation, two of the three SDG 15.3 sub indicators are used – land cover and soil organic carbon – as these are sufficiently well represented in the model framework.

- The pollution goal focuses on air pollution and is based on SDGs 3.9 and 11.6 (United Nations 2015) and the World Health Organization (WHO) air quality guidelines (WHO 2021). Ambient air pollution and toxic chemical pollution are among the most pressing and increasing modern risks to human and planetary health, with air pollution causing the highest number of deaths from environmental factors and

Table 9.1: Goals to be achieved in the two Transformation Pathways.

	Goal	Indicator	Target value	Global agreement	Related SDG target
Climate change	Limit global warming	Global mean temperature increase	1.5° C by 2100	Paris Agreement (UNFCCC 2015)	SDG 13
Biodiversity loss	Protect biodiversity	Mean Species Abundance in terrestrial systems	No further loss of biodiversity by 2030 and an increase towards 2050	Kunming-Montreal Global Biodiversity Framework (CBD 2022)	SDG 15.5
Land degradation	Achieve land degradation neutrality	Conversion of natural land and soil organic carbon	Halt loss of natural land by 2030; increase in soil organic carbon on 30% and 50% of agricultural lands by 2030 and 2050	UNCCD 2018-2030 Strategic Framework (UNCCD 2018); Kunming-Montreal Global Biodiversity Framework (CBD 2022)	SDG 15.3
Pollution	Improve air quality	Population exposed to ambient $PM_{2.5}$ > 25 µg/m³	<20% by 2030 and <10% by 2050	2030 Agenda for Sustainable Development (UN 2015) and WHO air quality guidelines (WHO 2021)	SDG 3.9 and 11.6
Food security	End hunger	Prevalence of undernourishment	0% by 2050*	2030 Agenda for Sustainable Development (UN 2015)	SDG 2.1
Water access	Achieve universal access to safe drinking water and adequate sanitation	Population using safely managed drinking water services and population using safely managed sanitation services	100% by 2050*	2030 Agenda for Sustainable Development (UN 2015)	SDG 6.1 and 6.2
Energy access	Ensure universal access to modern energy services	Population with access to electricity and population with primary reliance on clean fuels and technology	100% by 2050*	2030 Agenda for Sustainable Development (UN 2015)	SDG 7.1

Note: * Given that these SDGs are still largely off-track and the short time frame between publication of GEO-7 and 2030, the target year of the SDGs, the target year for these goals has been extended to 2050.

being the second-largest of all factors globally (Fuller et al. 2022). The WHO air quality guidelines include health-based, quantitative recommendations aimed at substantially reducing the health risks associated with exposure to ambient air pollution (WHO 2021). To assess trends in air pollution, the second interim target for $PM_{2.5}$ of 25 µg/m³ was selected, which coincides with the annual average threshold value of the European Union. The target values are based on van Vuuren et al. (2022).

There can be trade-offs between addressing the environmental crises and achieving human development goals if the transformations are not well-managed. To account for these interlinkages in the Transformation Pathways, three additional human development goals are incorporated into the set. These goals address the basic material needs aspect of human well-being (Rao and Min 2018) and are based on the 2030 Agenda for Sustainable Development (United Nations 2015). They include ending hunger (SDG 2.1), achieving universal access to safe drinking water and adequate sanitation (SDG 6.1 and SDG 6.2), and ensuring universal access

to modern energy services (SDG 7.1). Achieving these goals imposes additional constraints on the food, energy and resource systems. Including these additional targets in the analysis of Transformation Pathways provides good insights into the required effort for achieving environmental and human well-being goals simultaneously. Achieving many other SDGs have implications for resource use too and the three chosen SDGs have a much broader scope than only providing basic material needs. However, given the complexity involved, including the broad scope of the SDGs, it is impossible to address with the global models involved.

The two Transformation Pathways are designed to meet the seven goals simultaneously. In addition to these seven goals, a much broader set of indicators is used to assess the environmental and socioeconomic implications associated with the three scenarios. These indicators are based on the 2030 Agenda for Sustainable Development (UN 2015). For the assessment of environmental implications, additional indicators for water nutrient pollution (SDG 6.3) and freshwater scarcity (SDG 6.4) are used. To assess the socioeconomic implications, a range of indicators is used, structured according to Amartya Sen's development-as-freedom approach (Sen 1999). This approach defines the impact on human well-being as the effects on the freedom of choices and actions to meet basic material needs, achieve good health, attain gender equality, thrive in a fair and just society, and experience security (Rao and Min 2018; UNDP 2022). Implications are discussed along four dimensions of well-being: basic material needs (SDGs 2, 6 and 7), good health (SDG 3), fair and just societies (SDGs 1 and 10), and human security (SDG 16). Gender equality (SDG 5) is treated as a cross-cutting issue where possible when discussing these dimensions. The two Transformation Pathways do not assume that these goals are being met but, in line with the underlying narratives, they are expected to improve.

9.4 Process of building the narratives for the target-seeking scenarios

Historically, most global environmental scenarios were exploratory, asking, "Which futures might unfold under specified conditions and what are their implications?" (IPBES 2016). However, over the past decades, narratives have been developed for both exploratory (van't Klooster and van Asselt 2006; Alcamo 2008; Kok et al. 2015; IPBES 2016) and target-seeking scenarios (Aguiar et al. 2020). Interest in developing sustainability-oriented target-seeking scenarios on the global level was catalysed by the United Nations 2030 Agenda and its SDGs, as well as the Paris Agreement (van Vuuren et al. 2015; Nakicenovic et al. 2018; Rogelj et al. 2018; Soergel et al. 2021). Global target-seeking scenarios represent alternative Transformation Pathways to reach such globally defined goals. GEO-7's target-seeking scenarios are focused on the transformation of five systems to achieve a set of seven internationally agreed goals related to the global environmental crises (**Table 9.1**). This section details the process of building the narratives for these scenarios.

Previous research suggests that narratives of target-seeking scenarios should capture multiple perspectives and key debates in society about sustainability, explore alternatives, and compare their outcomes, thereby fostering debate about possible pathways at multiple levels (Rosa et al. 2017; Aguiar et al. 2020; Pereira et al. 2020). Since an infinite number of possible alternative pathways exist in each system and their combinations, the crucial challenge is how to select which pathways to represent, and the level of detail required to represent them. As such, the design of the GEO-7 narratives used two steps. The first step defined the general characteristics and core assumptions about the narratives. Rooted on these general assumptions, the second step defined coherent sets of solutions for each system.

Step 1: General characteristics and core assumptions

The first step involved a literature review covering environmental scenario archetypes (Hunt et al. 2012; van Vuuren et al. 2012; IPBES 2016; Raskin and Swart 2020; Carlsen et al. 2024) and typologies of sustainability pathways (Stirling 2011; Geels et al. 2014; Luederitz et al. 2017; D'Amato 2021). Additionally, the review incorporated global target-seeking scenario narratives (van Vuuren et al. 2015; Rogelj et al. 2019; Soergel et al. 2021, 2024; Kok et al. 2023) and the multiple perspectives on nature proposed in the IPBES Nature Futures Framework (Pereira 2020). Most studies explore two or three alternative combinations of assumptions around selected dimensions. In general, these scenario studies differ in their emphasis on changing consumption patterns, the role of technology, the focus on global versus more localized approaches, and the way nature is valued.

Based on this review, the decision was made to represent two contrasting Transformation Pathways. The rationale for selecting only two alternative pathways is to facilitate an understanding of the core assumptions and solutions adopted in each system, as well as the analysis of the results. Both narratives affect production and consumption patterns, but from a different rationale, assuming different degrees of structural change in society. The narratives are archetypal, representing extremes, and are meant to facilitate exploration of the solution space of possible pathways. Creating a third pathway combining solutions from both pathways could create the wrong perception of a prescriptive best option and was therefore omitted. The two narratives represent different perspectives about what a sustainable future would look like.

The two narratives are:

- Behaviour-focused Transformation Pathway: This pathway envisions a deep transformation in society's values, beliefs and norms towards sufficiency, moving away from human materialism and consumerism (Luederitz et al. 2017; Raskin and Swart 2020). The importance of living in a more communal and symbiotic relationship with nature increases, largely inspired by the philosophies and ways of living of Indigenous Peoples and local communities, aligning with the "Nature as Culture" perspective proposed by the IPBES Nature Futures Frameworks (Pereira et al. 2020). Solutions to environmental and social problems are sought by combining multiple forms of knowledge, including mainstream science and the philosophies, practices and values of Indigenous Peoples and local communities, for example, in the food and environmental systems. This transformation entails structural changes in production and consumption systems, including a balance among global, regional and local markets, as well as a significant decrease in consumption – particularly in affluent countries – while the basic needs of humanity are met.

- Technology-focused Transformation Pathway: This pathway envisions massive investments in technology development aimed at achieving efficiency gains and green technologies to address the global environmental crises. It aligns with and expands upon the taking the Green Road scenario of the SSPs (O'Neill et al. 2017) and the Global Sustainability archetype (van Vuuren et al. 2012), envisioning an economically globalized, commodified, liberal and urbanized world. In this narrative, the overall economic system remains unchanged, but the well-regulated and appropriately priced green economy becomes the dominant paradigm, shifting consumption towards environmentally and socially responsible products (D'Amato 2021). Indigenous Peoples live in protected areas, receiving payment for ecosystem services and integrated into a well-functioning bioeconomy market. The dominant perspective about nature is aligned with the "Nature as Service" and "Nature for Nature" perspectives proposed by the IPBES Nature Futures Frameworks (Pereira et al. 2020).

Step 2: System-level solutions

The alternative solutions in each system reflect key debates about sustainability, relating to the general assumptions of each narrative and creating cohesive stories. For example, a food system debate focuses on how to reconcile food production and conservation (Godfray and Robinson 2015; Bennett 2017). The definition of solutions for the systems in each Transformation Pathway was based on the analysis of recent and similar scenario exercises (Kok et al. 2023; Soergel et al. 2024), refined through internal consultation with systems experts (Chapters 14–18) and regional experts (Chapter 20). A series of Indigenous Knowledge and local knowledge dialogues were held to help GEO-7 strengthen that perspective in the narratives (IK & LK Dialogues 2025). The resulting narratives for each Transformation Pathway and the debates they capture are presented in full detail in Section 11.2.

The narratives provide sufficient detail to support the scenario quantification process without duplicating content from subsequent chapters while providing key elements to enrich discussions about transformative pathways for specific income groupings (Chapter 19) and regions (Chapter 20). The Solution Pathways analysis of Chapters 14–18 further explores key solutions in the narratives, providing details about the necessary levers and actions, as well as the responsible actors, for implementing these transformations. Besides avoiding redundancy, this design aims to ensure consistency across GEO-7. The narratives are defined at the solution

level of the Goal-Solution-Lever framework proposed in Chapter 13. Appendix 11.A shows how the solutions combined in the narratives relate to the solutions discussed in the Solution Pathways of Chapters 14–18.

The importance and use of the scenario narratives

The two Transformation Pathways should not be taken in isolation. The future will likely be shaped by combinations of them – depending on the context and priorities of a given country or region – as well as by unexpected turns of events, technological disruptions and cultural resistance, among other influences. By comparing their outcomes, it is possible to identify the roles of different pressures and the dynamics that drive various synergies and trade-offs.

On their own, the narratives are key to fostering discussion and further analysis about alternative solutions in each system transformation and region. However, their core use in this report is to provide consistency in assumptions across the five systems for the process of quantification. The next step for building the quantitative scenarios is to translate the qualitative assumptions into numeric assumptions used by the models, such as altering "reduction in meat consumption" to "50 per cent reduction in relation to current values". During the whole process of narrative development, modellers were consulted to guarantee that the modelling parameters required to inform the quantification of the scenario could be extracted from the narratives. Appendix 11.A describes the modelling protocol in terms of a translation from qualitative description in the narratives to quantitative assumptions for the modelling.

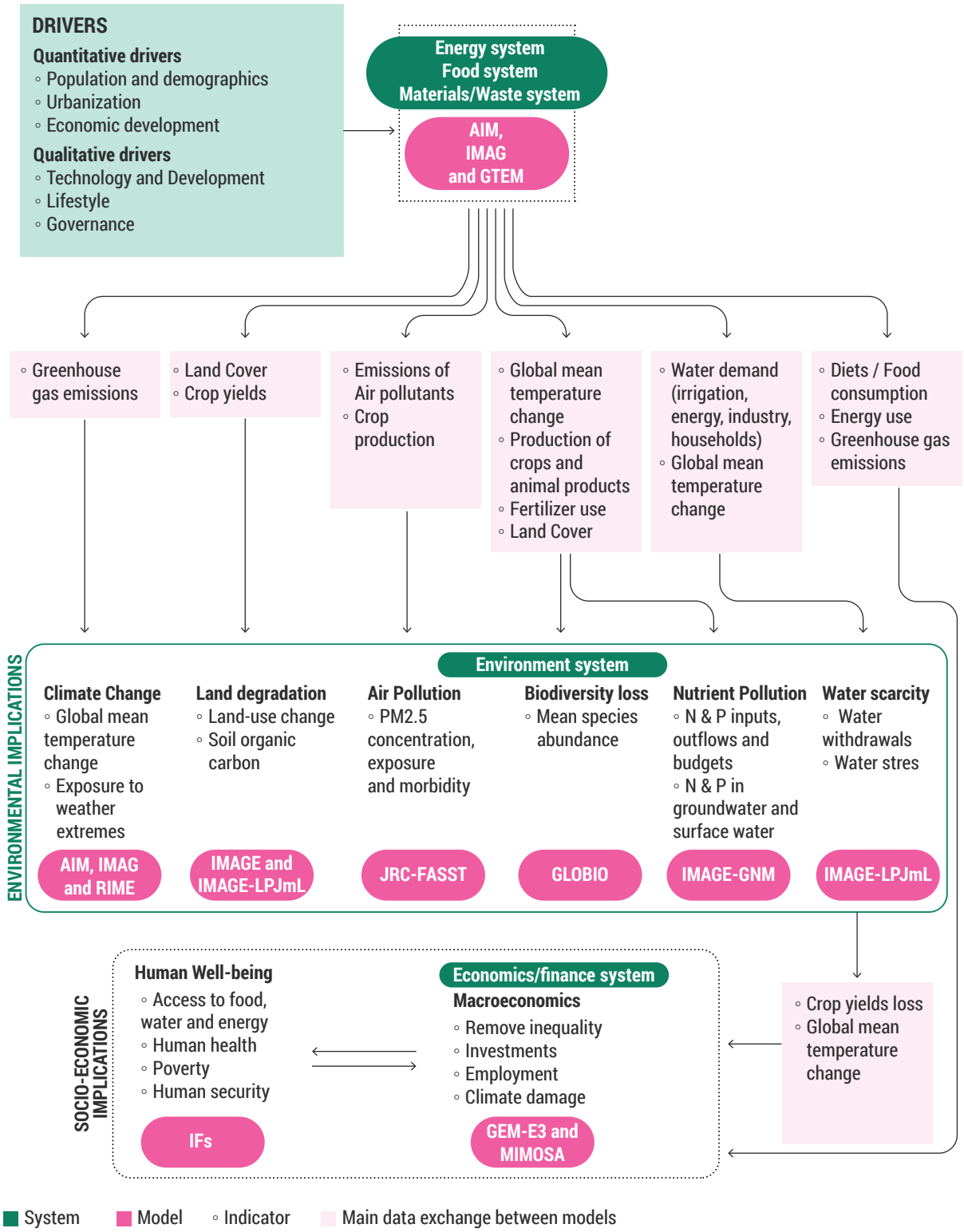
9.5 Models used to quantify the scenarios

A suite of models is used to quantify the three scenarios. Together, these models address most of the relevant issues for assessing future developments in the five systems, global environmental crises, and related goals, as well as environmental and socioeconomic implications (**Figure 9.3**). The models are all well-established and validated in the literature and extensively used in scientific assessments, including earlier GEOs, reports from the IPCC (Byers et al. 2022; IPCC 2022), the Global Assessment Report on Biodiversity and Ecosystem Services (IPBES 2019), the Global Resources Outlook (UNEP 2024), the Global Land Outlooks (UNCCD 2017; UNCCD 2022) and the International Nitrogen Assessment (UNEP forthcoming). To create the integrated scenarios, these models are soft-linked, where the outputs of one model serve as input for other models (**Figure 9.3**). Model linking enhances the representation of the overall system by explicitly accounting for critical interdependencies and feedback between the component models. For a brief description of each model, its use in GEO-7, how they are interrelated, and further documentation and references, see Appendix 9.A.

Two Integrated Assessment Models – AIM (Fujimori et al. 2017) and IMAGE (Stehfest et al. 2014) – are central to the analyses, covering the energy and food systems, as well as climate change and land degradation. The results presented for the Current Trends scenario are based on AIM and for the two Transformation Pathways on IMAGE. This model choice is based on their respective strengths in representing the underlying dynamics. The AIM model is a hybrid computable general equilibrium model linked to an energy system optimization model. It is well-suited to capture the incremental, market-driven adjustments characteristic of continuing existing market and policy trends, including responses to established policy instruments. The IMAGE model is a hybrid system dynamics model with a detailed representation of technological and behavioural aspects of production and consumption. It is thereby well-suited to model the more systemic shifts in consumption, technology and policy that distinguish the Transformation Pathways. In addition, GTEM (Cai et al. 2015) was used for the projections of resource use for both scenario types. This model, together with IMAGE, was central to the resource use projections in the Global Resources Outlook (UNEP 2024). Together, the three models provide projections for the energy, food, and materials systems, as well as related pressures, such as emissions, land use, and resource exploitation.

Connected to the outcome from these three models, additional models are used to assess the environmental and socioeconomic implications. These models are used for all three scenarios. For the environmental implications, RIME (Werning et al. 2024; Byers et al. 2025) was used for climate change impacts, GLOBIO (Schipper et al. 2020) for biodiversity loss, IMAGE-GNM (Stehfest et al. 2014) for nutrient pollution, IMAGE-LPJmL (Schaphoff et al. 2018) for land degradation and water scarcity, and JRC-FASST (van Dingenen et al. 2018) for air pollution. For the socioeconomic implications, international futures (Hughes 2019) was used for human

Figure 9.3: Models used, their role in framework and connections to the other models



well-being, and GEM-E3 (Capros et al. 2013) and MIMOSA (van der Wijst et al. 2023) for economic effects.

The scenarios are implemented in the different models by adjusting appropriate parameters in line with the narratives. These include, for example, technology availability and learning rates, consumption patterns, protected areas, government and private spending, and food distribution. The key drivers – population, urbanization and gross domestic product – are exogenous to the models and similar for all three scenarios. They are based

on the SSP2 "middle-of-the-road" scenario (Chapter 10, Section 10.2). For the Transformation Pathways, the models are explicitly constrained to achieve the goals described in **Table 9.1**. The climate change goal is achieved by setting a budget on greenhouse gas emissions in line with the Paris Agreement, while the elimination of hunger, universal access to clean water and sanitation, and modern energy services are enforced via explicit food and energy access. Further adjustments were made to technology developments and lifestyle changes to ensure the achievement of the goals related to biodiversity loss and land degradation, and pollution and waste.

9.6 Challenges and limitations of the scenario approach

The applied methodology has its drawbacks and limitations, including the scope of scenarios, structural and parametric uncertainties, limited translation of narratives into model parameters, partial coverage of the global environmental crises, aggregation levels, and challenges in model integration. Appendix 9.A provides model descriptions, including a high-level overview of each model's limitations.

First, this assessment only evaluates three scenarios, which clearly does not cover the full spectrum of possible futures. To ameliorate this limitation, results are presented with ranges from established scenario databases, such as the IPCC AR6 scenarios database (Byers et al. 2022; IPCC 2022), and existing literature. This approach helps identify to what extent they belong to the uncertainty space of wider scenario exercises. It allows for an assessment of the consistency of the projections with widely recognized benchmarks, thereby reinforcing their validity.

Second, the models employed have several limitations due to structural and parametric uncertainties. Structural uncertainty can arise from an incomplete representation of relationships and processes of the represented system within the model framework, while parametric uncertainty stems from the imprecise nature of the parameter values used in these models (Pastor et al. 2020). For example, while average climate damages are included in the analysis, high-impact weather events, which may have disproportionate and cascading consequences, are only represented simplistically as understanding and appropriate modelling for these outcomes are not currently available (Raymond et al. 2020; Seneviratne et al. 2023). To address this caveat, an extra section on tipping points linked to the global environmental crises is added to Chapter 10, based on the literature. Furthermore, as the models only cover some of the feedback between environmental change and human activities, where relevant, Chapter 10 also draws on the broader literature to provide additional evidence of the consequences of the global environmental crises on human well-being projections.

Third, not all the details of the narratives developed for the target-seeking scenarios could be rendered into model parameters. For example, while the narratives do, to a certain extent, account for Indigenous Knowledge systems, this is not quantified in the models. Challenges include incorporating uncertainty, addressing bias, ensuring reliability, and aligning the scale of experiential knowledge with regional and global scales (Stern and Humphries 2022). For Indigenous Peoples, time is viewed as a cycle (Pereira et al. 2024), which significantly influences how the scenarios are interpreted. Furthermore, due to a techno-economic focus and normative cost-optimization in most models used, the two Transformation Pathways are heavily assessed in terms of their techno-economic feasibility; however, the cultural, political and social feasibilities of these pathways are not explicitly modelled. This lapse is partly addressed in Chapters 14–18, which discuss necessary levers, actions and actors for implementing the Transformation Pathways.

Fourth, due to the practical limitations of analytic capacity, the analysis focuses on a limited set of environmental challenges and related consequences. Pollution, for example, only focuses on ambient air pollution and freshwater nutrient pollution, while oceans and marine life are not addressed at all. These missing issues are partly covered in Part B State and Trends Chapters 3–6 of this report, but without a forward-looking perspective.

Fifth, the modelled scenarios are not appropriate for interpretation at the national or subnational level. The regional aggregation level in most models is typically restricted to large regions comprising country aggregates, which limits insights at more detailed spatial levels. Consequently, the results are only presented at the global scale, in Chapters 10 and 11, or for large, aggregated regions as in Chapters 19 and 20. For certain biophysical indicators, such as land and water use, air pollution, and biodiversity

Credit: CreativeNature_nl/Envato

loss, the analysis is conducted on a gridded level, and appropriate maps are presented.

Finally, while the data exchange between models ensures internal consistency, it can create possible biases in the results due to the limited selection of variables that are exchanged. Model linking also introduces various interconnection challenges. Fundamentally, models are built with differing purposes, system and regional boundaries, and underlying assumptions that complicate their integration. Bridging differences in temporal and spatial granularity, such as annual versus hourly data or global versus regional scope, requires careful aggregation and disaggregation techniques and introduces further assumptions (Belete et al. 2017). Again, this is partly addressed by presenting the results within ranges from established scenarios, databases and literature, where available.

9.7 Presentation of results

The analysis focuses on the timeline from 2020 to 2050, a period that is critical for understanding the consequences of Current Trends and policy actions on future environmental and socioeconomic conditions. This time frame aligns with many of the goals that the Transformation Pathways aim to achieve and is also a relevant time frame for policymaking. For climate change, the time frame is extended to 2100 to ensure consistency with the long-term climate target of the Paris Agreement.

The scenario results are presented and discussed in different ways throughout GEO-7. Chapter 10 uses the Current Trends scenario to discuss the extent to which the world is on track to achieve internationally agreed goals related to the global environmental crises and examines related environmental and socioeconomic consequences. Chapter 11 uses the two Transformation Pathways to discuss alternative routes to achieve these internationally agreed goals, including synergies and trade-offs across the goals and systems, as well as related challenges and opportunities. Both chapters focus on global-level results only.

The global Transformation Pathways offer a framework for addressing the global environmental crises. However, their practical effectiveness hinges on their adaptation to regional contexts through concrete, multidimensional targets and inclusive governance that address both technological and sociopolitical challenges (Wolff et al. 2024). These will be discussed in subsequent chapters. Chapters 14–18 discuss the necessary levers, actions and actors for implementing the Transformation Pathways for the five systems. Chapter 19 examines the Transformation Pathways for countries at various stages of economic development, highlighting the challenges, opportunities and best practices that support this transformation. Chapter 20 discusses the regional implications of the Current Trends scenario and the two Transformation Pathways. It presents and discusses the scenario results aggregated to the five UNEP-defined regions in combination with peer-reviewed literature, focusing on regional similarities and differences.

Appendix 9.1: Models used in global analysis (Chapters 10 and 11)

Model name	IMAGE 3.3 (Integrated Model to Assess the Global Environment)
Purpose of model	IMAGE is an integrated assessment modeling framework that simulates the environmental consequences of human activities worldwide. It represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change, biodiversity and human well-being. The model can be used to explore the long-term pathways for future environmental and sustainable development problems as well as possible response strategies. It has representations of the energy, agriculture, land use, and climate systems. Typical outputs include projections of energy supply and demand, agricultural production, land use and land cover change, emissions of greenhouse gasses and other pollutants, and demand for water and material resources. The model is calibrated to datasets of energy supply and demand (International Energy Agency) and Agricultural production and land cover (Food and Agricultural Organisation). IMAGE participates in multiple model intercomparison projects covering energy, agriculture, emission scenarios, and sustainable development.
Solution mechanism	IMAGE is a hybrid systems dynamics model. It employs stylized optimization techniques when meeting climate targets. The model simulates the human and natural environment from 1971 to 2100, with the 1971-2018 period acting as a calibration and spin-up period. The model works on an annual timestep.
Main drivers / exogenous inputs	Population, economic activity are key exogenous drivers. Assumptions (across the food and energy systems) on technology availability and development, behavioural and lifestyle choices are also inputs. The model can incorporate land protection, energy, and other quantifiable policies.
Regional aggregation	IMAGE is a global model. Biophysical and land use are represented at a 0.5x0.5 degree grid, while socioeconomic processes are modelled on 26 regions. For details see the documentation.
Limitations	Model has a high level of aggregation concerning technologies, as well as social and economic dynamics. Thus, it may lack specific dynamics or insights concerning technological diffusion, bottlenecks, political/social constraints, and behavioural effects. Required changes in governance systems and consumer behaviour are enforced without assessing possible feedbacks.
Contribution to GEO7	**Use of results in GEO7** The IMAGE model is used to project the human-nature interaction of the Behavioural and Technology focused transformation Pathways. It provides the

	projections of the energy supply and demand, agricultural production, land use and land cover change, emissions of greenhouse gases and other pollutants, and demand for water. Its projections are presented in Chapter 12, particularly 12.3.1 and 12.3.2. **Data received from other participating models** None
Key Reference(s)	Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M. *et al.* (2014). *Integrated Assessment of Global Environmental Change with IMAGE 3.0 - Model description and policy applications*. Netherlands Environmental Assessment Agency (PBL),The Hague. https://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-image-30-model-description-and-policy-applications Contributed to, amongst others, to IPCC AR6 WGIII report, UNEP-IRP Global Resource Outlook 2024, OECD Environmental Outlook. Website/Documentation: www.pbl.nl/image

Model name	**AIM 2.0 (Asia and the Pacific Integrated Model)**
Purpose of model	AIM is an integrated assessment model framework that primarily aims to give information to better understand climate change mitigation policy implications by simulating long-term human and relevant environmental systems. The model can also be used for the more general assessment of environmental consequences induced by human systems and policy changes, such as biodiversity and air pollution. Moreover, the socioeconomic implications associated with measures of environmental problems such as poverty, hunger and health. The AIM model consists of several independent models that represent economy, energy, land use, and household consumption. The core of the AIM is AIM-Hub (formerly named AIM/CGE), which represents the entire economic activities with detailed sectoral classifications as a computable general equilibrium model. This AIM-Hub model integrates the latter land-use and energy system model outputs and also provides the exogenous conditions for other models, such as regionally aggregated land use, income levels, etc. AIM-PLUM deals with spatial explicit land use and provides land-use change CO_2 emissions and bioenergy supply curve. Regarding energy representation, AIM-Technology (formerly named AIM/Enduse) is used, which represents greater resolution in energy technologies. The climate (radiative forcing and global mean temperature), atmospheric ($PM_{2.5}$ concentration, nitrogen depositions, etc.), and biodiversity conditions are computed by MAGICC, GEOS-Chem and AIM-Biodiversity.

Solution mechanism	• Energy system model AIM-Technology is optimization model and annually solved towards 2100. • Computable general equilibrium model AIM-Hub is CGE and annually solved towards 2100. • Land-use model AIM-PLUM is an optimization model and 10 years step towards 2100. • Other models are simulation-type models.
Main drivers / exogenous inputs	The main drivers of the overall AIM are population, income growth, demand preferences (such as dietary preferences), technological progress in energy, agriculture and the general economy, and inequality conditions. Most of the drivers are built upon the Share Socioeconomic Pathways assumptions mostly described in Fujimori *et al.* (2017).
Regional aggregation	• The AIM-Hub geographical resolution is 17 socioeconomic regions. • The AIM-Technology geographical resolution is 31 socioeconomic regions. • The AIM-PLUM and AIM-Biodiversity geographical resolution is 0.5 degrees. • GEOS-Chem is normally run by 4 x 5 degrees.
Limitations	Representation in energy technology is very detailed, with more than 500 in total from both sides of demand and supply. However, behavioural representation is not well detailed. The land use and agricultural representation in regional aggregates could be realistic to an extent, but spatial distribution is resolved under optimization, which may include some differences from reality. In that sense, the interpretation of the spatial land use map would need special consideration.
Contribution to GEO7	**Use of results in GEO7** The AIM model is used to project the human–nature interaction of the Current Trends pathway. It provides the projections of the energy supply and demand, agricultural production, land use and land cover change, emissions of greenhouse gases and other pollutants, and demand for water. **Data received from other participating models** Changes in GDP projections from the GEM-E3 model were input into AIM
Key Reference(s)	Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Herran, D.S., Dai, H. *et al.* (2017) SSP3: AIM implementation of Shared Socioeconomic Pathways. Glob. Environ. Change 42, 268–283. http://dx.doi.org/10.1016/j.gloenvcha.2016.06.009. Website/Documentation: https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_AIM-Hub http://www.nies.go.jp/social/dp/pdf/2012-01.pdf
Contribution to Global Environmental Assessments	IPCC AR6 WGIII report

Model name	GTEM-Resource_2023 (Global Trade and Environment Model with a Resource module)
Purpose of model	GTEM is a global dynamic computable general equilibrium (CGE) model. It is a hybrid model that combines the top-down macroeconomic representation of a CGE model with the bottom-up engineering details of energy production along with a representation of greenhouse gas (GHG) emissions by economic sector. With a module of accounting for the physical flows of resources and materials built-in GTEM, GTEM-Resource is able to provide the global and regional demand for various categories of materials and resources that are consistent with the UN IRP database. By adding the module, its outputs can also be used to compute and project the material footprints into the future. In this version, the model baseline is calibrated to the SSP2 GDP and population projections, and the baseline global primary energy production and energy mix is calibrated to the STEPS scenario from the International Agency of Energy 's World Energy Outlook (WEO) 2021. The typical outputs from the model include GDP, GHG emissions, material uses (DE, DMC, etc.) by 61 categories, sector outputs, household demand by commodity, commodity prices, and international trade flows by region. GTEM can also integrate with GLOBIOM to provide LULUCF emissions and land use change.
Solution mechanism	GTEM is a recursive dynamic CGE model. It is solved on a yearly basis. In this version, the simulation goes to 2060, but it can be solved for 2100 for long-term purposes.
Main drivers / exogenous inputs	The population is exogenous input; the GDP in the *Current Trends* scenario is exogenous input, while the GDP in the Transformation Pathway scenario is endogenous output. The various energy efficiencies and material efficiencies are exogenous inputs. In the Transformation Pathway scenario, various policy shocks, technological changes and behavioural changes are exogenous inputs.
Regional aggregation	In this version of GTEM-Resource, the model has 34 regions, of which there are 28 individual countries covering most of the important countries in the world in terms of economic development and resource use.
Limitations	The model assumes homogenous households and therefore the behavioral changes across different income groups within a region are homogenous, which may cause some bias in the results. The model does not have explicit representation of biofuels, therefore results on biofuels are not available.
Contribution to GEO7	**Use of results in GEO7** GTEM-Resource provides the GEO-7 report with results on economy-wide material use on both global and regional levels. **Data received from other participating models** GTEM-Resource receives the GHG emissions pathways from

	IMAGE in the Behaviour-focused and Technology-focused Transformation Pathways.
Key Reference(s)	Schandl, H., Lu, Y., Che, N., Newth, D., West, J., Frank, S. *et al.* (2020). *Shared socio-economic pathways and their implications for global materials use*. Resour. Conserv. Recycl. 160(104866), 104866. http://dx.doi.org/10.1016/j.resconrec.2020.104866 Nong, D., Schandl, H., Lu, Y. and Verikios, G. (2023). *Resource efficiency and climate change policies to support West Asia's move towards sustainability: A computable general equilibrium analysis of material flows*. J. Clean. Prod. 421(138458), 138458. http://dx.doi.org/10.1016/j.jclepro.2023.138458
Contribution to Global Environmental Assessments	UNEP-IRP Global Resource Outlook 2019 and 2024

Model name	**JRC-FASST (JRC-FAst Scenario Screening Tool)**
Purpose of model	JRC-FASST is a global reduced-form air quality source–receptor model that has been designed to compute ambient pollutant concentrations as well as a broad range of pollutant-related impacts on human health, agricultural crop production, and short-lived pollutant climate metrics, taking as input annual pollutant emission data aggregated at the national or regional level. The annual average concentrations of air pollutants generated by JRC-FASST are tested by comparison with the Chemical Transport Model that was used to develop the emission-concentration sensitivities (see below). In addition, the historical years in the base-case scenario are validated by comparison with other models and with measurements.
Solution mechanism	JRC-FASST is based on linearized emission-concentration sensitivities derived with a full chemistry transport model (EMEP GLOBAL) and EDGAR emissions of atmospheric pollutants (https://edgar.jrc.ec.europa.eu).
Main drivers / exogenous inputs	The main exogenous input is the annual emissions of air pollutant precursors SO2, NOx, NH3, BC, OC, non-methane volatile organic carbon (NMVOC), CO, and CH4 in 76 source regions covering the entire globe. Population, all-cause and cause-specific mortality are used to estimate the share attributable to air pollution. Specific crop production and crop growing seasons are used to estimate the annual yield losses.
Regional aggregation	The model generates a gridded air pollution concentration output at 0.5 x 0.5 degree resolution. The impacts (health outcomes, crops, vegetation) are typically provided at the country level worldwide.

Limitations	The applied methodology is based on a reduced form model which reproduces the results of a full chemistry and transport model (EMEP) with a <5% uncertainty. The model adopts a simplified approach to estimate future climate-chemistry interactions.
Contribution to GEO7	**Use of results in GEO7** JRC-FASST is used to report the concentration of pollutants ($PM_{2.5}$, ozone), exposure indicators for human population and vegetation, number and share of population exposed to high pollution levels ($PM_{2.5}$ > 25 µg/m^3), mortality and morbidity attributable air pollution, and crop yield losses attributable to air pollution. **Data received from other participating models** Projected emissions of air pollutants and crop production are provided by AIM and IMAGE.
Key Reference(s)	Model description: Van Dingenen, R., F. Dentener, M. Crippa, J. Leitao, E. Marmer, S. Rao, E. Solazzo and L. Valentini. (2018) *TM5-FASST: A Global Atmospheric Source-Receptor Model for Rapid Impact Analysis of Emission Changes on Air Quality and Short-Lived Climate Pollutants*. Atmospheric Chemistry and Physics 18 (21): 16173-16211. doi:10.5194/acp-18-16173-2018 Belis, C.A. and Van Dingenen, R. (2023) *Air quality and related health impact in the UNECE region: source attribution and scenario analysis*. Atmos. Chem. Phys. 23(14), 8225-8240. http://dx.doi.org/10.5194/acp-23-8225-2023 Website: https://tm5-fasst.jrc.ec.europa.eu/index.html
Contribution to Global Environmental Assessments	IPCC AR6 WGI report

Model name	**GLOBIO 4.0 (Global Biodiversity Model for Policy Support)**
Purpose of model	The GLOBIO model quantifies local terrestrial biodiversity intactness, expressed as the Mean Species Abundance (MSA) indicator as a function of climate change, atmospheric nitrogen deposition, land use, roads, and hunting (tropical regions). The impact of habitat fragmentation, resulting from both land use and roads, is also included. The impact of the different pressures on MSA is quantified for plants and vertebrates separately and then combined into one overall MSA value. In this study, we applied version 4 of the GLOBIO model.

Solution mechanism	GLOBIO 4.0 is based pressure-impact relationships established through meta-analytical approaches based on empirical data in combination with data on pressure levels. Regression equations for each independent pressure factor are estimated using generalized linear mixed models.
Main drivers / exogenous inputs	Population changes and economic activity are key exogenous factors driving land use change, climate change and nitrogen pollution. These pressures are exogenous inputs for the GLOBIO model. Additional assumptions on nature protection and the level of protection, land use configuration and the level of infrastructure use can be adapted to address scenario assumptions and policies. The ESA-CCI land cover product is used as the basis for land use change calculations (ESA 2017). Global road data are from the GRIP database (Meijer et al. 2018). To quantify hunting pressure in tropical regions, the distance to settlements is required. We obtained locations of settlements from OpenStreetMap (http://download.geofabrik.de), the Humanitarian Data Exchange (www.data.humdata.org) and national databases.
Regional aggregation	GLOBIO is a global model. Biodiversity intactness is calculated using downscaled land use information at a resolution of 10 arcseconds. Aggregation of results can be calculated at all coarser resolutions.
Limitations	The model parameters are data-driven and data are derived from published scientific literature and other open sources. The distribution of available data are, therefore, unequally distributed. Major data gaps are from Europe, for a lack of pristine ecosystems, and eastern Asia, for a lack of accessible literature.
Contribution to GEO7	**Use of results in GEO7** The GLOBIO model is used to assess biodiversity intactness changes as projected in the baseline scenario and in the Transformation Pathways. **Data received from other participating models** Changes in land use, climate and nitrogen deposition are derived for the IMAGE model.
Key Reference(s)	Alkemade, R., Van Oorschot, M., Miles, L., Nellemann, C., Bakkenes, M., & Ten Brink, B. (2009) *GLOBIO3: A framework to investigate options for reducing global terrestrial biodiversity loss*. Ecosystems, 12, 374–390. https ://doi.org/10.1007/s10021-009-9229-5 Schipper, A.M., Hilbers, J.P., Meijer, J.R., Antão, L.H., Benítez-López, A., de Jonge, M.M. J., Huijbregts, M.A.J. (2020) *Projecting terrestrial biodiversity intactness with GLOBIO 4*. Glob. Chang. Biol. https://doi.org/10.1111/gcb.14848 Website/Documentation: www.globio.info
Contribution to Global Environmental Assessments	CBD Global Biodiversity Outlooks 2–5 , IPBES regional and global assessments, UNEP GEO-4, OECD Environmental Outlooks, and UNCCD Global Land Outlook 1 and 2.

Model name	IMAGE-GNM (Integrated Model to Assess the Global Environment – Global Nutrient Model)
Purpose of model	IMAGE-GNM is a globally distributed, spatially explicit model using hydrology from PCRGLOBWB as the basis for describing nitrogen (N) and phosphorus (P) delivery to surface water, transport and in-stream retention in rivers, lakes and reservoirs. IMAGE-GNM is hard-linked to the integrated assessment modelling framework IMAGE. IMAGE-GNM uses the land use information and nitrogen deposition from IMAGE and the associated agricultural production (grass, crop and animal production) to estimate the N and P fertilizer use for cropland and grassland. Human protein consumption is used to estimate the delivery of human and industrial sewage to rivers. Also, the delivery of nutrients from natural land to the rivers is estimated. The load is transported by the rivers to the coastal seas, taking into account the in-stream loss processes in the river. The model can be used to explore the long-term pathways for future environmental and sustainable development problems as well as possible response strategies. Typical outputs include projections of nutrient delivery to the rivers and the export of nutrients to the coastal seas, including the distribution of different nutrient sources.
Solution mechanism	IMAGE is a globally, distributed, spatially explicit model. The model works on an annual timestep but takes into account the historical loads. The model starts in 1900. This is needed to incorporate the storage of nitrogen in groundwater and the storage of phosphorus in the soil pools. The model is validated on a long-term time series of observed N and P concentrations in several river basins (e.g. Mississippi, Rhine, Meuse, Yangtze).
Main drivers / exogenous inputs	Next to the data that is used from IMAGE, there are other assumptions that are not provided by the IMAGE model. Nitrogen Efficiency Use (NUE) is used as the main driver to calculate future N fertilizer use. The P fertilizer use is determined by the P content of the soil and the P availability for the plant. The recycling of manure and soil conservation in the agricultural sector are policy options which can lead to a more sustainable sector. Assumptions on the number of people connected to a sewage system and the efficiency of the sewage treatment plants can improve the population's health and water quality. The production of aquaculture is another direct input of nutrients in the rivers and is one of the scenario assumptions.
Regional aggregation	IMAGE-GNM is a global model. Biophysical and land use are represented at a 0.5 x 0.5 degree grid.
Limitations	The IMAGE-GNM model uses land use information from the IMAGE model. This land use is consistent with the regional statistics but could deviate on a national scale. For example, the combination of total fertilizer use on a national scale with the IMAGE land use data could give high results in kg/ha. The total fertilizer is preserved on preserved a national level.

Contribution to GEO7	**Use of results in GEO7** The IMAGE-GNM model is used to project N and P pollution of groundwater and surface water. **Data received from other participating models** IMAGE-GNM is hard-linked to the IMAGE model, where it receives information concerning land cover, agricultural production (crops and animals), nitrogen deposition, population and human protein consumption.
Key Reference(s)	Beusen, A. H. W., Van Beek, L. P. H., Bouwman, A. F., Mogollón, J. M., and Middelburg, J. J. (2015) *Coupling global models for hydrology and nutrient loading to simulate nitrogen and phosphorus retention in surface water – description of IMAGE–GNM and analysis of performance, Geosci*. Model Dev., 8, 4045–4067 https://doi.org/10.5194/gmd-8-4045-2015.
Contribution to Global Environmental Assessments	OECD Environmental Outlook to 2050, UNCCD Global Land Outlook 1 and 2, INMS (Integral Nitrogen Management System), World Water Quality Assessment

Model name	**LPJmL 4: Lund Potsdam Jena managed Land**
Purpose of model	LPJmL is a global gridded model that describes the coupled carbon and water cycles. It simulates natural vegetation growth, crop growth and hydrology. The human impacts on the hydrological cycle, such as irrigation water withdrawals, other water withdrawals, water supply and the operation of large dams and reservoirs, are included. The effect of water limitation on vegetation growth is simulated. This makes LPJmL a very suitable tool to study the interactions between water and food production. The model is validated against discharge measurements, carbon fluxes, and vegetation patterns and calibrated against crop yields at country level.
Solution mechanism	LPJml is a simulation model based on a representation of biophysical processes. It can be run stand-alone or fully coupled to IMAGE. Daily time step, the time horizon is usually 2100, depending on the time horizon of input data.
Main drivers / exogenous inputs	In GEO, LPJmL is run fully coupled to IMAGE. This means that it gets annually gridded data on climate, non-agricultural water use, land use from IMAGE and sends back annual info on crop yields, agricultural water withdrawals, water availability, natural vegetation growth and the carbon cycle to IMAGE.
Regional aggregation	The LPJmL model represents all biophysical processes at 0.5 x 0.5 degree grid, but water balances are calculated with subgrid variability. Crop management parameters are calibrated at the country level. The model output can subsequently be aggregated to any regional level.

Limitations	Crop yield growth is impacted by climate change through changing temperature, precipitation and CO_2 fertilization, but other processes that affect yields are not represented, such as flooding and waterlogging, and pests and diseases. The hydrological cycle is represented in a simplified way, for example, lakes and lateral flow of deep groundwater is not taken into account.
Contribution to GEO7	**Use of results in GEO7** LPJmL is run fully coupled to IMAGE. In GEO-7 the model will be used in the Outlook chapters, both for the Current Trends as well as the Behaviour-focused and Technology-focused Transformation Pathways. The effects of current trends and measures in both pathways on green and blue water use and water scarcity will be assessed. **Data received from other participating models** Because LPJmL will be run fully coupled to IMAGE, it does not require any direct additional inputs from other participating models.
Key Reference(s)	Schaphoff, S., von Bloh, W., Rammig, A., Thonicke, K., Biemans, H., Forkel, M. et al. (2018a). *LPJmL4 – a dynamic global vegetation model with managed land – Part 1: Model description*. Geosci. Model Dev. 11(4), 1343-1375. http://dx.doi.org/10.5194/gmd-11-1377-2018 Schaphoff, S., Forkel, M., Müller, C., Knauer, J., von Bloh, W., Gerten, D. et al. (2018b) *LPJmL4 – a dynamic global vegetation model with managed land – Part 2: Model evaluation*. Geosci. Model Dev. 11(4), 1377-1403. https://gmd.copernicus.org/articles/11/1377/2018/ Model website: https://www.pik-potsdam.de/en/institute/departments/activities/biosphere-water-modelling/lpjml
Contribution to Global Environmental Assessments	OECD Environmental Outlook, UNCCD Global Land Outlook 1 and 2.

Model name	**International Futures (IFs) v 8.26.2**
Purpose of model	International Futures (IFs) is an integrated quantitative tool that forecasts hundreds of variables for 188 countries over long time horizons. The key submodules represented include agriculture, conflict, climate, demographics, economics, education, energy, gender, governance, health, infrastructure, international politics, and technology. The model is a hybrid structure drawing upon a variety of traditions that include a recursive dynamic computable general equilibrium tool with a full social accounting matrix, representation of income inequality and poverty across multiple thresholds by age and sex, partial equilibrium models of agriculture and energy, a cohort component demographic

	model, a proximate-distal driver model of mortality by age, sex across 15 disease categories, probabilistic models of conflict, and a fully elaborated schooling, attainment and education quality model across levels and sex. The underlying code is open source, and the user interface allows analysts to create their own scenarios by adjusting parameters.
Solution mechanism	The model "solves" each year, though it does not achieve equilibrium of supply and demand across any system that represents supply/demand. Instead, the model allows stocks of inventory to carry forward, dynamically "chasing" equilibrium across time.
Main drivers / exogenous inputs	The model has very few exogenous inputs, and population and economic development are endogenously computed for each country across time. The model creates a "base case" or "current path" scenario that is the most likely development trajectory across all indicators and is used as a basis for analysis and scenarios. This scenario generally behaves somewhere between SSP2 and SSP3 (depending on the SSPs and IFs version) and reflects a future development trajectory where most SDG goals are not met by mid-century, and the climate pathway is between RCP4.5 and RCP6.0 in the future.
Regional aggregation	IFs is global and represents development for 188 countries. The inclusion criteria tend to be global data availability and population size above 100,000 individuals, irrespective of sovereign status.
Limitations	The limits of the model are vast. The representation of greenhouse gas emissions in particular and natural systems in general are simplistic and not state-of-the-art. The unit of analysis deployed is geographically fixed, and the model does not have the ability to disaggregate and look at within-country factors. The representation of energy and agricultural systems is not as granular as many other tools in this area. Understanding the forecasting accuracy of the tool is also a significant challenge, and historical validation helps us understand strengths and weaknesses, but the future will be characterized by a different set of factors than the past.
Contribution to GEO7	**Use of results in GEO7** IFs is used to track a reference pathway for human and social development and then to operationalize the transformation pathways using exogenous inputs from IMAGE and JRC-FASST in addition to assumptions related to the distribution of calories, electricity access, and water and sanitation access. The variables presented in GEO from IFs include water and sanitation, electrification, the probability of civil war onset, poverty, and health outcomes across various categories disaggregated by sex. The tool was also used to explain the additional policy steps needed to achieve some of the core human development results, highlighting the complexity of achieving these transformation pathways. Specifically, IFs takes SSP2 pathways for population and the Gini coefficient for income inequality for the reference pathway and SSP1 for population and Gini coefficient for income inequality for the Transformation Pathways. For the Transformation Pathways, the model forces the elimination of poor access to electricity, water, sanitation, and undernutrition. For all GEO-7 scenarios, the model takes projections from IMAGE for agricultural production, land use,

	agricultural yield change, carbon emissions, traditional cookstoves, and total energy production, as well as renewable energy production. In addition, it takes global projections from FASST for air pollution over $PM_{2.5}$. **Data received from other participating models** Data was received from IMAGE concerning projections of the energy and land use systems, including the use of traditional cooking fuels. JCR-FASST provided projections of a population exposed to ambient particulate matter.
Key Reference(s)	Hughes, B.B. (2019) *International futures*. San Diego, CA: Academic Press. http://dx.doi.org/10.1016/c2014-0-04231-1 Hughes, B.B., Kuhn, R., Peterson, C.M., Rothman, D.S. and Solorzano, J.R. (2011) *Improving Global Health*. Routledge. http://dx.doi.org/10.4324/9781315634012 Moyer, J.D. (2023) *Blessed are the peacemakers: The future burden of intrastate conflict on poverty*. World Dev. 165(106188), 106188. http://dx.doi.org/10.1016/j.worlddev.2023.106188 Model documentation: https://pardeewiki.du.edu/index.php?title=Understand_the_Model
Contribution to Global Environmental Assessments	UNEP GEO-4

Model name	**GEM-E3 (General Equilibrium Model for Economy, Energy and Environment)**
Purpose of model	GEM-E3 represents the operation of the economic system and its interaction with energy and environment. It is a global large-scale applied Computable General Equilibrium (CGE) Model that represents all economies simultaneously linking them with endogenous bilateral trade flows (using the Armington assumption). The key innovations of the model relate to the explicit representation of the financial sector, semi-endogenous dynamics based on R&D-induced technical progress and knowledge spillovers, the representation of multiple households, unemployment in the labour market and endogenous formation of labour skills. The model is calibrated to a wide range of datasets comprising Input-Output (IO) tables, financial accounting matrices, institutional transactions, energy balances, GHG inventories, bilateral trade matrices, investment matrices and household budget surveys. Particular focus is placed on the representation of the energy system where specialized bottom-up modules of the power generation, buildings and transport sectors have been developed. The model is founded on rigorous and

	sound microeconomic theory allowing it to study in a consistent framework the interlinkages of the economic sectors and to decompose the impacts of policies to their key driving factors.
Solution mechanism	GEM-E3 is recursive dynamic CGE coupled with a forward-looking expectations mechanism and produces projections of the economic and energy systems until 2100 (the base year is 2021, the first simulation year is 2025 and then five-year time steps until 2100). The model optimizes firms and household behaviour and ensures macroeconomic closure at the global level through the interest rate (alternative closures apply).
Main drivers / exogenous inputs	The key exogenous inputs to the model are: i) Technical Progress/ Productivity (partial exogenous – endogenous R&D and learning can apply); ii) Population, Active Population and Participation Rate; iii) Long Term Expectations on Capital Accumulation; iv) International Energy Prices; v) Energy and Climate policies; vi) Technology Costs, especially for low-carbon technologies.
Regional aggregation	The model is global and aggregates the world in 46 countries/regions. All EU Member states are represented individually, all G-20 countries individually, and main energy-producing countries individually. The model aggregates the economy in 51 economic activities, with a focus on energy supply (coal, oil, gas, electricity, biofuels, renewable energy) and energy-intensive industries (steel, cement and non-metallic minerals, chemicals, paper and pulp).
Limitations	The model does not capture all physical climate impacts and extreme events, and this may lead to an underestimation of the cost of climate change
Contribution to GEO7	**Use of results in GEO7** The GEM-E3 model is used to assess the socioeconomic impacts of the Behaviour-focused and Technology-focused Transformation Pathways. It provides projections of the GDP and sectoral production, employment and unemployment rate by scenario until 2100. **Data received from other participating models** The energy system (fuel mix per industry, power generation mix, fuel mix in transport) is calibrated to the output of IMAGE. The baseline GDP projections are calibrated to the AIM model. Morbidity and labour productivity effects are taken from IFs and impact on land use from the IMAGE model.
Key Reference(s)	Capros, P., Van Regemorter, D., Paroussos, L., Karkatsoulis, P., Fragkiadakis, C., Tsani, S. et al. (2013) *GEM-E3 Model Documentation*. Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC83177 Paroussos, L., Mandel, A., Fragkiadakis, K. et al. (2019) *Climate clubs and the macro-economic benefits of international cooperation on climate policy*. Nat. Clim. Chang. 9, 542–546. https://doi.org/10.1038/s41558-019-0501-1 Available at https://e3modelling.com/modelling-tools/gem-e3/

Contribution to Global Environmental Assessments	IPCC AR6 WGIII Report

Model name	**RIME (Rapid Impact Model Emulator)**
Purpose of model	RIME enables the rapid assessment of climate impact indicators using global warming level approaches. For a given input global warming scenario, RIME uses multidimensional interpolation methods, primarily based on global warming levels, to produce a suite of climate impact indicators, in both global gridded formats as well as aggregated to regions like countries or river basins. Depending on the input data available, it can be used for a suite of climate impact drivers including temperature, precipitation and hydrological indicators, as well as extending to assess exposure to impacts, for example of population, land area or GDP.
Solution mechanism	RIME's current implementation is deterministic.
Main drivers / exogenous inputs	As inputs, RIME requires: • the global mean surface temperature trajectory through time, e.g. from a simple climate model like FaIR or MAGICC • an input impacts database with data stored by global warming levels, e.g. Werning et al. (2024)
Regional aggregation	RIME is flexible in region aggregation, which depends only on the resolution of input data. Typically: • For gridded data, 0.5 x 0.5 degree gridded data is used, the output being the same • For regional data, RIME has used UNEP 5-region + World data as input and output. Other aggregations, e.g. country, river basin, and IPCC region, are possible but not used here.
Limitations	The pattern-scaling approach means that natural climate variability cannot be captured. Thus, the impact estimates are to be interpreted as a snapshot indicator representative of that global warming level, and indicative of the long-term change. The data should also be used with caution for scenarios exceeding 3°C global mean temperature or scenarios in scenarios with post-peak temperature reductions >0.2°C.
Contribution to GEO7	**Use of results in GEO7** In the case of GEO-7, greenhouse gas emissions from the integrated assessment models IMAGE and AIM are run through MAGICC to provide global mean surface temperature, which is used as input into RIME. The results presented show the regional changes by indicator between 2020 and 2050 for the transformation and reference scenarios, as well as estimates of the population exposed to each climate impact indicator.

	Data received from other participating models Global Mean Temperature timeseries from the IMAGE and AIM models.
Key Reference(s)	Data: Werning, M., Frank, S., Hooke, D., Nguyen, B., Rafaj, P., Satoh, Y. et al. (2024) *Climate Solutions Explorer – hazard, impacts and exposure data* (0.4) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.10868066 Methodology: Werning, M., Hooke, D., Krey, V., Riahi, K., van Ruijven, B. and Byers, E. (2024) *Global warming level indicators of climate change and hotspots of exposure*. Environ. Res.: Climate 3 045015 https://doi.org/10.1088/2752-5295/ad8300?urlappend=%3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle Byers, E., Werning, M., Perette, M., Schwind, N., Krey, V., Riahi, K. et al. (2025 – in review). *Fast climate impact emulation for global temperature scenarios with the Rapid Impact Model Emulator (RIME)*. EarthArXiv preprint. https://doi.org/10.31223/X5GH8Z Software: https://github.com/iiasa/rime
Contribution to Global Environmental Assessments	None

Model name	**MIMOSA (Integrated Assessment Model for Cost-Benefit Analysis)**
Purpose of model	MIMOSA is an Integrated Assessment Model (IAM) part of the IMAGE family, with 26 regions covering the whole world. It is a relatively simple Cost-Benefit IAM that still covers the relevant technological and socioeconomic dynamics. The climate impacts are calculated using state-of-the-art COACCH damage functions, and the mitigation costs have been directly calibrated to the IPCC AR6 WGIII database. Its main purpose is to calculate the economic impacts of climate change, costs of inaction, benefit-cost ratios of climate policy, and perform cost-benefit analysis of global climate policy.
Solution mechanism	MIMOSA is a global optimization model that tries to maximize the net present value of welfare. When emission pathways are not imposed beforehand, the model distributes mitigation efforts across regions and time while taking into account each region's marginal mitigation costs, climate damages, and per capita income. The model works on 5-year timesteps from 2020 to 2150, but the results are focused on the period 2020 to 2100 since the years 2100 to 2150 are used to avoid end-of-horizon problems.
Main drivers / exogenous inputs	Population, baseline emissions, technological assumptions and baseline carbon intensity are exogenous and dependent on SSP. The key parameters

	are discount factor, level of climate impacts (in percentiles of literature range), climate sensitivity (TCRE, in percentiles of AR6 range), SSP, and mitigation cost level (in percentiles of AR6 range).
Regional aggregation	MIMOSA is a global model running on the same 26 regions as IMAGE.
Limitations	MIMOSA uses a simple linear relation between cumulative CO_2 emissions and temperature. While this is shown to yield better results than a slightly more detailed 2-box-climate module, this does introduce uncertainty since non-CO_2 gases are not explicitly modelled. Also, the linear (TCRE) relation between cumulative emissions and temperature might not be as accurate after a temperature peak, when emissions become net negative.
Contribution to GEO7	**Use of results in GEO7** MIMOSA is used to calculate the economic impacts of climate change in both transformation pathways and the costs of inaction in the no-policy scenario. **Data received from other participating models** Baseline regional GDP (without mitigation costs or climate impacts) and regional population are used from the IMAGE reference scenario. For the Current Trends Scenario, global emissions are used from AIM, while for the two Transformation Pathway Scenarios, the global emissions are obtained from the IMAGE runs.
Key Reference(s)	van der Wijst, KI., Bosello, F., Dasgupta, S. et al. (2023) *New damage curves and multimodel analysis suggest lower optimal temperature.* Nat. Clim. Chang. 13, 434–441. https://doi.org/10.1038/s41558-023-01636-1 van der Wijst, K.I., Hof, A.F. and van Vuuren, D.P. (2021) *On the optimality of 2°C targets and a decomposition of uncertainty*. Nat Commun 12, 2575. https://doi.org/10.1038/s41467-021-22826-5 Detailed documentation: https://utrechtuniversity.github.io/mimosa/ Source code: https://github.com/UtrechtUniversity/mimosa
Contribution to Global Environmental Assessments	IPCC AR6 WGIII Report

Models used in Regional Analysis (Chapter 21)

Model name	**T21-iSDG® (Integrated Sustainable Development Goal model that evolved from the Threshold 21 model)**
Purpose of model	The iSDG is a modelling framework of the Millennium Institute (MI). The model is designed to support integrated planning and policy analysis for sustainable development at the national level. It allows for scenario analysis, enabling users to

	explore different policy options and evaluate their effects on various sustainability indicators. The iSDG model includes 30 modules that span social, economic, and environmental sectors and includes 78 indicators and relevant policies across all 17 UN SDGs. Additional indicators can be included in the process of customization to a country's characteristics and analytical needs. Model validation is embedded in the broader implementation process. Structural validation tests involve direct verification of the assumptions made in the model structure and parameters. Behavioural validation tests involve the assessment of the model's ability to replicate the historical behaviour through means of calibration. The calibration process evaluates the goodness-of-fit for the model application through statistical indicators.
Solution mechanism	The iSDG model is built using the system dynamics methodology. Depending on the dynamics of interest, it typically simulates the dynamics from 2000 to 2030/2050, with the 2000–present time used for calibration. The model commonly simulates dynamics on a quarterly or annual timestep, with time units at a monthly or yearly scale. The standard calibration process makes use of the Stella® optimization function to obtain a reasonable calibration rapidly.
Main drivers / exogenous inputs	iSDG's fundamental approach is to endogenously represent variables that are considered an essential part of the development mechanisms under analysis. For example, GDP, population, and the demand and supply of natural resources and their main determinants are endogenously calculated. Variables that have an important influence on the issues analysed, but are only weakly influenced by the issues analysed, are exogenously represented. For example, rain cycles, the grants received, or the exchange rate are exogenously determined. Since the focus of iSDG is on long-term development issues, inflation and interest rates are also exogenously represented. For specific country applications, where supported by evidence, these variables can be made endogenous in the model.
Regional aggregation	The base iSDG model is structured as a national model, and, from a geographic perspective, data are aggregated at the national level. The main social, economic and environmental variables are further broken down into subcomponents. For example, population is divided into 101 age cohorts and two genders. Customization of the level of aggregation of iSDG is possible. In this instance, national dynamics can be disaggregated by degree of remoteness or at a regional scale, though this is highly context specific and dependent on data availability. Full details on the level of aggregation are provided in the model documentation.
Limitations	The model's results inherently embed a high degree of uncertainty, being long-term in nature (a large variety of unforeseeable changes can take place) and broad in scope (including a large number of parameters with uncertain future values). The iSDG model is not intended to substitute short-term or sector-specific models.
Contribution to GEO7	**Use of results in GEO7** Outputs from the iSDG model are included in Chapter 20 (Regional similarities and differences) to provide an example of the use of the iSDG to support national development in sub-Saharan Africa. **Data received from other participating models** The iSDG model does not receive data from the models currently used in the

	GEO-7 assessment, though future work can incorporate evaluating the Solution Pathways scenarios for different country contexts. iSDG data is typically sourced from national databases and documents or may be sourced from the government and relevant stakeholders. In the absence of national datasets, global data sources can also be used (e.g. World Bank, IMF, IEA, FAO, UNDP and UNSTATs).
Key Reference(s)	Allen, C., Biddulph, A., Wiedmann, T., Pedercini, M. and Malekpour, S. (2024) *Modelling six sustainable development transformations in Australia and their accelerators, impediments, enablers, and interlinkages*. Nat. Commun. 15(1), 594. http://dx.doi.org/10.1038/s41467-023-44655-4 Pedercini, M., Arquitt, S. and Chan, D. (2020) *Integrated simulation for the 2030 agenda*. Syst. Dyn. Rev. 36(3), 333-357. http://dx.doi.org/10.1002/sdr.1665 Website: https://www.millennium-institute.org/isdg-simulator
Contribution to Global Environmental Assessments	UNEP GEO-5

Model name	**IMED (Integrated Model of Energy, Environment and Economy for Sustainable Development)**
Purpose of model	The IMED integrated assessment model addresses key scientific challenges and policy imperatives crucial for facilitating green and low-carbon transitions in alignment with national and global sustainability objectives. Central to its investigations are questions surrounding the mitigation costs associated with ambitious climate targets and their co-benefits, particularly in terms of improvements in air pollution, human health, and resource efficiency. Outputs of the IMED model include projections of energy supply and demand, emissions of greenhouse gases and other air pollutants, and demand for various material resources like industrial water use. IMED model can also be connected with the GLOBIOM model from IIASA to get the outputs about land-use change. The model is calibrated to national and global Input-Output tables, air pollutant emissions (multi-resolution Emission Inventory for China), and energy supply and demand (International Energy Agency).
Solution mechanism	The IMED model includes several interconnected submodels. The IMED|CGE is a general equilibrium model solved by Mathematical Programming System for General Equilibrium under the General Algebraic Modeling System (GAMS/MPSGE) at a one-year time step. IMED|TEC model draws on the energy system cost minimization based on linear optimization programming. These two models could be combined with the IMED|HEL model for human health impact assessment and GLOBIOM from IIASA for

	land-use change assessment, forming the core of the entire IMED model system.
Main drivers / exogenous inputs	Exogenous inputs of the IMED model include population and economic activity, the cost of technology in some important sectors, land use data and food production yields. The main drivers are the energy and resource-intensive sectors, future energy services, and low-carbon pathways.
Regional aggregation	The IMED/CGE model includes 31 Chinese provinces and 26 global regions. The IMED/TEC model includes 31 Chinese provinces and the IMED/HEL model operates at a global 0.5 x 0.5 degree grid.
Limitations	Currently, the IMED framework primarily integrates Computable General Equilibrium (CGE) modeling and energy system models centered on economic indicators and energy flows. However, it lacks dedicated modules and foundational datasets for projecting material demands. The absence of algorithms focused on resource and material flows undermines the system's ability to evaluate future policies comprehensively. This limitation not only weakens the accuracy of energy and emission pathway estimations in physical terms, but also constrains the assessment of resource circulation strategies and demand-side management policies.
Contribution to GEO7	**Use of results in GEO7** The IMED model is used for analyzing the Transformation Pathways to reach carbon neutrality by 2060 for China in the national case study box, revealing the subregional and rural–urban differences regarding the water-energy-food nexus and consequently different impacts on air pollution, human health and land use. **Data received from other participating models** GDP projections could be compared with the GEM-E3 model, and air pollutant concentration data could be obtained from the FASST model to calculate health impacts.
Key Reference(s)	Ma, T., Zhang, S., Xiao, Y., Liu, X., Wang, M., Wu, K. et al. (2023). *Costs and health benefits of the rural energy transition to carbon neutrality in China*. Nat. Commun. 14(1), 6101. http://dx.doi.org/10.1038/s41467-023-41707-7 Dai, H. (2025) *Handbook of the IMED model framework: An introduction to the model structure and research progress*. Retrieved from https://www.jianguoyun.com/p/DZnI8a8QIL7CBhi913M Website: http://scholar.pku.edu.cn/hanchengdai/imed_general
Contribution to Global Environmental Assessments	IPCC AR6 WG I and III reports

References

Aguiar, A.P.D., Collste, D., Harmáčková, Z.V., Pereira, L., Selomane, O., Galafassi, D. et al. (2020). Co-designing global target-seeking scenarios: A cross-scale participatory process for capturing multiple perspectives on pathways to sustainability. Global Environmental Change 65, 102198. https://doi.org/10.1016/j.gloenvcha.2020.102198

Alcamo, J. (2008). Chapter six the SAS approach: Combining qualitative and quantitative knowledge in environmental scenarios. In Environmental Futures - The Practice of Environmental Scenario Analysis. Elsevier. 123-150. http://dx.doi.org/10.1016/s1574-101x(08)00406-7

Bakkes, J., Cheatle, M., Mžavanadze, N., Pintér, L. and Witt, R.G. (2022). Keeping the World's environment under review: An intellectual history of the global environment outlook. Central European University Press. https://library.oapen.org/bitstream/handle/20.500.12657/57088/9789633864326.pdf?sequence=1

Belete, G.F., Voinov, A. and Laniak, G.F. (2017). An overview of the model integration process: From pre-integration assessment to testing. Environ. Model. Softw. 87, 49-63. http://dx.doi.org/10.1016/j.envsoft.2016.10.013

Bennett, E.M. (2017). Changing the agriculture and environment conversation. Nat. Ecol. Evol. 1(1), 18. http://dx.doi.org/10.1038/s41559-016-0018

Byers, E., Krey, V., Kriegler, E., Riahi, K., Schaeffer, R., Kikstra, J. et al. (2022). AR6 Scenarios Database. Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis, http://dx.doi.org/10.5281/ZENODO.5886911

Byers, E., Mahé Perrette , M., Schwind, N., Krey, V., Riahi, K. and Schleussne, C. (2025). Fast climate impact emulation for global temperature scenarios with the Rapid Impact Model Emulator (RIME). Earth ArXiv. https://eartharxiv.org/repository/view/8825/

Cai, Y., Newth, D., Finnigan, J. and Gunasekera, D. (2015). A hybrid energy-economy model for global integrated assessment of climate change, carbon mitigation and energy transformation. Appl. Energy 148, 381-395. http://dx.doi.org/10.1016/j.apenergy.2015.03.106

Capros, P., Van Regemorter, D., Paroussos, L., Karkatsoulis, P., Fragkiadakis, C., Tsani, S. et al. (2013). GEM-E3 Model Documentation. Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC83177

Carlsen, H., Talebian, S., Pedde, S. and Kok, K. (2024). Diversity in global environmental scenario sets. Global Environmental Change 86, 102839. https://doi.org/10.1016/j.gloenvcha.2024.102839

Convention on Biological Diversity (2022). Decision Adopted by the Conference of The Parties to The Convention on Biological Diversity. CBD/COP/DEC/15/4. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf

D'Amato, D. (2021). Sustainability narratives as transformative solution pathways: Zooming in on the circular economy. Circ. Econ. Sustain. http://dx.doi.org/10.1007/s43615-021-00008-1

Elsawah, S., Hamilton, S.H., Jakeman, A.J., Rothman, D., Schweizer, V., Trutnevyte, E. et al. (2020). Scenario processes for socio-environmental systems analysis of futures: A review of recent efforts and a salient research agenda for supporting decision making. Science of The Total Environment 729, 138393. https://doi.org/10.1016/j.scitotenv.2020.138393

Esch, S., Sewell, A., Bakkenes, M., Berkhout, E., Doelman, J., Stehfest, E. et al. (2021). The global potential for land restoration: Scenarios for the Global Land Outlook 2. Netherlands Environmental Assessment Agency(PBL) ,The Hague. https://www.pbl.nl/uploads/default/downloads/pbl-2022-the-global-potential-for-land-restoration-glo2-4816_0.pdf

Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Herran, D.S., Dai, H. et al. (2017). SSP3: AIM implementation of Shared Socioeconomic Pathways. Glob. Environ. Change 42, 268-283. http://dx.doi.org/10.1016/j.gloenvcha.2016.06.009

Fuller, R., Landrigan, P.J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M. et al. (2022). Pollution and health: a progress update. Lancet Planet. Health 6(6), e535-e547. http://dx.doi.org/10.1016/S2542-5196(22)00090-0

Geels, F.W. (2014). Regime resistance against low-carbon transitions: Introducing politics and power into the multi-level perspective. Theory Cult. Soc. 31(5), 21-40. http://dx.doi.org/10.1177/0263276414531627

Godfray, H. C. J. and Robinson, S. (2015). Contrasting approaches to projecting long-run global food security, Oxford Review of Economic Policy, Volume 31, Issue 1. https://doi.org/10.1093/oxrep/grv006

Hughes, B.B., 2019. International futures: Building and using global models. Academic Press.

Hunt, D.V.L., Lombardi, D.R., Atkinson, S., Barber, A.R.G., Barnes, M., Boyko, C.T. et al. (2012). Scenario Archetypes: Converging Rather than Diverging Themes. Sustainability, 4. https://doi.org/10.3390/su4040740

IK & LK Dialogues (2025). Indigenous Knowledge and Local Knowledge Dialogues. Global Environment Outlook 7. Mexico City: CopIt-arXives https://copitarxives.fisica.unam.mx/SC0011EN/SC0011EN.php

Intergovernmental Panel on Climate Change (2018) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge University Press, Cambridge UK and New York, NY, USA.http://dx.doi.org/10.1017/9781009157940

Intergovernmental Panel on Climate Change (2022) Summary for Policymakers [P.R. Shukla, J. Skea, A. Reisinger, R. Slade, R. Fradera, M. Pathak, A. Al Khourdajie, M. Belkacemi, R. van Diemen, A. Hasija, G. Lisboa, S. Luz, J. Malley, D. McCollum, S. Some, P. Vyas, (eds.)]. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, UK and New York, NY, USA. http://dx.doi.org/10.1017/9781009157926.001

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2016): The methodological assessment report on scenarios and models of biodiversity and ecosystem services. S. Ferrier, K. N. Ninan, P. Leadley, R. Alkemade, L. A. Acosta, H. R. Akçakaya, L. Brotons, W. W. L. Cheung, V. Christensen, K. A. Harhash, J. Kabubo-Mariara, C. Lundquist, M. Obersteiner, H. M. Pereira, G. Peterson, R. Pichs-Madruga, N. Ravindranath, C. Rondinini and B. A. Wintle (eds.). Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany. https://files.ipbes.net/ipbes-web-prod-public-files/downloads/pdf/2016.methodological_assessment_report_scenarios_models.pdf

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Version 1). Zenodo. https://doi.org/10.5281/zenodo.6417333

Kok, K., Bärlund, I., Flörke, M., Holman, I., Gramberger, M., Sendzimir, J. et al. (2015). European participatory scenario development: strengthening the link between stories and models. Clim. Change 128(3-4), 187-200. http://dx.doi.org/10.1007/s10584-014-1143-y

Kok, M.T.J., Meijer, J.R., van Zeist, W.-J., Hilbers, J.P., Immovilli, M., Janse, J.H. et al. (2023). Assessing ambitious nature conservation strategies in a below 2-degree and food-secure world. Biol. Conserv. 284(110068), 110068. http://dx.doi.org/10.1016/j.biocon.2023.110068

Lauer, A., de Castro, C. and Carpintero, Ó. (2024). Between continuous presents and disruptive futures: Identifying the ideological backbones of global environmental scenarios. Futures 163(103460), 103460. https://doi.org/10.1016/j.futures.2024.103460

Luederitz, C., Schäpke, N., Wiek, A., Lang, D.J., Bergmann, M., Bos, J.J. et al. (2017). Learning through evaluation – A tentative evaluative scheme

for sustainability transition experiments. J. Clean. Prod. 169, 61-76. http://dx.doi.org/10.1016/j.jclepro.2016.09.005

Nakicenovic, N. et al. (2000). Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf

Nakicenovic, N., Riahi, K., Boza-Kiss, B., Busch, S., Fujimori, S., Goujon, A. et al. (2018). Transformations to Achieve the Sustainable Development Goals. Report prepared by The World in 2050 initiative. http://dx.doi.org/10.22022/TNT/07-2018.15347

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S. et al. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Change 42, 169-180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

Pastor, A.V., Vieira, D.C.S., Soudijn, F.H. and Edelenbosch, O.Y. (2020). How uncertainties are tackled in multi-disciplinary science? A review of integrated assessments under global change. CATENA 186(104305), 104305. http://dx.doi.org/10.1016/j.catena.2019.104305.

Pereira, H.M., Ferrier, S., Walters, M., Geller, G.N., Jongman, R.H.G., Scholes, R.J. et al. (2013). Ecology. Essential biodiversity variables. Science 339(6117), 277-278. http://dx.doi.org/10.1126/science.1229931

Pereira, H.M., Martins, I.S., Rosa, I.M.D., Kim, H., Leadley, P., Popp, A. et al. (2024). Global trends and scenarios for terrestrial biodiversity and ecosystem services from 1900 to 2050. Science 384(6694), 458-465. https://doi.org/10.1126/science.adn3441

Pereira, L.M., Davies, K.K., Belder, E., Ferrier, S., Karlsson-Vinkhuyzen, S., Kim, H. et al. (2020). Developing multiscale and integrative nature–people scenarios using the Nature Futures Framework. People Nat. (Hoboken) 2(4), 1172-1195. http://dx.doi.org/10.1002/pan3.10146

Rao, N.D. and Min, J. (2018). Decent living standards: Material prerequisites for human wellbeing. Soc. Indic. Res. 138(1), 225-244. http://dx.doi.org/10.1007/s11205-017-1650-0

Rao, S., Klimont, Z., Smith, S.J., Van Dingenen, R., Dentener, F., Bouwman, L. et al. (2017). Future air pollution in the Shared Socio-economic Pathways. Glob. Environ. Change 42, 346-358. http://dx.doi.org/10.1016/j.gloenvcha.2016.05.012

Raskin, P., Monks, F., Ribeiro, T., van Vuuren, D. and Field, C. (2005). Global Scenarios in Historical Perspective. In Ecosystems and Humun Well-Being: Scenarios-Findings of the Scenarios Working Group Millenium Ecosystem Assessment SeriesIsland Press: Washington, DC, USA. https://www.millenniumassessment.org/documents/document.326.aspx.pdf

Raskin, P. and Swart, R. (2020). Excluded futures: the continuity bias in scenario assessments. Sustain. Earth 3(1). http://dx.doi.org/10.1186/s42055-020-00030-5

Raymond, C., Horton, R.M., Zscheischler, J., Martius, O., AghaKouchak, A., Balch, J. et al. (2020). Understanding and managing connected extreme events. Nat. Clim. Chang. 10(7), 611-621. http://dx.doi.org/10.1038/s41558-020-0790-4

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S. et al. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob. Environ. Change 42, 153-168. http://dx.doi.org/10.1016/j.gloenvcha.2016.05.009

Rogelj, J., Forster, P.M., Kriegler, E., Smith, C.J. and Séférian, R. (2019). Estimating and tracking the remaining carbon budget for stringent climate targets. Nature 571(7765), 335-342. http://dx.doi.org/10.1038/s41558-018-0091-3

Rogelj, J., Popp, A., Calvin, K.V., Luderer, G., Emmerling, J., Gernaat, D. et al. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. Nat. Clim. Chang. 8(4), 325-332. http://dx.doi.org/10.1038/s41558-018-0091-3

Rosa, I.M.D., Pereira, H.M., Ferrier, S., Alkemade, R., Acosta, L.A., Akcakaya, H.R. et al. (2017). Multiscale scenarios for nature futures. Nat. Ecol. Evol. 1(10), 1416-1419. http://dx.doi.org/10.1038/s41559-017-0273-9

Schaphoff, S., von Bloh, W., Rammig, A., Thonicke, K., Biemans, H., Forkel, M. et al. (2018a). LPJmL4 – a dynamic global vegetation model with managed land – Part 1: Model description. Geosci. Model Dev. 11(4), 1343-1375. http://dx.doi.org/10.5194/gmd-11-1377-2018

Schipper, A.M., Hilbers, J.P., Meijer, J.R., Antão, L.H., Benítez-López, A., de Jonge, M.M.J. et al. (2020). Projecting terrestrial biodiversity intactness with GLOBIO 4. Glob. Chang. Biol. 26(2), 760-771. http://dx.doi.org/10.1111/gcb.14848

Sen, A. (1999). Development as Freedom. London, England: Oxford University Press.

Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Luca, A. et al. (2021). Weather and climate extreme events in a changing climate. In Climate Change 2021 – The Physical Science Basis. Cambridge University Press. 1513-1766. http://dx.doi.org/10.1017/9781009157896.013

Soergel, B., Kriegler, E., Weindl, I., Rauner, S., Dirnaichner, A., Ruhe, C. et al. (2021). A sustainable development pathway for climate action within the UN 2030 Agenda. Nat. Clim. Chang. 11(8), 656-664. http://dx.doi.org/10.1038/s41558-021-01098-3

Soergel, B., Rauner, S., Daioglou, V., Weindl, I., Mastrucci, A., Carrer, F. et al. (2024). Multiple pathways towards sustainable development goals and climate targets. Environ. Res. Lett. 19(12), 124009. 10.1088/1748-9326/ad80af.

Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M. et al. (2014). Integrated Assessment of Global Environmental Change with IMAGE 3.0 - Model description and policy applications. Netherlands Environmental Assessment Agency (PBL),The Hague. https://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-image-30-model-description-and-policy-applications

Stern, E.R. and Humphries, M.M. (2022). Interweaving local, expert, and Indigenous knowledge into quantitative wildlife analyses: A systematic review. Biol. Conserv. 266(109444), 109444. http://dx.doi.org/10.1016/j.biocon.2021.109444

Stirling, A. (2011). Pluralising progress: From integrative transitions to transformative diversity. Environ. Innov. Soc. Transit. 1(1), 82-88. http://dx.doi.org/10.1016/j.eist.2011.03.005

United Nations (2015) Resolution adopted by the General Assembly on 25 September 2015. 10/1.Transforming our world: the 2030 Agenda for Sustainable Development. https://docs.un.org/en/A/RES/70/1

United Nations Convention to Combat Desertification (2018). The UNCCD 2018–2030 Strategic Framework. Decision 7/COP.13, ICCD/COP(13)/21/Add.1. https://www.unccd.int/resources/other/unccd-2018-2030-strategic-framework

United Nations Convention to Combat Desertification (2017). The Global Land Outlook, first edition. Bonn, Germany. https://www.unccd.int/resources/publications/global-land-outlook-1st-edition

United Nations Convention to Combat Desertification (2022). The Global Land Outlook, second edition. UNCCD, Bonn. https://www.unccd.int/resources/global-land-outlook/global-land-outlook-2nd-edition

United Nations Development Programme (2022). New threats to human security in the Anthropocene: Demanding greater solidarity. https://hs.hdr.undp.org/pdf/srhs2022.pdf

United Nations Environment Programme (2002). Global Environment Outlook 3. https://www.unep.org/resources/global-environment-outlook-3

United Nations Environment Programme (2007). Global Environment Outlook 4. https://www.unep.org/resources/global-environment-outlook-4

United Nations Environment Programme (2012). Global Environment Outlook 5. https://www.unep.org/resources/global-environment-outlook-5

United Nations Environment Programme (2019). Global Environment Outlook – GEO-6: Healthy Planet, Healthy People. Nairobi. https://www.unep.org/resources/global-environment-outlook-6

United Nations Environment Programme (2021). Making peace with nature: A scientific blueprint to tackle the climate, biodiversity and pollution emergencies. United Nations Environment Programme, Nairobi. https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/34948/MPN.pdf

United Nations Environment Programme (2024). Global Resources Outlook 2024: Bend the Trend – Pathways to a liveable planet as resource use spikes. Nairobi: United Nations Environment Programme. https://www.resourcepanel.org/sites/default/files/documents/document/media/gro24_full_report_1mar_final_for_web.pdf

United Nations Framework Convention on Climate Change (2015). Adoption of the Paris Agreement.FCCC/CP/2015/L.9/Rev.1. United Nations Framework Convention on Climate Change, Paris. https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

van der Wijst, K.-I., Bosello, F., Dasgupta, S., Drouet, L., Emmerling, J., Hof, A. et al. (2023). New damage curves and multimodel analysis suggest lower optimal temperature. Nat. Clim. Chang. http://dx.doi.org/10.1038/s41467-021-22826-5

Van Dingenen, R., Dentener, F., Crippa, M., Leitao, J., Marmer, E., Rao, S. et al. (2018). TM5-FASST: a global atmospheric source–receptor model for rapid impact analysis of emission changes on air quality and short-lived climate pollutants. Atmos. Chem. Phys. 18(21), 16173-16211. http://dx.doi.org/10.5194/acp-18-16173-2018

van 't Klooster, S.A. and van Asselt, M.B.A. (2006). Practising the scenario-axes technique. Futures 38(1), 15-30. http://dx.doi.org/10.1016/j.futures.2005.04.019

van Vuuren, D.P., Kok, M., Lucas, P.L., Prins, A.G., Alkemade, R., van den Berg, M. et al. (2015). Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. Technol. Forecast. Soc. Change 98, 303-323. http://dx.doi.org/10.1016/j.techfore.2015.03.005

van Vuuren, D.P., Zimm, C., Busch, S., Kriegler, E., Leininger, J., Messner, D. et al. (2022). Defining a sustainable development target space for 2030 and 2050. One Earth 5(2), 142-156. https://doi.org/10.1016/j.oneear.2022.01.003

van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., Carter, T.R. et al. (2014). A new scenario framework for Climate Change Research: scenario matrix architecture. Climate Change 122(3), 373-386. http://dx.doi.org/10.1007/s10584-013-0906-1

van Vuuren, D.P., Riahi, K., Calvin, K., Dellink, R., Emmerling, J., Fujimori, S. et al. (2017). The Shared Socio-economic Pathways: Trajectories for human development and global environmental change. Glob. Environ. Change 42, 148-152. http://dx.doi.org/10.1016/j.gloenvcha.2016.10.009

van Vuuren, D.P., Riahi, K., Moss, R., Edmonds, J., Thomson, A., Nakicenovic, N. et al. (2012). A proposal for a new scenario framework to support research and assessment in different climate research communities. Glob. Environ. Change 22(1), 21-35. https://doi.org/10.1016/j.gloenvcha.2011.08.002

Werning, M., Hooke, D., Krey, V., Riahi, K., van Ruijven, B. and Byers, E.A. (2024). Global warming level indicators of climate change and hotspots of exposure. Environmental Research: Climate 3(4), 045015. https://dx.doi.org/10.1088/2752-5295/ad8300

Wolff, F., Fischer, C., Gensch, C., Hanke, G., Kenkmann, T., Löw, C. et al. (2024). Analysis of transformation paths for global, sustainable development. https://www.umweltbundesamt.de/publikationen/analyse-von-transformationspfaden-fuer-eine-globale

World Health Organization (2021). WHO global air quality guidelines: particulate matter ($PM_{2.5}$ and PM10) ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. https://www.who.int/publications/i/item/9789240034228

10 Continuation of Current Trends: Global Implications

Coordinating Lead Authors: Paul Lucas (PBL Netherlands Environmental Assessment Agency) and Shinichiro Fujimori (Kyoto University)

Lead Authors: Alaa Al Khourdajie (Imperial College London), Lindsay Beevers (University of Edinburgh), Claudio Belis (European Commission, Joint Research Centre), Hester Biemans (Wageningen University and Research), Edward Byers (International Institute for Applied Systems Analysis, IIASA), Vassilis Daioglou (PBL Netherlands Environmental Assessment Agency, Utrecht University), Jonathan Davies (University of British Columbia), Jonathan Doelman (PBL Netherlands Environmental Assessment Agency), Panagiotis Fragkos (E3 Modelling), Taylor Hanna (Pardee Institute University of Denver), Jiang Kejun (Energy Research Institute), Yolanda López-Maldonado (Indigenous Science), Jonathan D. Moyer (Pardee Institute University of Denver), Leonidas Paroussos (E3 Modelling), Heinz Schandl (CSIRO), Audrone Telesiene (Kaunas University of Technology), Detlef van Vuuren (PBL Netherlands Environmental Assessment Agency, Utrecht University) and Carol Zavaleta-Cortijo (Universidad Peruana Cayetano Heredia)

Contributing Authors: Rob Alkemade (PBL Netherlands Environmental Assessment Agency), Michel Bakkenes(PBL Netherlands Environmental Assessment Agency), Arthur Beusen (PBL Netherlands Environmental Assessment Agency), Ricardo O. Barra (University of Concepcion), Dimitris Fragiadakis (E3 Modelling), Stephen Cró Maycock (PBL Netherlands Environmental Assessment Agency), Stephan Harrison (University of Exeter), Tomoko Hasegawa (Ritsumeikan University), Mulako Kabisa (University of the Witwatersrand), Yingying Lu (CSIRO), Le Yu (Tsinghua University), Indu K Murthy (Center for Study of Science, Technology and Policy), Ravendra Naidu (University of Newcastle), Yuki Ochi (E-konzal), Ken Oshiro (Hokkaido University), Dulce Flores-Renteria Center for Research and Advanced Studies of the National Polytechnic Institute), Elias Symeonakis (Manchester Metropolitan University), Fiffy Hanisdah Binti Saikim (Universiti Malaysia Sabah), Kazuaki Tsuchiya (National institute for Environmental Studies, Japan), Natalia Tarasova (D.Mendeleev University of Chemical Technology of Russia), Kaj-Ivar van der Wijst (Utrecht University), Laszlo Vreedenburgh (PBL Netherlands Environmental Assessment Agency) and Michaela Werning (International Institute for Applied Systems Analysis, IIASA)

Fellow: Michael Ruggeri (University of Oxford) and Pushp Raj Tiwari (University of Hertfordshire)

Credit: GroundPicture/Envato

Chapter summary

Credit: SeanPavone/Envato

Current socioeconomic development patterns and prevailing approaches to valuing land and nature are failing to meet many internationally agreed environmental goals (*well established*). This chapter discusses future environmental and socioeconomic developments if the current development trajectories continue by presenting and discussing the *GEO-7 Current Trends Scenario,* developed specifically for the seventh Global Environment Outlook (GEO-7) report. This scenario follows historical trajectories of social, economic, and technological developments. Under this scenario, most environmental pressures are projected to intensify, including further rising greenhouse gas (GHG) emissions, continuing land-use change, and intensifying resource exploitation. Major drivers of these trends include population growth, increasing urbanization, further economic growth, and resource-intensive lifestyles. Consequently, negative trends in the global environmental crises of climate change, biodiversity loss, land degradation and desertification, and pollution and waste are projected to worsen through 2050 {10.2, 10.3, 10.4}.

In the energy system, rising energy demand and persistent dependence on fossil fuels drive increases in GHG emissions (*well established*). Despite improvements in energy efficiency, increasing demand leads to an estimated 25 per cent rise in primary energy use between 2020 and 2050. While the share of renewable energy in total energy production increases, by 2050 fossil fuels still dominate the overall energy mix, sustaining high GHG emissions. Air pollution levels gradually decrease but remain high {10.3.1, 10.4.1, 10.4.2}.

In the food system, population growth and shifting preferences to more animal-based foods drive agricultural land expansion, rising GHG emissions, as well as increasing air and nutrient pollution (*well established*). Meeting the growing food demand of a larger, wealthier population with increasing shares of animal-based foods will require a roughly 50 per cent increase in crop production between 2020 and 2050. This demand outpaces projected yield gains, leading to further expansion of agricultural land. Other

environmental pressures include increasing GHG and ammonia emissions linked to crop and livestock production and fertilizer application {10.3.2, 10.4.1, 10.4.2, 10.4.3}.

In the resources system, population growth and economic development are key drivers of a sharp increase in global materials extraction (*well established*). The extraction of material resources, including biomass, fossil fuels, minerals and metals, is projected to rise by 70 per cent between 2020 and 2050, peaking around mid-century. The largest increase comes from non-metallic minerals, primarily driven by rapid increases in infrastructure expansion and construction in low- and middle-income economies that are expected to have rapid economic growth {10.3.3}.

Depending on if and how current policies and Nationally Determined Contributions are implemented, global temperatures could increase to 2.4 - 3.9°C this century, falling short of meeting the Paris Agreement temperature goal (*well established*). Global mean temperature rise is likely to exceed 1.5°C in the early 2030s, while with inadequate implementation of current policies, global mean temperature is projected to increase by about 3.9°C by 2100. Full implementation and continuation of current policies is expected to limit temperature increase this century to approximately 2.9°C (range: 1.8-3.5), while full implementation of unconditional Nationally Determined Contributions could reduce it to about 2.6°C (range: 1.8-3.4) and, for conditional Nationally Determined Contributions, to approximately 2.4°C (range: 1.8-3.3). All projections have at least a 50 per cent likelihood {10.4.1}.

Air and nutrient pollution of water are projected to remain high, with an increasing number of people exposed to levels above World Health Organization guidelines (*established but incomplete*). While globally most air pollution emissions are projected to decrease slightly between 2020 and 2050, the absolute number of people exposed to fine particulate matter concentrations ($PM_{2.5}$) above 25 µg/m^3 is projected to rise from 3.7 billion to 4.2 billion, mainly due to increasing urbanization and population growth in areas with high emissions. As a result, Sustainable Development Goal (SDG) 3.9 on mortality from environmental pollution and 11.6 on reducing environmental impacts of cities are unlikely to be achieved. Nutrient pollution, such as excess nitrogen and phosphorus, is also projected to increase, largely driven by growing levels from agriculture and human waste. The total area of groundwater, exceeding the World Health Organization standard levels of nitrogen concentration for drinking water (11.3 mg N/l), is projected to grow from 5.0 Mkm^2 in 2020 to 5.7 Mkm^2 by 2050 {10.4.2, 10.4.5}.

Land-use change and soil degradation are projected to continue through 2050, undermining progress towards land-degradation neutrality (*established but incomplete*). Around 100 million hectares of natural lands are projected to be lost between 2020 and 2050, mainly from cropland conversion. This is at the lower end of similar scenario projections in the literature. In addition, soil organic carbon in croplands is projected to decline by an average of 2.2 tC/ha, primarily due to intensive farming practices {10.4.3}.

Biodiversity is expected to decline across almost all dimensions, moving further away from the targets set in the Kunming-Montreal Global Biodiversity Framework (*well established*). Mean-species abundance, a measure of biodiversity intactness, is projected to drop from 59 per cent in 2020 to 56 per cent in 2050, compounding similar historic rates of loss since 1900. This loss in biodiversity is equivalent to the conversion of 4.6 million km^2 of pristine habitat, roughly comparable to the size of the European Union, to a habitat where all the original species are extinct. Land-use change remains the dominant driver, although the impacts of climate change on biodiversity are growing {10.4.4}.

The intensifying global environmental crises and associated pressures may trigger major shifts in the Earth system (*well established*). Tipping points, critical thresholds beyond which a system reorganizes, often abruptly and/or irreversibly, are a major concern. At least 25 Earth system tipping points have been identified, and 16 intersect the biosphere. Crossing Earth's tipping points could have catastrophic and hard to reverse impacts, affecting ecosystems and humanity. Examples of such tipping points include arctic sea ice loss that might alter the position and strength of the jet stream and the collapse of parts of the Antarctic and Greenland ice sheets that can cause significant and irreversible sea-level rise. In the tropics, the pressures of temperature rise, drought, deforestation and more intense and frequent wildfires may transform the

Amazon rainforest into a low tree-cover savanna. Similarly, Boreal and Temperate forests face potential dieback, while a 2°C rise in global mean temperature could nearly eliminate warm-water coral. Several tipping points are expected to be exceeded within this century, even with urgent global action. If the Equilibrium Climate Sensitivity is higher than generally assumed many climate-related impacts will be greater than currently estimated, and many climate-related tipping points will be breached much earlier than previously expected {10.5, Box 10.6}.

Not accounting for the full impacts of the global environmental crises, most dimensions of human well-being are projected to improve. However, progress remains unequal and insufficient to achieve socioeconomic SDG targets (*well established*). Basic material needs, such as access to food (SDG2), water (SDG6) and energy (SDG7), are projected to improve, and poverty (SDG1) to reduce. Also, health outcomes, including under-5 mortality (SDG5), are projected to improve over time. Nonetheless, the progress is insufficient to meet related SDG targets by 2030, and likely not even before 2050. {10.6.1, 10.6.2, 10.6.3, 10.6.4}.

Gains in human well-being are increasingly threatened by the intensifying global environmental crises, affecting human health, food systems and livelihoods (*well established*). By the 2050s, climate change could significantly increase the exposure of billions of people to extreme events, including heat waves, heavy rainfall, and droughts. Global environmental crises may reduce crop yields, undermining food security through changes in temperature and precipitation patterns, increasing pollution of air and soils, reduced soil quality, and decreasing pollination and pest control. Urban air pollution with fine particulate matter alone could be causing around 4 million premature deaths annually in 2050, a similar value to that in 2020. Global environmental crises could also increase injuries and the incidence of mental health problems in the general population and exacerbate health inequities for Indigenous Peoples. Additionally, the economic consequences of environmental degradation may slow poverty reduction and widen inequality between and within countries {Box 10.2, Box 10.6, 10.4.1, 10.4.2, 10.6.1, 10.6.2, 10.6.3}.

The economic costs of failing to address the global environmental crises are substantial and increasing over time (*established but incomplete*). While the economic costs and damages of climate change are relatively well investigated,, those associated with other environmental challenges remain fragmented and uncertain. Focusing solely on climate change, median estimates of the economic impacts are projected at about 4 (range: 0-7) per cent of the global gross domestic product in 2050, rising to approximately 20 (range: 3-37) per cent in 2100, including from reduced agricultural yields, damages to assets located in coastal or flood-prone areas, and a decline in labour productivity. As that assessment does not account for all four global environmental crises, broader societal impacts, or tipping points, the true economic burden of insufficient action on the global environmental crises could well be higher than this estimate suggest {10.6.5}.

10.1 Introduction

The central question of this chapter is:

What are the likely environmental and socioeconomic outcomes if the current development trajectories continue?

To explore it, this chapter presents and discusses the GEO-7 Current Trends Scenario, developed specifically for this report (9.2). This scenario presents a future in which social, economic, and technological trends follow historical patterns. It is based on the Shared Socioeconomic Pathway 2 (SSP2) middle-of-the road scenario (O'Neill et al. 2017) and does not account for current policies and policy objectives. For climate change and air pollution, additional scenarios that incorporate these are presented, drawing on the existing literature.

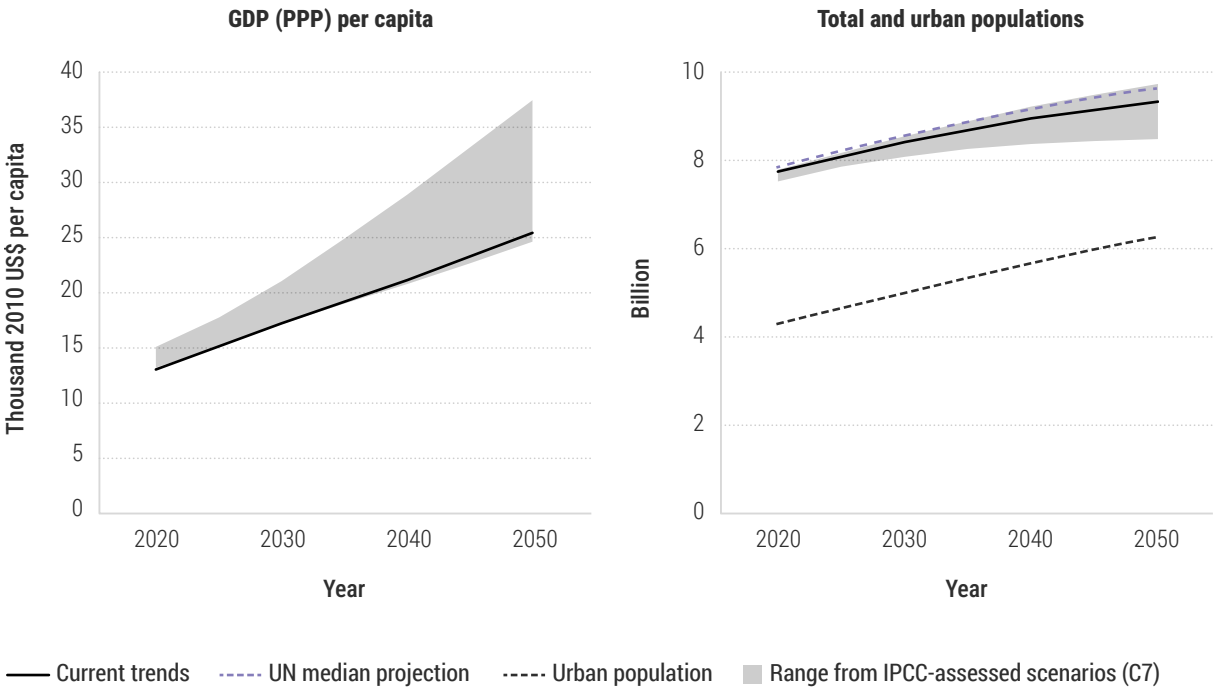
By assessing the likely environmental and socioeconomic implications, the scenario is used to assess the extent to which internationally agreed environmental goals (9.3) are to be achieved without increased effort to address the global environmental crises of climate change, biodiversity loss and land degradation, and pollution and waste. In addition, the Current Trends scenario serves as a reference for the Transformation Pathway scenarios discussed in Chapter 11, highlighting the effort required to achieve the internationally agreed environmental goals. Note that this chapter focuses on the global level. Results for different income groupings and geographical regions are discussed in Chapters 19 and 20, respectively.

10.2 Drivers of environmental change under current trends

Chapter 2 provides an in-depth discussion of the drivers of environmental change, primarily focusing on historic trends. In this chapter, we present future projections of three core drivers within the Current Trends scenario: population and demographics, urbanization, and economic development (**Figure 10.1**). These drivers are the main inputs for the models used in the analysis presented in this chapter. Other drivers are incorporated in the overall broader narrative (O'Neill et al. 2017; Box 10.1).

Credit: pawopa3336/Envato

Figure 10.1: Global GDP per capita in PPP terms and total and urban populations



Source: Dellink et al. (2017); Jiang and O'Neill (2017); KC and Lutz (2017); AR6 Scenario Database, UNDESA (2024)

Box 10.1: Narrative of the SSP2 Middle of the Road scenario

The world continues along a path where social, economic, and technological trends follow historical patterns with little deviation. Development and income growth remain uneven, with some countries advancing while others lagging behind. Most economies are politically stable. Globally connected markets function, albeit imperfectly. Technological development continues steadily, but without fundamental breakthroughs. Global population growth is moderate and stabilizes in the second half of the century, transitioning to low birth and death rates as the demographic transition proceeds. However, insufficient investment in education slows the transition to low fertility rates in low-income countries, keeping population growth higher than it could be. Gross Domestic Product (GDP) growth continues, but income inequality persists or improves only slowly, resulting in societal stratification and limited social cohesion. These factors hinder efforts to reduce vulnerability to societal and environmental changes and constrain significant advances in sustainable development.

Source: O'Neill et al. (2017)

It is important to note that the population and urbanization numbers used in the Current Trends scenario differ slightly from those presented in Chapter 2, which follows the United Nations medium projection (United Nations Department of Economic and Social Affairs 2024). Despite these variations, the basic narrative and overall future trends remain similar.

Although the global population growth rate is projected to decline, the population will continue to increase, from 8 billion people in 2020 to around 9.5 billion people in 2050, primarily driven by sustained high growth in Africa (KC and Lutz 2017). Also, urbanization trends are projected to continue, with most growth occurring in low- and middle-income countries. In 2025, around 55 per cent of the global population will live in urban areas, and that share is projected to rise to 67 per cent in 2050 (Jiang and O'Neill 2017). Finally, GDP per capita is projected to grow at around 2 per cent per year, nearly doubling global GDP, from 14,000 US$ (2010/capita) in 2020 to 28 0000 US$ (2010/capita) in 2050 (Dellink et al. 2017). Income inequality follows a generally flat trajectory (Rao et al. 2019).

10.3 Systems development under current trends

10.3.1 Energy

Although a range of international and national policy developments, such as the Paris Agreement and the responses to the 2022 energy crisis, have initiated a gradual shift toward carbon neutrality, the overall progress is insufficient to change the main drivers of greenhouse gas emissions significantly.

The Current Trends scenario projects a substantial increase in the renewable energy use in the total primary energy supply, driven by advances in technology like solar photovoltaics, wind power, electric vehicles and battery storage (**Figure 10.2**). However, fossil fuels will remain the dominant energy source by 2050. The most significant energy transition progress occurs in power generation, with low-carbon sources, including solar photovoltaics, wind, and nuclear energy, projected to hold a much larger share in 2030 and 2050, while coal use decreases slowly.

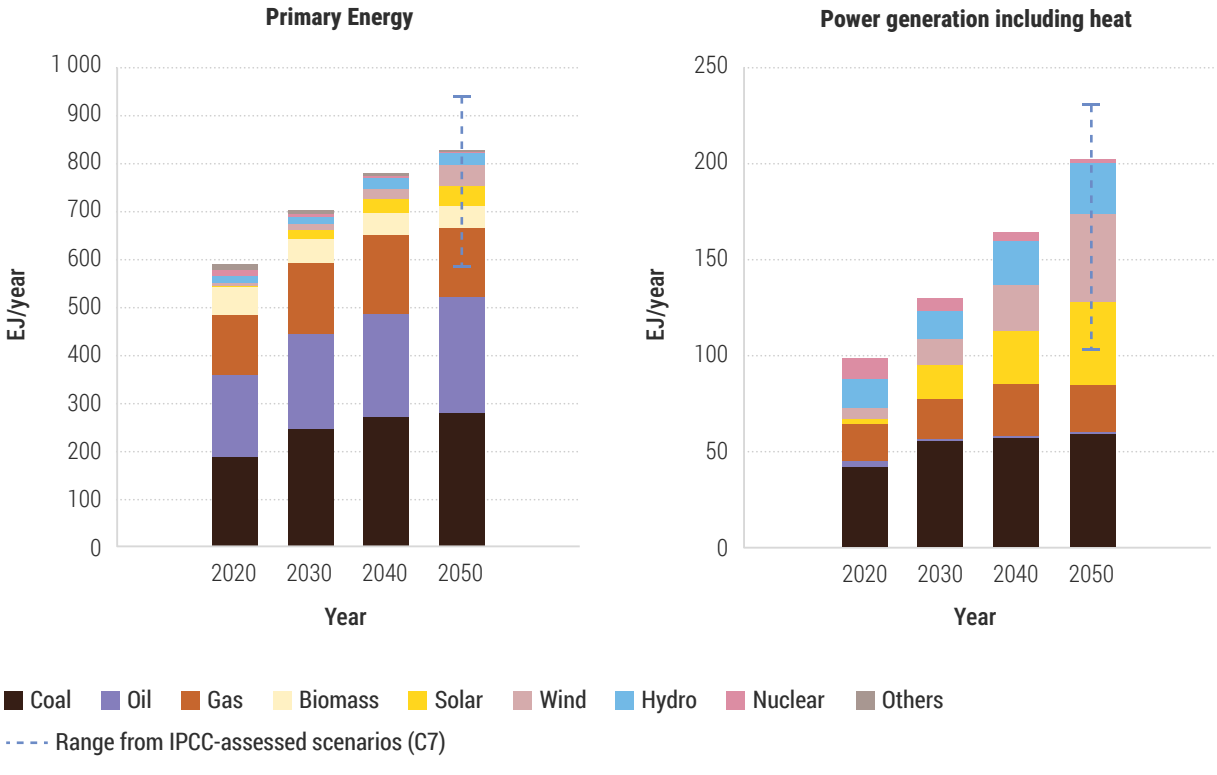
Energy demand is projected to increase sharply, but the growth rate varies by sector and over time (**Figure 10.3**). The transport sector shows the most significant growth due to a higher energy service demand and challenging electrification, while the residential and commercial sectors see a more gradual increase.

Technological progress and a shift from solid fuel use, including traditional biomass, to much cleaner and more efficient forms of energy, including electricity and gases, significantly improved energy efficiency in residential and commercial use. However, an increased energy demand driven by population and income growth offsets these efficiency gains.

The rapid increase in electricity in the energy mix is mainly driven by high economic growth in low-income countries where electrification remains limited. Falling costs of renewable electricity generation further enhance this trend (Intergovernmental Panel on Climate Change [IPCC] 2022a). Overall, the share of electricity in total final energy consumption is projected to increase from 15 per cent in 2020 to 25 per cent in 2050.

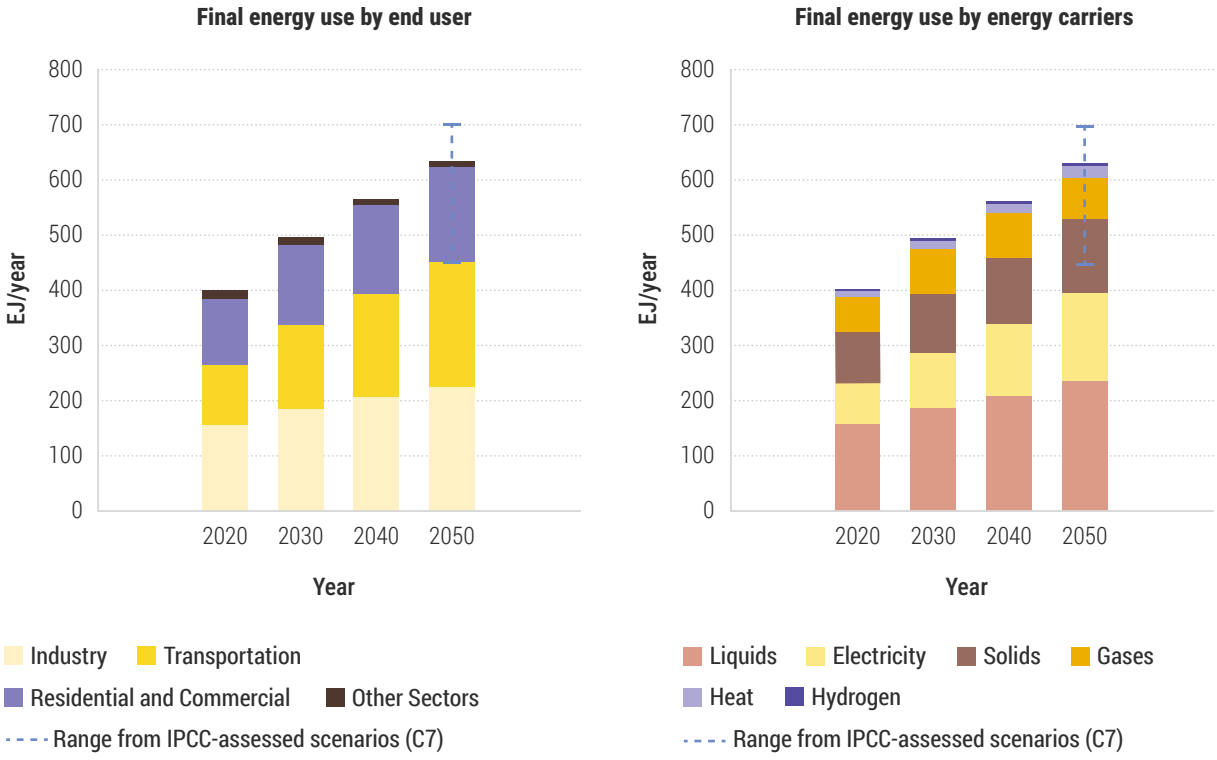
However, despite the growth in electrification, the overall energy mix remains largely dependent on fossil fuel-based energy carriers, such as coal, oil, and

Figure 10.2: Primary energy use and power generation including heat



Source: AIM model and AR6 Scenario Database

Figure 10.3: Final energy use by end user and by technology



Source: AIM model and AR6 Scenario Database

natural gas, due to their relative affordability. As a result, this would imply that greenhouse gas (GHG) emissions remain high (10.4.1).

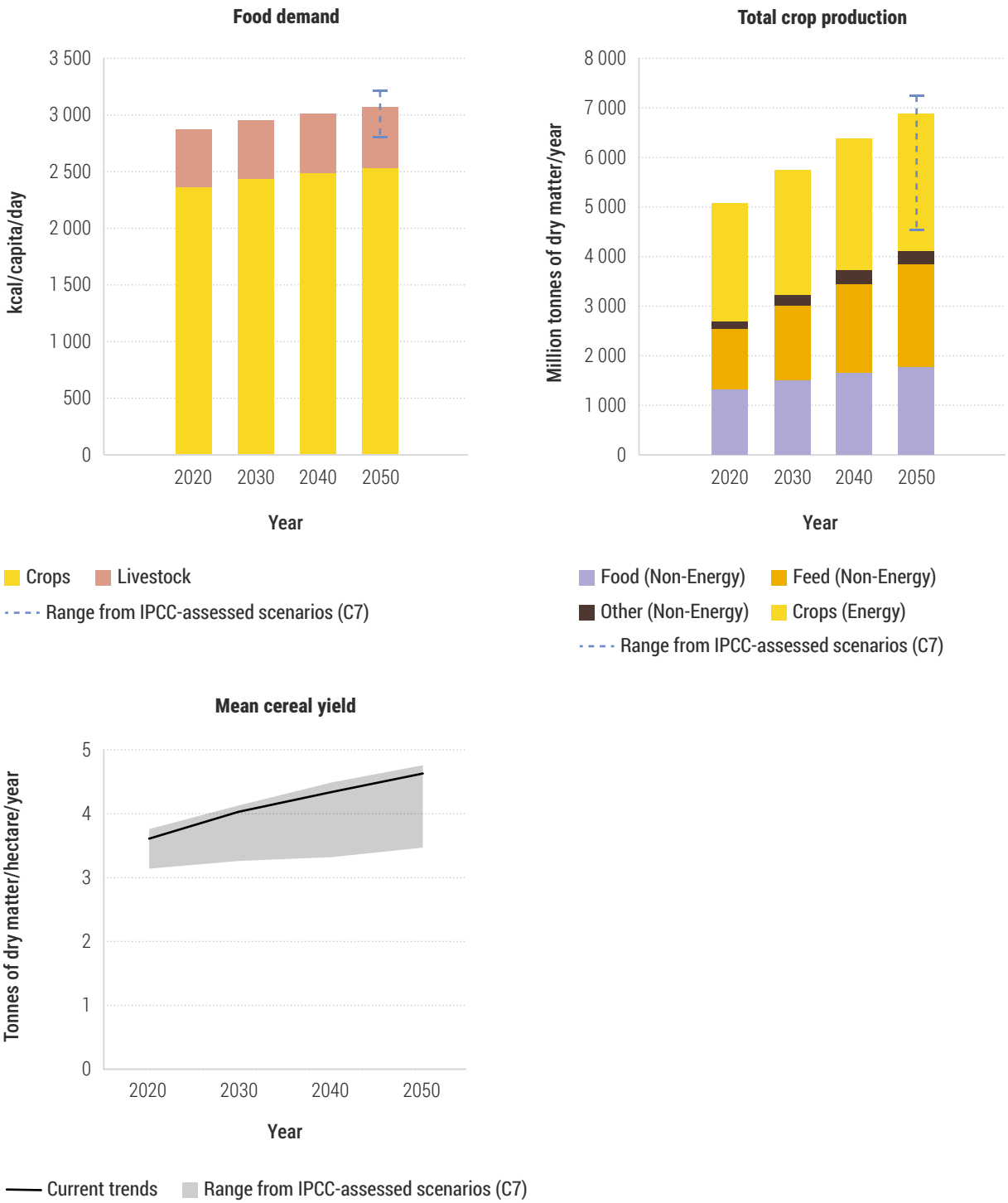
10.3.2 Food

Under the Current Trends scenario, the global food demand is projected to increase significantly by 2050 (**Figure 10.4**), driven both by an increase in per capita food demand and population growth. As incomes rise worldwide, the average daily food availability is projected to increase from almost 2900 kcal per capita per day in 2020 to a small 3100 kcal per capita per day in 2050. Low-income countries will see faster increases than the global average and the high-income countries, where food consumption rates are expected to remain relatively stable. For low-income populations, even modest income gains lead to sharp growth in food demand, while high-income groups show only slight increases (Muhammad et al. 2011). Moreover, low-income regions are more likely to shift from plant-based food to more animal-based food.

Global crop production is projected to increase by 40 per cent between 2020 and 2050 (**Figure 10.4**). During the same period, the total population is projected to increase by 20 per cent. This growth can be explained by the increase in per capita food consumption and the shift to animal-based diets, which raises the proportion of crops used as animal feed. While demand for biofuels is projected to increase slightly, it is not expected to significantly affect the production of major food crops or global crop production area. Alongside increased production and consumption, the food waste from production, processing, retail, and consumption is expected to rise (United Nations Environment Programme [UNEP] 2024a).

During the same period, the average global crop yield is projected to increase by 0.5 per cent per year (Figure 10.4), with higher gains in low-income regions (0.7 per cent/year) than in high-income regions (0.3 per cent/year), reflecting higher potential to improve agricultural technology and irrigation. The increase in yields is however much lower than the growth in agricultural production, indicating an expansion of agricultural land (10.4.3). However, due to model limitations, these projections only partially account for the effects of the global environmental crises on crop yields (**Box 10.2**).

Figure 10.4: Food demand, total crop production, and mean cereal yield



Source: AIM model and AR6 Scenario Database

10.3.3 Material resources

Over the past five decades, the global extraction of material resources – biomass, fossil fuels, metal ores and non-metallic minerals – has increased significantly, rising from 31.1 billion tons in 1970 to 96.5 billion tons in 2020 (UNEP 2024b). However, only 9 per cent of these materials were re-used in manufacturing and construction activities, resulting in significant economic loss and environmental impact.

Under the Current Trends scenario, the global extraction of material resources is projected to peak at 165 billion tons by 2050 (**Figure 10.5**), consistent with earlier

Box 10.2: Impacts of the global environmental crises on crop yields.

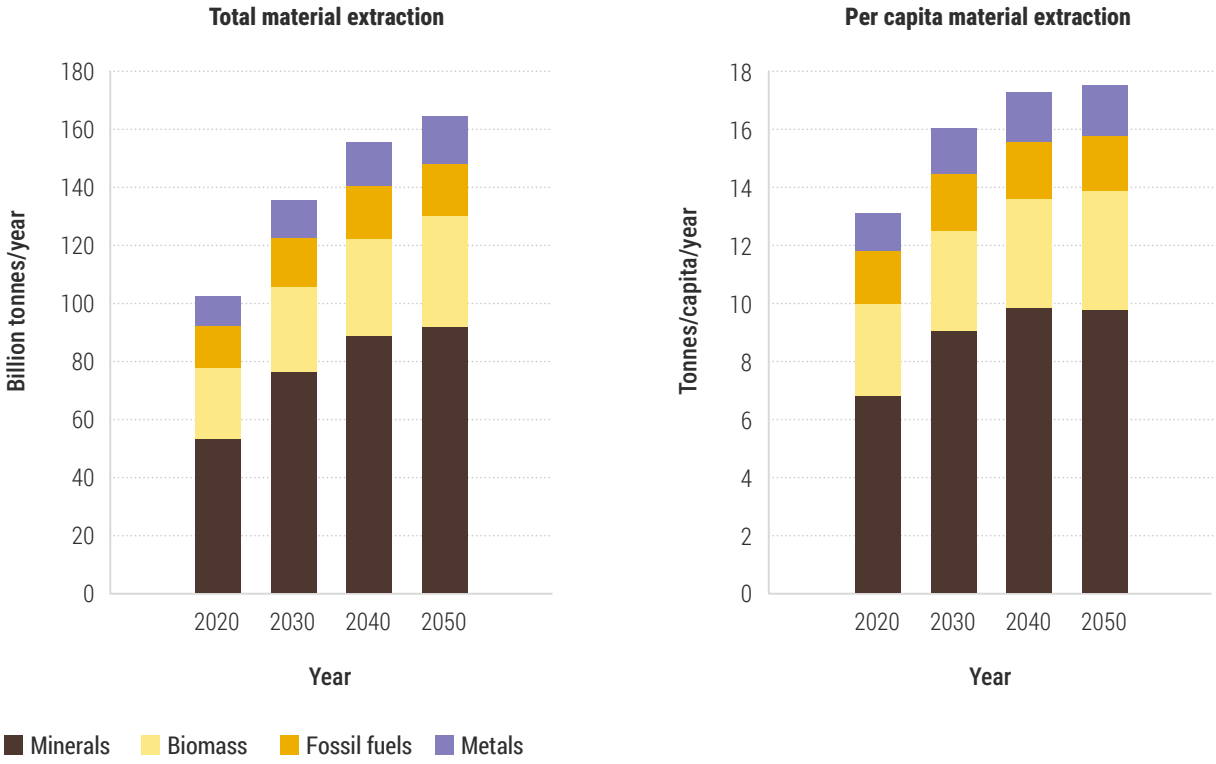
The impacts of changing temperature and precipitation patterns, along with higher levels of carbon dioxide (CO_2) fertilization on crop yields, are well documented, although high uncertainty remains. On average, temperate and boreal regions are projected to experience substantial increases in potential crop yields, while tropical regions may experience declines (Jägermeyr et al. 2021). Uncertainty mainly arises from potentially negative impacts of climate change, such as droughts and flooding, indicating the need for continued model development.

Different forms of pollution can affect crop yield. Air pollution leads to higher ozone levels, negatively affecting plant growth. Regions with high air pollution levels may see crop yield losses of up to 20 per cent (Chuwah et al. 2015). Soil pollution, including contamination with heavy metals or persistent organic compounds, directly harms crop yields (van der Esch et al. 2017). Additionally, inefficient irrigation systems or poor-quality water may lead to salinization or sodification, further diminishing productivity.

Land degradation processes significantly affect crop yields (van der Esch et al. 2022). For example, soil carbon loss due to ploughing and insufficient crop residue input leads to lower soil quality and water retention. Soil erosion from water or wind removes the fertile topsoil, while unsustainable soil management leads to crusting or compaction of soils.

Ecosystem services, such as pollination and pest control that depends on biodiversity, enable agricultural production (Dainese et al. 2019). However, the impact of biodiversity loss on crop yields varies widely per crop type and remains uncertain (Albrecht et al. 2020). Integrating impacts of biodiversity changes in crop and food system projection models remains a major challenge (Seppelt et al. 2020).

Figure 10.5: Total and per capita global material extraction



Source: GTEM Model

studies (Organisation for Economic Co-operation and Development [OECD] 2019; UNEP 2024b). Asia and the Pacific will remain the largest consumers of global materials, peaking at 88 billion tons by 2050 and then gradually declining. The fastest growth is projected in Africa, with demand rising from 7.4 billion tons in 2020 to 19 billion tons in 2050. As a result, if current trends continue, global material per capita will increase from 13 tons per capita in 2020 and peak at 17 tons per capita by 2050.

The share of non-metallic minerals extraction is projected to grow from 52 per cent in 2020 to 56 per cent in 2050, mainly driven by the expansive growth of production in building, infrastructure and construction in low- and middle-income economies in Africa, and Asia and the Pacific that are expected to have rapid economic growth (Bleischwitz et al. 2018). Biomass extraction is also projected to increase, driven by rising food demand and dietary shifts to animal-based food in low-income countries, leading to a greater demand of fast grazed biomass and fodder crops (10.3.2). Due to the energy transition, the global fossil fuel use is projected to increase at a slower rate, compared to other categories of material resources (10.3.1).

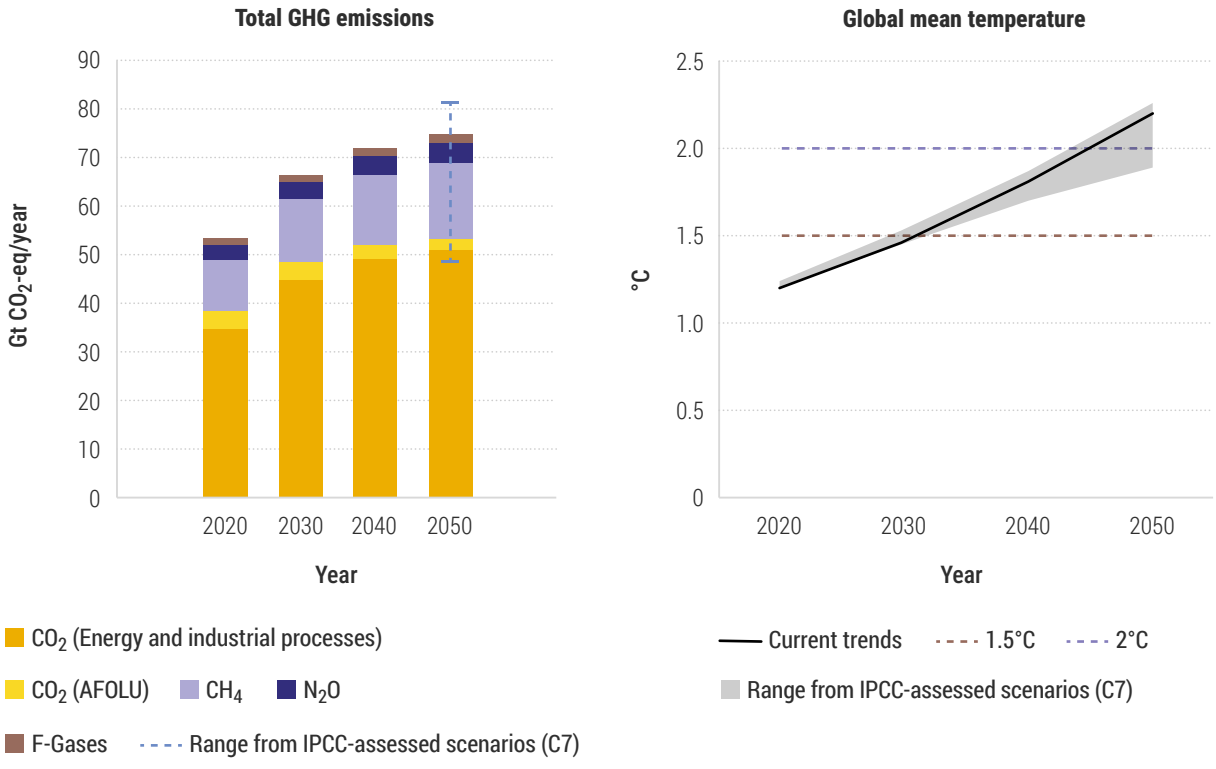
10.4 Environmental implications under current trends

10.4.1 Climate change

The primary drivers of anthropogenic climate change are GHG emissions, including CO_2, methane (CH_4), nitrous oxide (N_2O) and fluorinated gases linked to the energy, food and materials/waste systems. Under the Current Trends scenario, GHG emissions are projected to increase and peak around mid-century (**Figure 10.6**), followed by a slight decline towards the end of the century. The energy sector remains the primary source of CO_2 emissions, due to continued use of fossil fuels (Clarke et al. 2022) (10.3.1). Land-use change is the second largest contributor, mainly driven by crop and pastureland expansion, linked to growing food demand (10.3.1, 10.4.3).

CH_4 and nitrous oxide emissions are projected to continue rising. The major drivers are increased food production through rice crops, livestock, and fertilizer use; waste generation; and other human activities. As a result of increasing GHG emissions, end-of-century warming could reach as high as 3.9°C, with a 50 per cent likelihood

Figure 10.6: Total GHG emissions and global mean temperature increase



Source: AIM model and AR6 Scenario Database

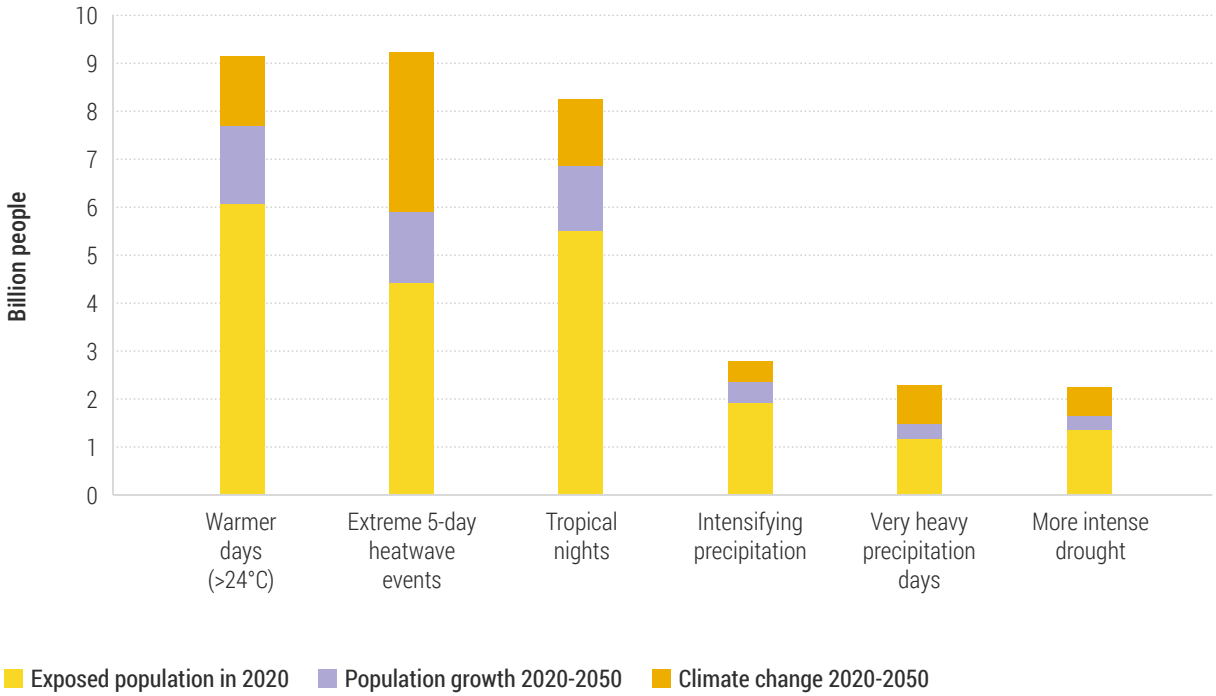
(Figure 10.6). This projected warming of 3.9°C falls at the high end of the mitigation scenario category C7 presented in the sixth Assessment Report of the International Panel of Climate Change (IPCC), (IPCC 2022).

The Current Trends scenario does not explicitly include policies and policy objectives currently being implemented. UNEP (2024c) concludes that if current mitigation policies continue without integrating future Nationally Determined Contributions (NDCs), the global temperatures would increase this century to 2.9°C (range: 1.8-3.5) above preindustrial levels, with a 50 per cent likelihood. Including NDCs would only reduce the increase to 2.4°C (range 1.8-3.3) for conditional pledges and 2.6°C (range 1.8-3.4) for unconditional pledges. This underscores the importance of current climate policies, while highlighting their insufficiency in meeting the Paris Agreement goal of holding global average temperature increase to well below 2°C, with efforts to limit it to 1.5°C. During the early 2030s, the global mean temperature will likely exceed 1.5°C (IPCC 2023a).

Temperature increase will significantly affect climate system components, some of which will respond over decades, while others will take centuries (IPCC 2021). Under the Current Trends scenario, the global population exposed to the impacts of climate change is projected to increase significantly between 2020 and 2050 (**Figure 10.7**). While the population growth contributes, the primary driver of the increased exposure is climate change itself. Exposure for temperature-based impacts, such as heat stress and increased cooling needs (Tollefson 2025), will be much higher than for hydrological impacts. The number of people exposed to consecutive tropical nights, with minimum air temperatures above 20 °C, will rise, potentially affecting sleep patterns and health. Meanwhile, increased exposure to heavy precipitation poses risks for agriculture and increased flooding, while increased droughts could lead to critical water scarcity (10.4.6).

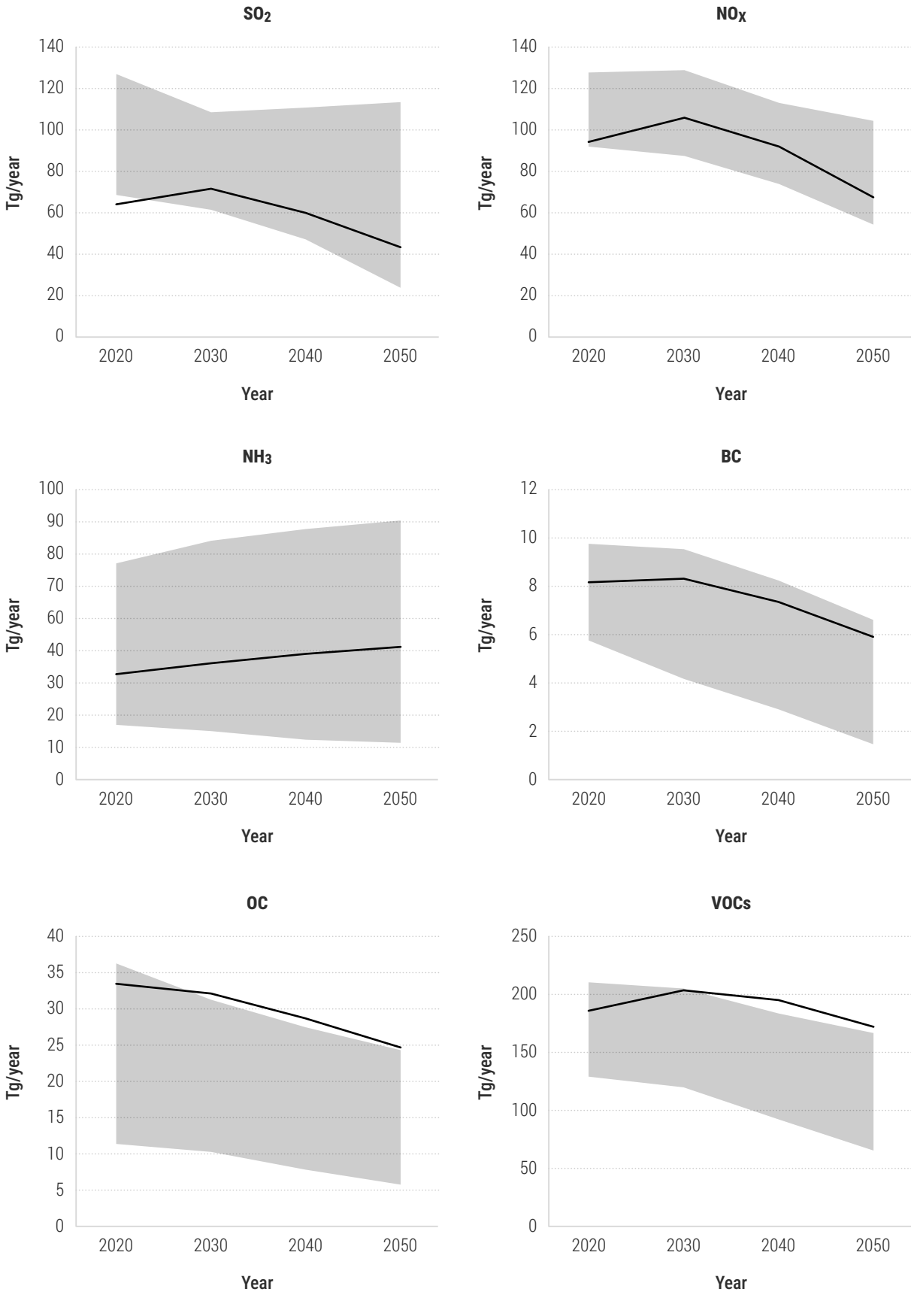
Climate change adaptation strategies, such as heat action plans, enhanced water management, strengthening agricultural resilience, and safeguarding vulnerable ecosystems, will play a crucial, yet limited role in reducing the impacts of these temperature increases. Soft and hard adaptation limits are already being reached in both human and natural systems, these challenges will intensify with further warming. Achieving climate-resilient development becomes increasingly complex, especially if 1.5°C warming is exceeded in the near term (IPCC 2022a).

Figure 10.7: People exposed to temperature- and precipitation-related climate impacts in 2050



Source: RIME Model

Figure 10.8: Global emission trends of air pollutants



Source: AIM model and AR6 Scenario Database

10.4.2 Air pollution

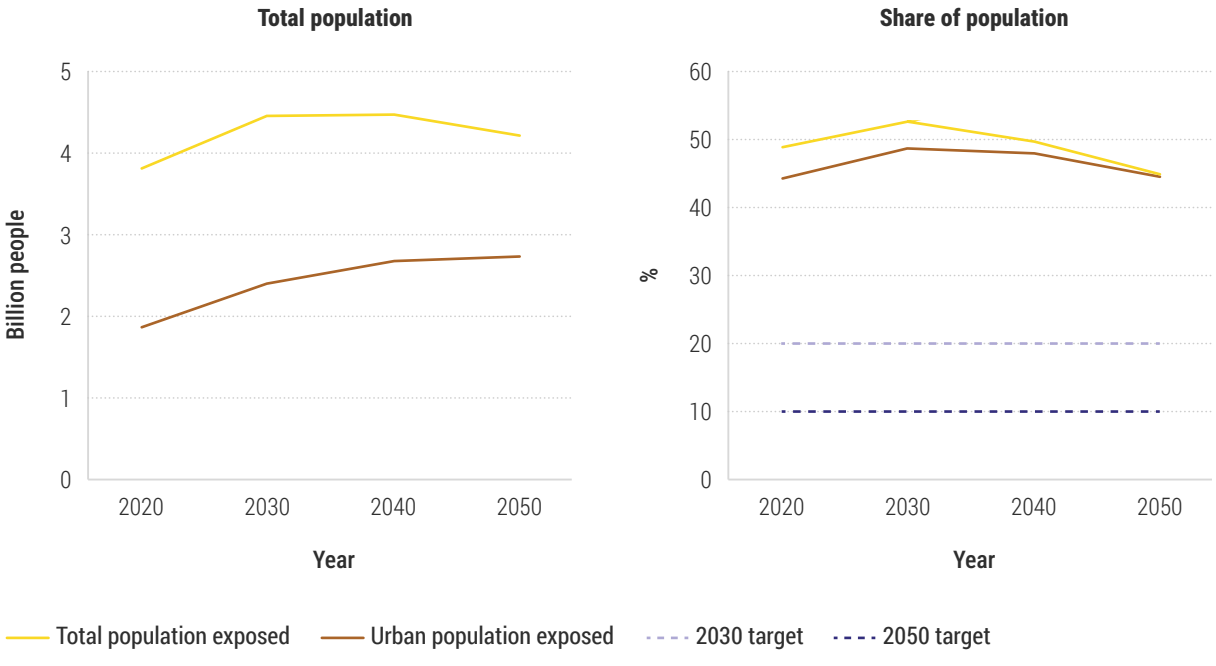
Fine particulate matter ($PM_{2.5}$) and ozone are the most harmful air pollutants for human health and ecosystems (Health Effects Institute 2024; 3.1). Both are mostly secondary pollutants formed in the atmosphere due to physical and chemical processes (Vallero 2014). $PM_{2.5}$ precursors include sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), black carbon (CB), and organic carbon (OC). Ozone formation includes NO_x, non-methane volatile organic compounds (VOCs), carbon monoxide (CO), and CH_4.

Under the Current Trends scenario, most air pollution emissions are projected to decline between 2030 and 2050 (**Figure 10.8**). The reduction in sulphur dioxide emissions is mainly associated with reduced use of solid fuels in power plants and industrial facilities. At the same time, the drop in NO_X derives from abatement in the transportation sector and reduced combustion in power generation and other industries. The drop in OC and primary $PM_{2.5}$ emissions, including black carbon, would mainly result from emissions reductions in the building sector, while non-methane volatile organic compounds would primarily be reduced by industrial and residential combustion improvements. CH_4 and NH_3 emissions are projected to increase throughout the observed period. This upward trend is mainly linked to the limited mitigation in agricultural production, particularly in livestock management and fertilizer application.

Driven by these emissions trends, global $PM_{2.5}$ and ozone concentration are projected to decrease slightly by 2050. $PM_{2.5}$ global annual average population-weighted concentration is projected to drop from 28 µg/m^3 in 2020 to 27 µg/m^3 in 2050. Ozone annual average global population-weighted concentration is projected to decrease from 42 ppb in 2020 to 41 ppb in 2050. These pollution levels vary by region. $PM_{2.5}$ concentrations are thehighest in Africa, Asia and the Pacific, while ozone concentrations are most pronounced in Asia and the Pacific.

Despite the slight decrease in $PM_{2.5}$ levels, the number of people exposed to concentrations above 25 µg/m^3 is projected to increase, from 3.7 billion in 2020 to 4.2 billion in 2050 (Figure 10.9), due to population growth, particularly in urban areas in low-income countries. So, while the proportion of the global population exposed to $PM_{2.5}$ levels above 25 µg/m^3 is projected to decrease slightly from 50 per cent in 2020 to 45 per cent in 2050, the urban share of this exposed population remains relatively stable at 45 per cent (**Figure 10.9**). This trend indicates that Sustainable Development Goal (SDG) targets 3.9 and 11.6, which aim to reduce death and illness from air pollution and improve urban air quality, are unlikely to not be met.

Figure 10.9: Total population and share of population exposed to $PM_{2.5}$ levels above 25 µg/m^3



Source: JRC-FASST model

The Current Trends scenario shows only limited improvement in air quality, primarily because it does not account for the announced air pollution abatement measures and the Paris Agreement NDCs. According to the International Institute for Applied Systems Analysis (2019), including these measures could further reduce the global average exposure by 2050: $PM_{2.5}$ by 19 per cent and ozone by 13 per cent. However, these lower levels still fall short of meeting the SDG targets. The projected decrease in air pollution levels mainly stems from significant additional abatement in sulphur dioxide (50 per cent) and NO_X (30 per cent) emissions, driven by a reduction in fossil fuel use in the energy, industrial and transport sectors. Other contributing factors are modest reductions in black carbon and primary $PM_{2.5}$ emissions from the building sector, while there are little to no reductions in NH_3 and CH_4 emissions due to the lack of robust policies targeting the agriculture sector.

10.4.3 Land degradation

The United Nations Convention to Combat Desertification defines land degradation neutrality as maintaining land's capacity to provide ecosystem services, such as food production, carbon storage and biodiversity, measured by trends in land cover, carbon stocks and land productivity (Orr et al. 2017). The Current Trends scenario projects continued conversion of natural land and soil carbon losses in agricultural lands, implying that land degradation neutrality will not be achieved (**Box 10.3**).

Agricultural land is projected to increase slightly towards 2050, as yield improvements fail to meet the growing food demand (10.3.2). Although to a much lesser extent, increased bioenergy demand, particularly in the transport sector, also contributes to this growth. As a result, total cropland is projected to expand by almost 150 Mha between 2020 and 2050 (**Figure 10.10**). During the same period, both pastureland and natural land are projected to decrease by almost 100 Mha each. This projected decrease in natural land is at the lower end of similar scenario projections (Popp et al. 2017; PBL 2022).

Land-use change and shifts in climate dynamics lead to significant changes in carbon stocks, both above and below ground. Aboveground carbon losses are most pronounced in Sub-Saharan Africa and Latin America, where deforestation and conversion of other natural land, as well as forest degradation related to wood harvesting, reduce carbon storage. Conversely, in the boreal regions, a substantial increase in carbon stocks is projected due to climate change leading to the expansion of forests. Existing forests may also show modest increases in carbon stocks due to CO_2 fertilization. The positive and negative effects

Box 10.3: Land restoration pledges under different conventions.

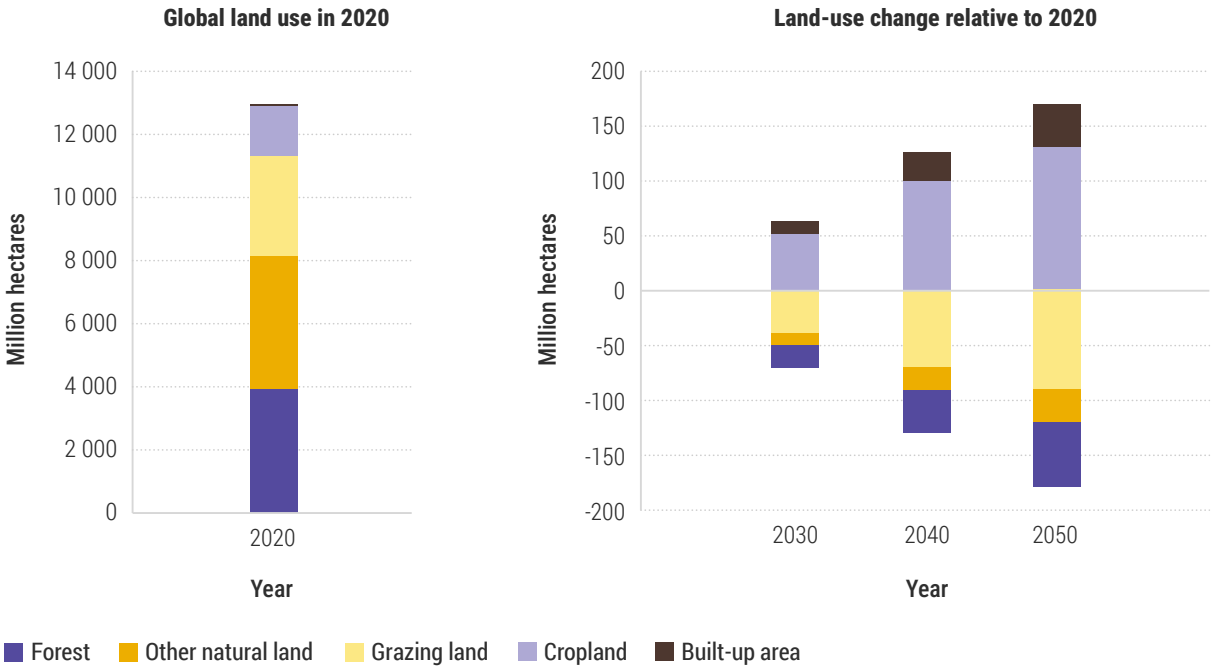
As of 2020, at least 115 countries have committed to restoring 1 billion hectares of land (Sewell, van der Esch and Löwenhardt 2020). These commitments include:

- 450 million hectares through the land degradation neutrality national voluntary target-setting programme,
- 250 million hectares committed through the NDCs under the Paris Agreement
- 90 million hectares pledged in the National Biodiversity Strategies and Action Plans (NBSAPs) under the Convention on Biological Diversity (CBD).
- 210 million hectares under the Bonn Challenge and associated regional initiatives

Nearly half of these restoration commitments are concentrated in sub-Saharan Africa. South Asia, China, and Central and South America also have significant commitments relative to their land area.

The commitments are relatively equally divided between ecological restoration and protection, and improved land management and the rehabilitation of degraded land. Overall, the current commitments cover roughly one-fifth of global cropland, one-tenth of all forest area, and a small share of pastures.

Figure 10.10: Global land use and land-use changes relative to 2020



Source: AIM Model

counterbalance on the global scale, leading to a modest net reduction in total vegetation carbon stocks of 14 GtC between 2020 and 2050.

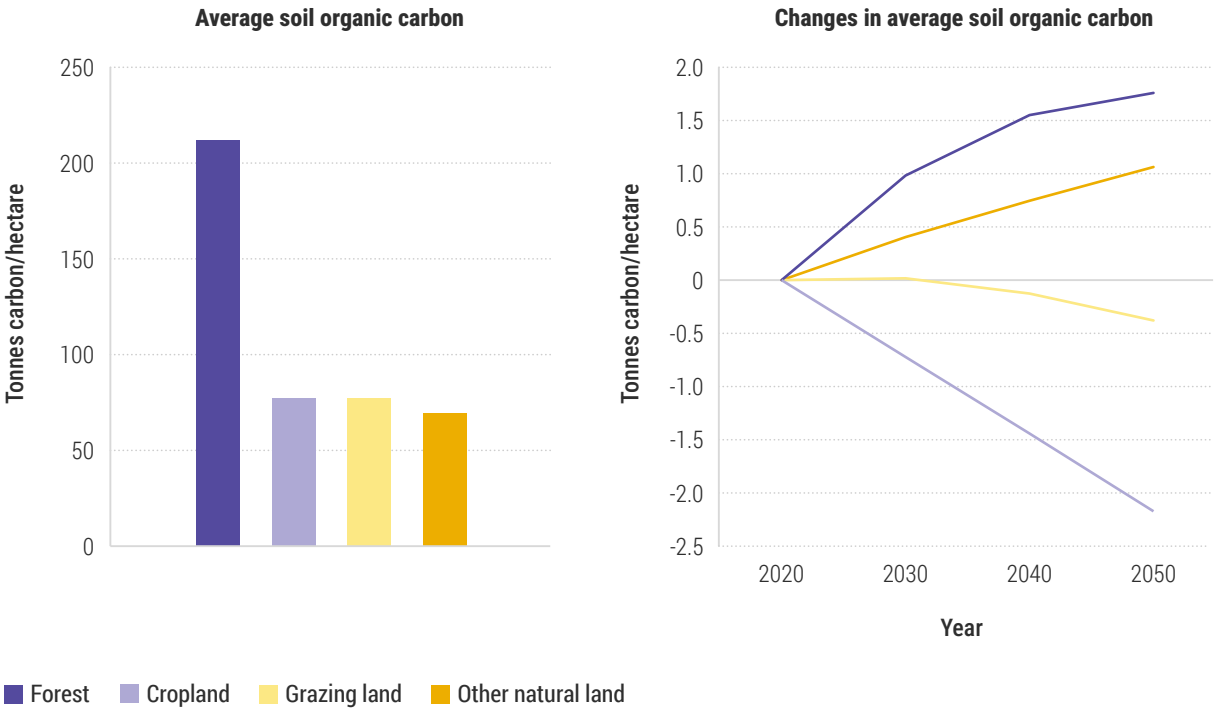
Changes in soil organic carbon (OC) are projected to show mixed patterns, with decreases in soil OC in agricultural lands and increases in natural lands (**Figure 10.11**). In cropland, soil OC continues to decline, with intensive management practices leading to an average loss of 2.2 tC/ha from 2020 to 2050. Additionally, the expansion of agriculture into natural lands reduces soil OC. In natural lands, higher temperatures accelerate decomposition rates, reducing stocks. However, faster vegetation growth rates increase litter input, increasing carbon stocks. Overall, the Current Trends scenario projects a slight increase of 5 GtC in soil OC between 2020 and 2050. It should be noted that these model-based estimates carry considerable uncertainty, and estimates from other studies vary widely (Krause et al. 2017).

10.4.4 Biodiversity loss

Biodiversity loss is driven by a range of factors, including land-use change, climate change, pollution, natural resource use and exploitation, and invasive species (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services 2019; Jaureguiberry et al. 2022). Under the Current Trends scenario, Mean Species Abundance (MSA) (Schipper et al. 2020), a measure of biodiversity intactness, is projected to decrease by 3.5 per cent points, from 59 per cent in 2020 to 56 per cent in 2050 (**Figure 10.12**), compounding similar historic rates of loss since 1900 (Pereira et al. 2024). This decline is equivalent to converting 4.6 million km^2 of pristine habitat, roughly the size of the European Union, to a habitat where all the original species are locally extinct. While the relationship between MSA and species extinction is not linear, the decline in 3.5 per cent points could result in the extinction of approximately 16,000 to 160,000 species (Pereira et al. 2024). As a result, global biodiversity targets, including the halt of biodiversity loss by 2030, are unlikely to be met. **Box 10.4** describes implications of biodiversity loss on Indigenous Knowledge.

Land-use change (10.4.3) remains the most significant driver of biodiversity loss, accounting for 23 per cent of MSA loss in 2020, and increasing to 25 per cent in 2050. The impact of climate change is projected to become increasingly significant, contributing 7 per cent of MSA loss in 2020, and rising to 10 per cent in 2050, driven mainly by global temperature increase (10.4.1). The impacts of nitrogen deposition (10.4.5) remains relatively stable towards 2050, contributing around 4 per cent of MSA loss. Other factors of biodiversity loss, not explicitly accounted for in this projection, include the increase of invasive exotic species and

Figure 10.11: Average soil organic carbon in 2020 and changes in average soil organic carbon



Source: IMAGE-LPJmL Model

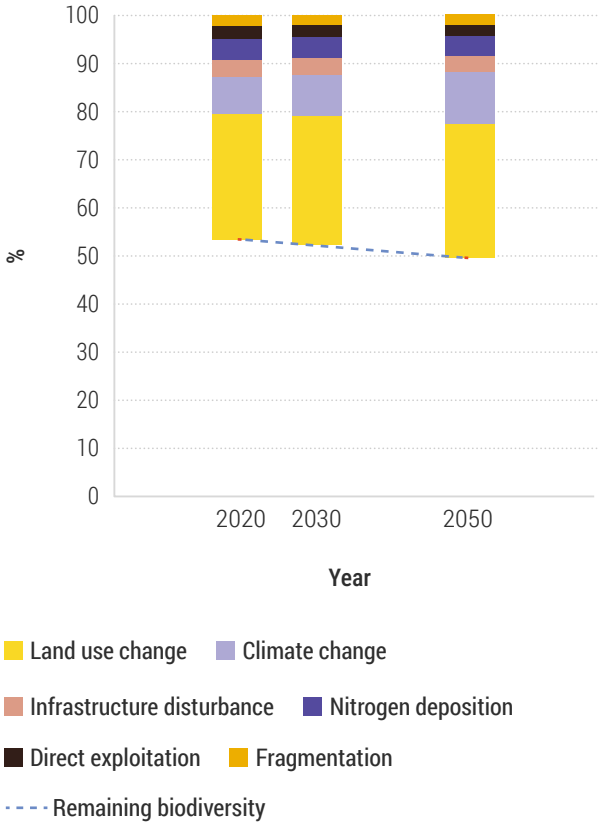
ongoing pollution by many different substances, such as pesticides, plastics, medicines and many others (Balvanera et al. 2019) (4.3; 6.5).

The projected trend aligns with earlier studies on MSA projections (Secretariat of the Convention on Biological Diversity [CBD] 2020; Van der Esch et al. 2022; Kok et al. 2023) and is consistent with the broader literature. Model projections indicate negative trends across almost all dimensions of biodiversity, from local population declines and reduced diversity to global species extinction rates (Pereira et al. 2024). The extent of suitable habitats for terrestrial vertebrates, including mammals, birds, amphibians and reptiles, may decrease by about 50 per cent between 2010 and 2100. Estimated global extinctions – species committed to extinction – could range between 2 per cent and 8 per cent by 2100.

10.4.5 Nutrients pollution

Excess nitrogen (N) and phosphorus (P) are causing eutrophication in freshwater, estuaries and coastal waters (Seitzinger et al. 2010; Bouwman et al. 2024). Eutrophication occurs when nutrient accumulation stimulates overgrowth of organisms that may deplete the oxygen in the water, harming aquatic life. Excess nutrients from agriculture, aquaculture,

Figure 10.12: Loss of Mean Species Abundance (MSA)



Source: GLOBIO Model

Box 10.4: Implications of biodiversity loss on Indigenous Knowledge

Evidence highlights the crucial role of Indigenous Peoples and Indigenous Knowledge and philosophies for biodiversity preservation and enhancement (World Health Organization and the Secretariat of the CBD 2015; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services 2019). Indigenous methods of biodiversity management are deeply rooted in local contexts, emphasizing reciprocity, responsibility, and care toward the soil, animals, plants, and other entities on their lands (Ogar, Pecl, and Mustonen 2020; Reyes et al. 2024). Indigenous Knowledge systems are built on empirical observations of local weather patterns, seasonal cycles, and the behaviours of flora and fauna, passed down through generations (Savo et al. 2016; Nkuba et al. 2020; Fernández-Llamazares et al. 2021).

The most biodiverse areas in the world are often inhabited by Indigenous Peoples (Fa et al. 2020, O'Bryan 2021). Biodiversity is integral to various Indigenous cultural, food, medicinal and economic systems (IK & LK Dialogues 2025). In Canada, Indigenous Peoples maintain reciprocal relationships with the entire landscape, encompassing water, air, flora, and wildlife (Galway, Esquega, and Jones-Casey 2022). In the Amazon, Indigenous Peoples sustainably use, conserve, and regenerate forest and farm resources (Arotoma-Rojas et al. 2022; Pesantes et al. 2024). Traditional medicinal knowledge, which is valuable for both Indigenous and public health, plays a significant role, with 40 per cent of pharmaceutical products derived from traditional knowledge (World Health Organization 2023; Chaachouay and Zidane 2024).

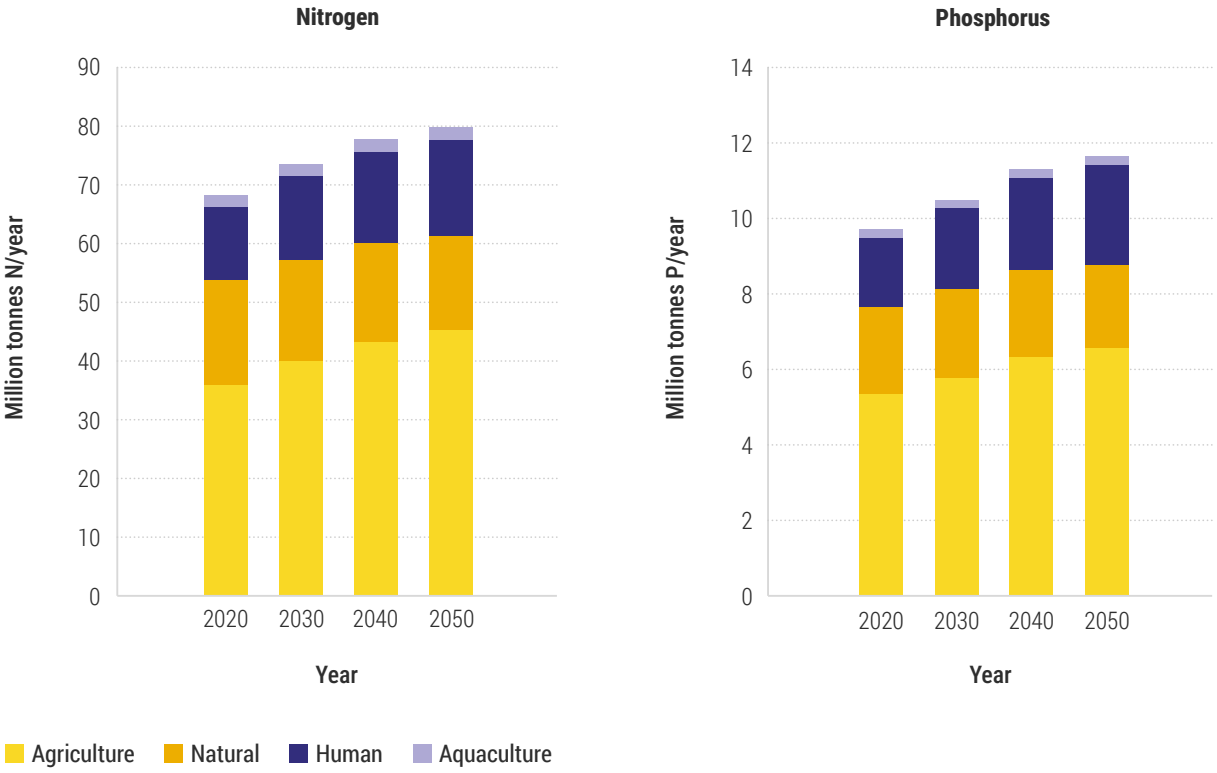
Current trends in environmental change threaten the transmission of Indigenous Knowledge. This, in turn undermines the sustainable management of wild and domesticated biodiversity and jeopardizes traditional and allopathic medicines, posing a risk to human health (Mistry, Bilbao and Berardi 2016; Hoffman et al. 2021). Urbanization, pollution, and climate change are key drivers of biodiversity loss in lands inhabited by Indigenous Peoples (Savo et al. 2016; Brubacher et al. 2024). Furthermore, the historical and ongoing impacts of colonization and social exclusion compound with environmental changes, leading to forced displacement and the loss of ancestral lands and languages (Fa et al. 2020; Zavaleta-Cortijo et al. 2020; Redvers et al. 2023). These challenges not only affect the well-being and health of Indigenous Peoples (IK & LK Dialogues 2025), but also have negative repercussions for broader societal efforts to adapt to climate change and foster biodiversity resilience in the future.

and human and industrial waste are key contributors to groundwater and surface water pollution. While industrial wastewater was the leading cause of nutrient pollution in the early 20th century, agriculture has now become the predominant contributor.

In the Current Trends scenario total delivery of N and P to surface water is projected to increase by 2050, primarily driven by agricultural activities and human waste (**Figure 10.13**). The results for N are in line with the International Nitrogen Assessment (forthcoming). Nutrients pollution from agriculture stem from fertilizer use, manure application to cropland and grassland, expansion of soybean cultivation, and nitrogen deposition due to increasing NH_3 and NO_x emissions from livestock production, and NO_x emissions from fossil fuel combustion. The rise of nutrient pollution from human waste is driven by population growth and increased sanitation levels, resulting in higher waste loads, while increased wastewater treatment partly offsets this increase.

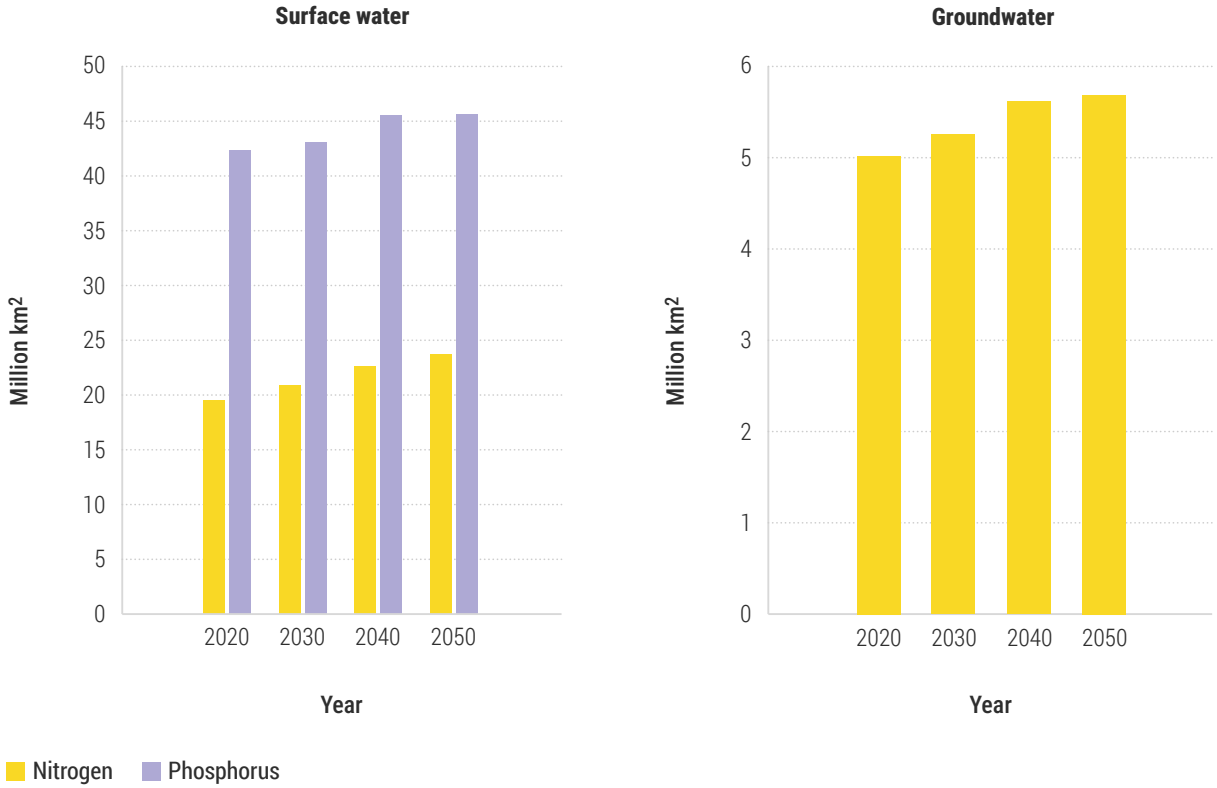
As a result of increasing nutrient delivery, water quality is projected to decline, albeit with substantial geographic differences. The total area of groundwater and surface water that exceeds water quality thresholds is projected to grow (**Figure 10.14**). While each country and water body has their thresholds and standards, here, we use the global water quality standards proposed by Bouwman et al. (2024). For N, in 2020, almost 19.5 Mkm^2 exceeded the environmental threshold of 2.5 mg N/l in surface water. This area is projected to increase to 23.7 Million Km^2 by 2050, accounting for 18 per cent of the total land area globally. For P, the area exceeding the ecosystem threshold of 0.1 mg P/l in surface water is projected to increase from 42 Mkm^2 in 2020 to 46 Mkm^2 by 2050. Finally, for groundwater, the area exceeding the World Health Organization drinking water standard threshold of 11.3 mg N/l is estimated to rise from 5.0 Mkm^2 in 2020 to 5.7 Mkm^2 by 2050.

Figure 10.13: Delivery of nitrogen and phosphorus to surface water



Source: IMAGE-GNM Model

Figure 10.14: Area with nitrogen and phosphorus concentrations above threshold levels in surface water and groundwater



Source: IMAGE-GNM Model

10.4.6 Water scarcity

Increasing water withdrawal, combined with the impacts of climate change on water availability, will intensify pressure on water resources, potentially leading to water scarcity in certain regions. Water scarcity can affect various sectors, including energy generation, domestic use and agriculture. Reduced water availability can decrease hydropower generation and limit cooling capacity in conventional energy plants. Furthermore, restrictions on domestic water use may be necessary, while water scarcity in agriculture can lead to decreased crop yields.

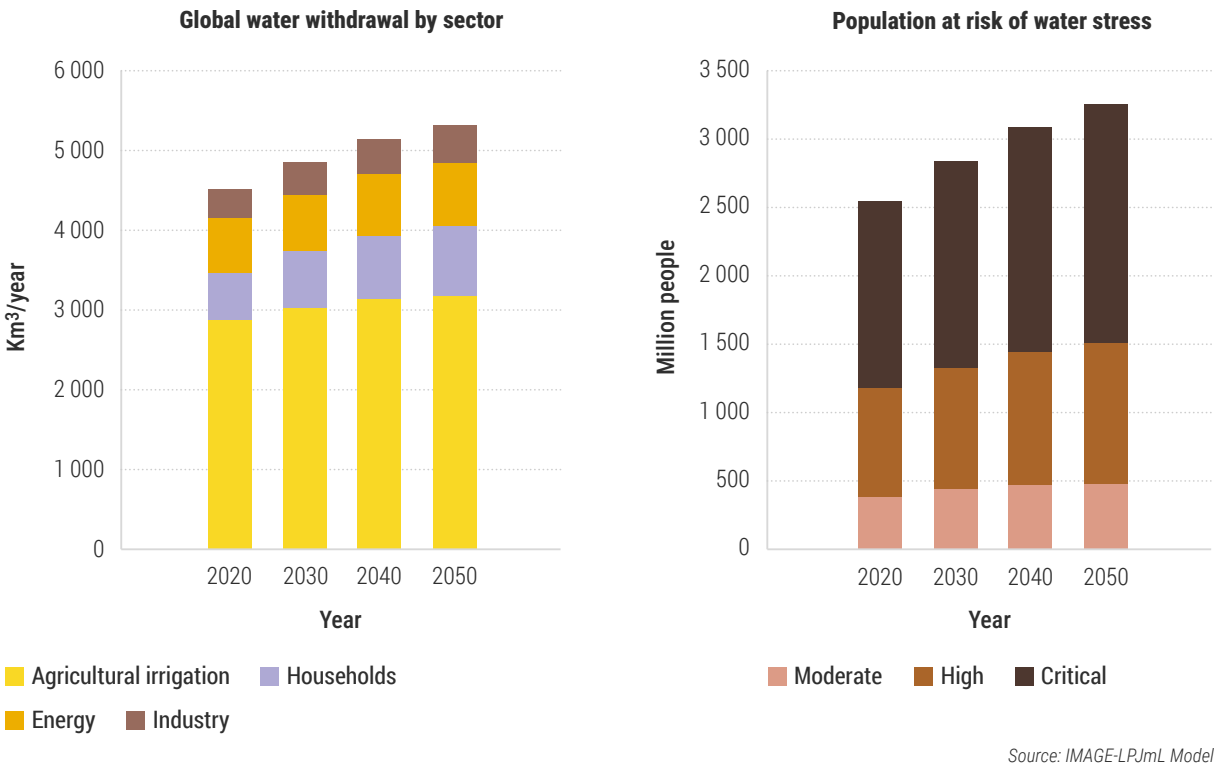
Under the Current Trends scenario, global annual water withdrawal is projected to rise by around 18 per cent (800 km^3) between the 2020 and 2050, with an increase of 11 per cent (310 km^3) for irrigation water, despite improvements in irrigation efficiency, and 30 per cent (490 km^3) for households, industry and energy (**Figure 10.15**). Key drivers are population growth, economic development, cropland expansion, and a growing demand for industrial and cooling water (Wada et al. 2016). A significant increase in total water use is expected from both municipal and industrial sources (Bijl et al. 2016).

Due to changes in precipitation and snowmelt patterns, combined with limited surface water availability, withdrawals from groundwater are projected to increase further. Groundwater is generally not a renewable source, further affecting future water scarcity. Significant withdrawals are expected in South Asia, Northeastern China, the western United States, Mexico, and the Nile region.

A location is considered at risk of water stress if more than 10 per cent of its water withdrawals come from non-renewable sources, such as deep aquifers or desalination, due to the lack of surface water or renewable groundwater. Between 2020 and 2050, the overall area at risk of water stress is projected to increase by 1 per cent, while the number of people living in water-stressed areas is projected to increase by 28 per cent, equivalent to 710 million people (**Figure 10.15**). As, during the same period, the global population is projected to increase by 17 per cent, this trend reflects high population growth in already water-stressed areas.

Agriculture is the major water consumer. In irrigated farming, surface water scarcity will drive the use of non-renewable groundwater, as long as it remains

Figure 10.15: Global water withdrawal and population at risk of water stress



Source: IMAGE-LPJmL Model

Credit: JuiceFlair/Envato

accessible. However, when groundwater levels drop too low, absolute water shortages become inevitable (de Graaf et al. 2019), resulting in a decline in crop production. For rainfed crops, reduced precipitation or "green water scarcity" immediately affects crop yields or can even lead to crop failure. Since rainfed agriculture accounts for approximately 80 per cent of cropland and 60 per cent of total crop production, green water management is crucial for ensuring food security (Liu et al. 2022).

10.5 Tipping points and non-linearities

The global environmental crises pose a significant risk of triggering major shifts in the Earth's system. Tipping points, critical thresholds beyond which a system reorganizes, often abruptly and/or irreversibly (Solé and Levin 2022), are of particular concern (Lenton 2013).

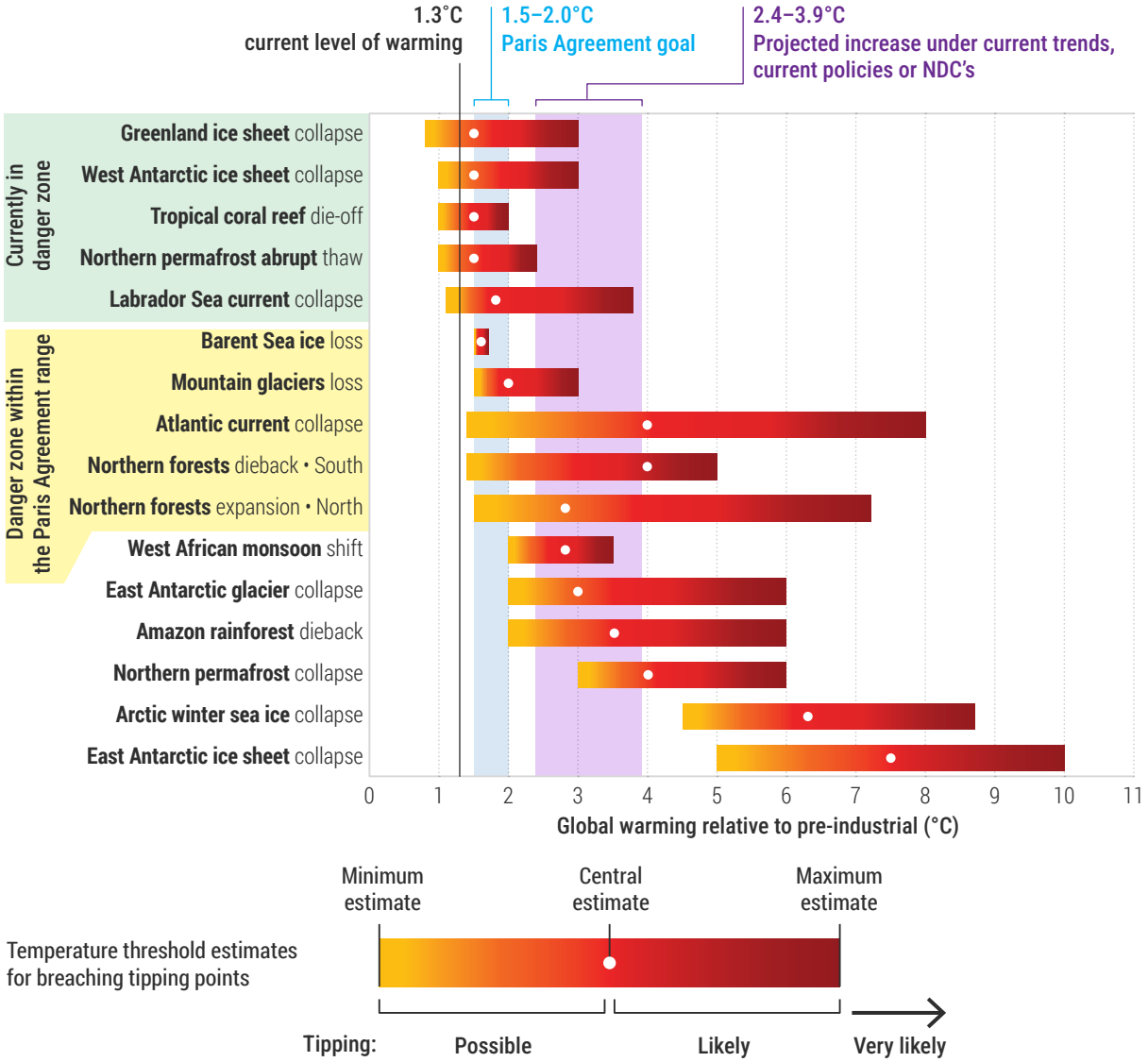
Researchers have identified more than 25 Earth system tipping points, 16 of which intersect the biosphere (Lenton et al. 2019; Lenton et al. 2023). Crossing these tipping points could have catastrophic and potentially irreversible impacts on people and biodiversity (Lenton et al. 2023). Under the Current Trends scenario, several system tipping points are expected to be breached within this century, and even if the Paris Agreement goal of holding global average temperature increase to well below 2°C is met, some may be unavoidable (**Figure 10.16**).

The global environmental crises exhibit non-linear dynamics, characterized by accelerated rates of change and distinct tipping points. As tipping points are not part of the modelling framework, this section is based on literature.

10.5.1 Tipping points in the cryosphere

Arctic sea ice loss: The loss of Arctic sea ice, driven by atmospheric and ocean warming, reduces the Earth's albedo effect, its reflectivity, and influences weather patterns (Stroeve et al. 2012). This is likely to affect mid-latitude Northern Hemisphere weather by altering the position and strength of the jet stream and cyclogenesis (Previdi et al. 2021), resulting in

Figure 10.16: The risk of climate tipping points is rising rapidly as the world heats up



Note: Crossing a tipping point is categorized as "possible" beyond its minimum temperature threshold, "likely" beyond its central estimate, and "very likely" beyond its maximum temperature threshold. Additional tipping points not shown in the diagram include: Congo & SE Asia rainforest dieback, savanna & grassland degradation, dryland degradation, lake eutrophication-driven anoxia, lake invasive species, kelp forest collapse, Southern Ocean Overturning Circulation / Antarctic Overturning, Indian summer monsoon collapse / shift to low-precipitation states and ocean hypoxia.

Data source: McKay et al. (2022), UNEP (2024c), GEO-7 current trends scenario
Illustration: Modified from GLOBAÏA (2025)

more frequent and intense extreme weather events. Such changes could increase the persistence of particular blocking weather systems, which in summer are associated with droughts and heatwaves, and in winter, with extreme snowfall and low temperatures. Some models suggest that the Arctic could be ice-free during parts of the summer by 2030-2050 (National Snow and Ice Data Center 2024).

Ice sheet collapse: The rapid melting and collapse of parts of the Antarctic and Greenland ice sheets (Otosaka et al. 2023) are a major concern for global sea level rise. Between 2002 and 2020, 150 gigatons of Antarctic ice were lost per year. Under the Representative Concentration Pathway (RCP8.5), a high-emission scenario adopted by the IPCC, the melting of the Antarctic ice sheet could lead to global sea level rise of 34cm by 2100 and 1m by 2125 (DeConto et al. 2021). The RCP8.5 scenario projects a global mean surface temperature of 3.3 to 5.8°C, with a mean value of 4.3°C (IPCC 2021). This is slightly above the 3.9°C projected for the Current Trends scenario, which could be an underestimate if the Equilibrium Climate Sensitivity is higher than generally assumed (**Box 10.5**).

The Greenland ice sheet melt could contribute at least 27 cm to sea level rise by 2100, regardless of climate pathways (Box et al. 2022; Hanna et al. 2024). A complete melting of the Greenland ice sheet would increase sea level by 5-7 meters (Aschwanden et al. 2019), and a complete melting of the West Antarctic ice sheet could cause an additional 5-meter sea level rise (Chambers et al. 2022). Ice sheet collapse would be irreversible on societally relevant timescales, with profound consequences for coastal communities (Naughten et al. 2023).

Thawing of permafrost: Permafrost covers 15–25 per cent of the Northern Hemisphere and stores an estimated 1,700 billion tons of carbon (Miner et al. 2023). The loss of permafrost, driven by Arctic warming, would result in a feedback loop through reduced albedo and increased GHG emissions further accelerating warming. Permafrost thawing destabilizes landscapes, damages infrastructure, and poses risks to ecosystems and Arctic communities. Thermokarst thaw lakes now cover more than 1 million km² (Miner et al. 2023), and thawing is predicted to accelerate over the next 10 to 20 years. An abrupt thaw could result in the rapid release of carbon and methane within days to years (Miner et al. 2023).

Glacial retreat: Triggered by atmospheric warming and changes in precipitation, glacial retreat impacts freshwater availability and is likely to increase mountain hazards, including glacial lake outburst floods (Harrison et al. 2018) and rock slope failures (Shugar et al. 2021, Potter et al. 2023). These will have substantial negative impacts on local and regional infrastructure and energy systems (e.g. Li et al. 2022). Significant glacier losses are already occurring and accelerating, from 231 billion tons of ice per year between 2000 and 2011 to 314 billion tons per year between 2012 and 2023, reaching 548 billion tons in 2023 (Zempt et al. 2025). By 2100, between 49-83 per cent (Rounce et al. 2023) of global glacier mass could be lost, with between 34-46 per cent in the Alps by 2050 (Cook et al. 2023).

10.5.2 Tipping points in the biosphere

Amazon rainforest dieback: The Amazon rainforest is facing the risk of transitioning to a low tree-cover savanna landscape due to pressures of global temperature rise, drought, deforestation and increased intensity and frequency of wildfire (Boulton et al. 2022). The region is home to 2.2 million Indigenous peoples and stores the carbon equivalent of 15-20 years of global CO_2 emissions (Flores et al. 2024). Amazon rainforest dieback would have catastrophic impacts on biodiversity, alter local and regional climates, and transition the Amazon from a carbon sink to a carbon source, with some estimates suggesting the loss of tropical rainforest reaching over 50 per cent by end of the century (Nath, Nath and Chen 2024), and up to 47 per cent of Amazon forest at risk of ecosystem transition by 2050 (Flores et al. 2024). Amazon dieback could also expose approximately 6 million people to

Box 10.5: Climate tipping points may be reached much earlier than generally assumed

Several tipping points in the climate system are expected to be crossed within the next few decades if global temperature rise persists (**Figure 10.16**). While the exact timing is uncertain, the probability and severity of tipping points increase with warming. As a result, understanding the rate and extent of the temperature rise is crucial for assessing and preparing for the shifts that follow tipping points. Equilibrium Climate Sensitivity (ECS) measures the long-term change in global surface temperature after a doubling of the atmospheric CO_2 concentration (Forster et al. 2021). The precise estimates of ECS are uncertain because the strength and duration of the size of feedback mechanisms are not fully understood. Despite these uncertainties, most assessments show that the distribution of temperatures related to ECS is asymmetric, with a long tail on the higher end. Based on multiple lines of evidence, IPCC (2021) provides a best estimate of 3°C, with the likely range being 2.5°C to 4°C, and the very likely range of 2°C to 5°C. They concluded that it is virtually certain that ECS is larger than 1.5°C. and that increases over 5°C are still possible, albeit less likely. As a result, some climate scientists are concerned that the ECS is underestimated (Hansen et al. 2023), meaning that climate change is occurring faster and tipping points can be reached much earlier than currently forecasted (Ditlevsen and Ditlevsen 2023). This underscores the urgency to reduce emissions, as the potential consequences could be more severe than current models suggest.

the risk of heat stress (Alves de Oliveira et al. 2021) and cause an estimated US$1-3.5 trillion in economic damage over 30 years (Lapola et al. 2018).

Boreal and temperate forest dieback: Proximate drivers of boreal and temperate forest dieback include pest outbreaks and wildfires associated with climate change. Forest loss threatens biodiversity, increases carbon emissions and has complex climate cycle feedbacks (Magney and Pierrat 2025). The boreal forest is the largest biome on Earth and stores approximately one-third of the world's terrestrial carbon stocks (Rao et al. 2023). Earth System Models suggest that forest dieback at the southern margin could begin at around 1.5 C° of warming, becoming widespread at around 3.5°C, and approaching a biome-wide tipping point at around 4°C (Rao et al. 2023). In addition to being a carbon store, temperate forests contribute to local cooling (Lenton et al. 2023) and provide economically vital ecosystem services (Food and Agriculture Organization of the United Nations and the United Nations Economic Commission for Europe 2023). Hotter droughts, coupled with increased pest intensity and fire risks, are already transforming temperate forests into shrublands and grasslands in Australia and the south-central United States (Millar and Stephenson 2015).

Warm-water coral reef die-off: Warm-water coral reefs are among the most productive and highly biodiverse habitats, yet they are vulnerable to the impacts of warming seas, marine heatwaves, ocean acidification, and increased eutrophication. These stressors may shift biodiverse, coral-dominated ecosystems to low-diversity, macroalgae-dominated ecosystems (Rhoades, Brandt, and Witman 2023; Pearce-Kelly et al. 2025). This transformation would lead to the collapse of reef-associated commercial and artisanal fisheries, as well as increase coastal vulnerability to extreme weather events. Projections suggest that a 1.5°C warming could cause coral loss of 70-90 per cent, while a 2°C rise in global temperatures could result in a near-total loss of 99 per cent (Armstrong McKay et al. 2022, IPCC 2018, IPCC 2022c).

10.5.3 Tipping points in the ocean and atmospheric circulations

Shifts in the intensity and timing of monsoons: The monsoons are increasingly influenced by aerosols such as $PM_{2.5}$ in the atmosphere, GHGs, and land-use change (Seth et al. 2019), which significantly alter their timing and intensity. A substantial increase in rainfall intensity may lead to an expansion of vegetation in the Sahel and Saharan regions. However, this same weather pattern could push the desert into the African Mediterranean (Maghreb) region (Tian et al. 2023). In South-East Asia, 2˚C of warming could increase monsoon rainfall intensity (average rainfall in mm/h or mm/min) by 10 per cent (Yaduvanshi et al. 2021). These shifts would have negative socioeconomic consequences for regions dependent on rain-fed agricultural production or those with low adaptive capacity, and pose challenges for water resource management (Mutton et al. 2022).

Atlantic Meridional Overturning Circulation (AMOC) slowdown: The AMOC plays a critical role in the global climate system, transporting heat to northern latitudes and regulating the oceans' thermohaline circulation. Recently, the AMOC has shown signs of slowing down (Caesar et al. 2018; Zhu and Liu 2020), likely due to an increased influx of freshwater into the North Atlantic, raising concerns about a potential rapid collapse. This would produce a range of large-scale climate impacts, including cooling across the Northern Hemisphere, an expansion of Arctic sea ice, and a southward shift of the Intertropical Convergence Zone (Ma et al. 2024). Further effects would include a likely rearrangement of tropical monsoon systems (Ben-Yami et al. 2024), heatwaves in eastern Europe (Meccia et al. 2025), as well as accelerated ice melt in Antarctica and subsequent global sea level rise.

10.5.4 Interactions and feedback loops

One of the characteristics of global environmental change is the interaction among crises, generating positive feedback loops that worsen their impacts. These interactions are particularly evident among climate change, land degradation and biodiversity loss. For example, permafrost degradation driven by warming and thawing can alter landscape structure, disrupt vegetation dynamics, and affect nutrient cycling. Crucially, these processes also release stored CH_4 and CO_2 (Schuur et al. 2015), accelerating climate change. Similarly, deforestation and climate change both contribute to land degradation. As land degrades, it has less biomass and lower productivity, potentially shifting from a carbon sink to a carbon source (IPCC 2019).

10.6 Socioeconomic implications under current trends

Human well-being and socioeconomic development are shaped by a range of interdependent social, cultural, economic, political, and environmental factors, with multiple negative implications resulting from the global environmental crises (Chapter 7). This section discusses projected progress towards socioeconomic SDG targets under the Current Trends scenario (10.6.1-10.6,4), as well as the economic impacts of the global environmental crises (10.6.5). Since the impacts of global environmental crises on human well-being and the economy could only be partially modelled, the discussion also draws on existing literature.

Overall, since 2020, the progress toward the SDGs has slowed (Malekpour et al. 2023; Sachs, Lafortune and Fuller 2024). Under the Current Trends scenario, human well-being is projected to improve generally; however, none of the well-being-related SDGs are projected to be fully achieved, not even by 2050 (**Figure 10.17**). This is in line with other analyses and assessments (Moyer and Hedden 2020; van Vuuren et al. 2022; Fu and Zhang 2024; Sachs, Lafortune and Fuller 2024; United Nations Department of Economic and Social 2024). Furthermore, projected gains in humanwell-being are increasingly threatened by the intensifying global environmental crises, affecting health, food systems and livelihoods.

The projected improvements in well-being are unevenly distributed, with some vulnerable communities and groups experiencing slower progress and disproportionately worse effects from the environmental crisis. Those most affected include women, the elderly, young children, ethnic minorities, and individuals with pre-existing health conditions (7.2.5). In Indigenous populations, the impacts of poverty, environmental pressures, and lack of access to basic public services such as education, health, and social protection are particularly felt by women and girls (Carmen 2017; Bryson et al. 2021; Vecchio et al. 2022).

10.6.1 Basic material needs

Basic material needs include nutrition (SDG2), access to safely managed drinking water sources and sanitation (SDG6), and access to clean cooking fuels and technologies (SDG7) (**Figure 10.17**).

As of 2023, 9 per cent of the global population was estimated to be undernourished (FAO 2023). In line with the projected increase in average per capita food intake (section 10.3.2), the total number of undernourished people is projected to decline by 60 per cent from 2020 to 2050. However, this progress is insufficient to meet SDG 2.1, and hunger hotspots are likely to persist, particularly in Africa. Children under 5 are especially vulnerable. While today children make up roughly 16 per cent of the undernourished population, this share is projected to increase to 20 per cent by 2050.

Despite overall improvements, progress in reducing undernutrition will be hindered by environmental crises to varying extents across regions and contexts. Broadly, climate change, land degradation, and water stress affect the food supply by reducing agricultural yields (Vermeulen, Campbell and Ingram 2012; **Box 10.2**), altering marine productivity (Vermeulen, Campbell and Ingram 2012; Watts et al. 2021; Palacios-Abrantes et al. 2022; IPCC 2023a), and causing losses from flooding, wildfires, and other extreme events (Vermeulen, Campbell and Ingram 2012; Pacetti, Caporali and Rulli 2017; Rahman and Di 2020). For example, scenario studies show that climate change could reduce per-person food availability by 3.4 per cent (Springmann et al. 2016), and could increase the population at risk of hunger by 24 million in 2050 (Hasegawa et al. 2018). Furthermore, an increased frequency of extreme events could push this number higher by 11 to 36 per cent by 2050 (Hasegawa et al. 2021). Women and girls are often hit harder by food insecurity due to limited access to financing and resources and intra-household inequalities, where they are expected to eat last (Agarwal 2018). Moderate and severe food insecurity, as measured by the Food Insecurity Experience Scale, is projected to be two percentage points higher for women than for men worldwide.

As of 2022, 27 per cent of the world's population lacked access to safely managed drinking water sources, of which around 5 per cent relied on unimproved sources, and 43 per cent lacked access to safely managed sanitation (United Nations Children's Fund [UNICEF] and World Health Organization 2023). Access to safe water and sanitation is crucial for human health, particularly for young children (Nounkeu and Dharod 2021; 6.6.4). Women and girls are disproportionately affected by a lack of access to safe water and sanitation (Kayser et al. 2019; Pouramin et al. 2020). While access levels is projected to improve, by 2050 hundreds of

Figure 10.17: Trend in selected socioeconomic SDG targets

Source: IFs Model

Credit: Great_bru/Envato

millions would still lack access to improved water and sanitation services, failing to meet SDG 6.1 and 6.2.

In 2023, 9 per cent of the global population, including 16 per cent of the rural population, lacked access to electricity. Additionally, around one-fourth of the global population lacked access to clean cooking fuels and technologies (International Energy Agency [IEA], International Renewable Energy Agency [IRENA], United Nations Statistics Division, World Bank, World Health Organization 2024; 7.2.7). Electricity is essential for human development (Fuso Nerini et al. 2017; United Nations Department of Economic and Social Affairs 2014). Lack of access to clean cooking fuels increases indoor air pollution, generating health issues (3.5; 10.6.2), which disproportionately affect women and children (Martin, Hollingsworth, and Ramanathan 2014; Kuhn et al. 2016). Although access to modern energy is projected to improve in the Current Trends scenario by 2050, 5 per cent of the global population and 10 per cent of the rural population would still lack electricity access, and 7 per cent of the global households would still rely on traditional cookstoves, failing to meet SDG7.1.

Global environmental crises will increase pressure on electrical grids due to hotter weather and extreme events (Vermeulen, Campbell and Ingram 2012; Panteli and Mancarella 2015). Furthermore, rising temperatures and extreme weather events increase the demand for heating, cooling, and disaster recovery, leading to higher costs and energy insecurity, particularly among low-income households. This, in turn, can limit digital access, hinder education, and reduce access to clean cooking (Jessel, Sawyer and Hernandez 2019; Bezgrebelna et al. 2021).

10.6.2 Good health

Under the Current Trends scenario, health outcomes are projected to improve by 2050, with average life expectancy rising from around 73 years in 2020 to 78 by 2050 (Sellers 2020). However, many health-related SDGs will remain unmet. For example, SDG target 3.2

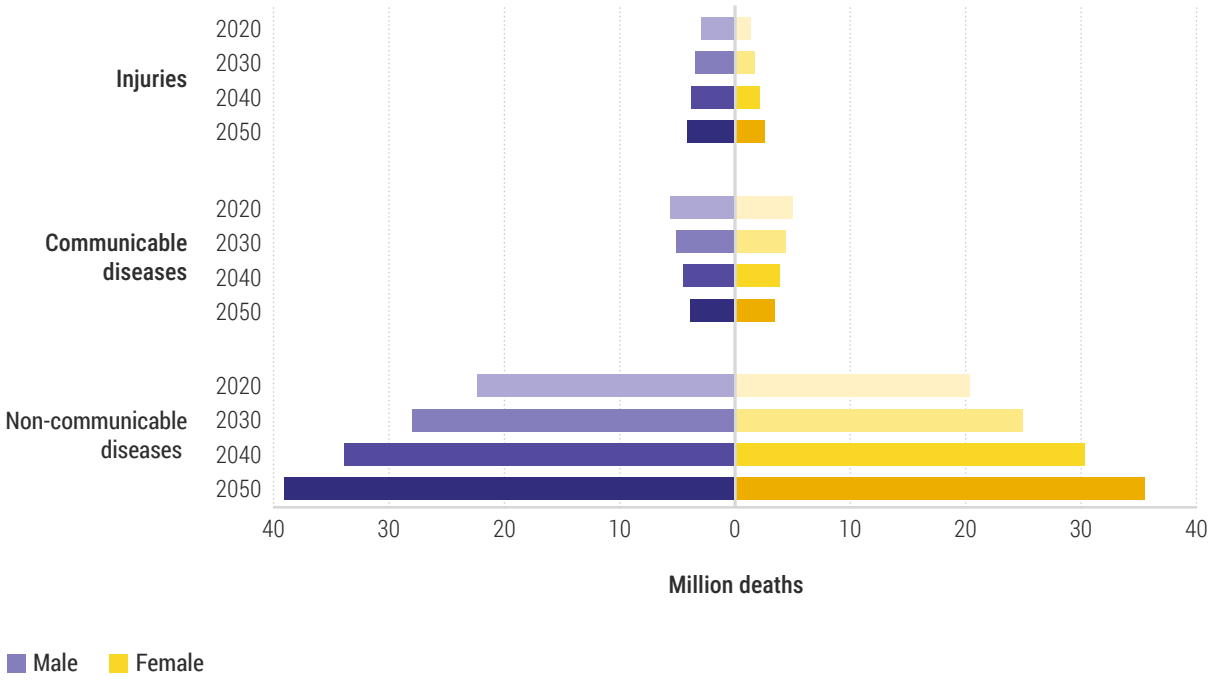
on neonatal and under-5 mortality is projected to be met globally only after 2040, while low- and lower middle-income countries may lag by another decade (**Figure 10.17**), mainly due to inadequate provision of basic material needs (Lucas et al. 2019).

In 2020, communicable diseases – including AIDS, diarrheal disease, malaria, respiratory infections, and others – made up roughly 18 per cent of total deaths worldwide, with nearly half occurring in low-income countries. Under the Current Trends scenario, nutrition, health systems, and improved infrastructure in terms of water and energy are projected to reduce the burden of communicable diseases (**Figure 10.18**). However, the global environmental crises may impede this progress. Improved nutrition, access to water and clean cooking reduce diarrheal diseases and respiratory infections (Prüss-Ustün et al. 2014; Cohen et al. 2017; Prüss-Ustün et al. 2019; Chen et al. 2023; Sen et al. 2023), while warming and shifting precipitation patterns increase the risk of vector-borne diseases, like malaria (Rocklov and Dubrow 2020; Watts et al. 2021).

In 2020, non-communicable diseases, including heart disease, diabetes, digestive disease, cancer, respiratory disease, and others, accounted for 74 per cent of deaths globally. By 2050, this share is projected to exceed 80 per cent (**Figure 10.18**), driven by increasing affluence and aging populations. The global environmental crises are likely to increase premature death from non-communicable diseases further. Air pollution, both urban (10.4.2) and indoor from traditional cookstoves (10.6.1), contributes to an increased incidence of respiratory disease (Faizan and Thakur 2019; Pratiti et al. 2020). In the Current Trends scenario, urban air pollution alone, resulting from $PM_{2.5}$, could result in an estimated 4 million deaths in 2050, similar to 2020 levels (10.4.2). Mining activities increase exposure to toxic dust (González 2024) and contaminate freshwater, leading to bioaccumulation of toxins and heavy metals, like mercury, contributing to chronical diseases, such as higher rates of cancer, heart and lung disease, and neurological damage (Fuller et al. 2022). Rising temperatures increase the risk of heat stroke, heat stress, cardiovascular disease (Green et al. 2019; Watts et al. 2021), as well as mental health issues (Byun et al. 2024).

In 2020, 8 per cent of deaths globally were attributed to injuries. The injury burden is projected to increase slightly by 2050 (Figure 10.18), due to demographic and epidemiological changes, including population growth, development, urbanization, and a rise in traffic accidents (Haagsma et al. 2020). Global

Figure 10.18: Global mortality by overall category of cause and sex



Source: IFs Model

environmental crises may exacerbate injuries resulting from extreme events, such as wildfires, storms, and flooding, and contribute to an increase in mental health problems in the general population (Rataj, Kunzweiler, and Garthus-Niegel 2016; Cruz et al. 2020). **Box 10.6** describes implications of the global environmental crises on the mental health of Indigenous Peoples.

10.6.3 Fair and just societies

In 2020, the COVID-19 pandemic led to a rise in the global poverty rate for the first time in decades (Moyer et al. 2022). While poverty reduction has resumed since 2020, progress has been slow (World Bank 2024). Under the Current Trends scenario, as economies grow, the poverty rate is projected to fall, but not fast enough to meet SDG target 1.1 by 2030 or even by 2050 (**Figure 10.17**). While the overall income inequality is projected to remain stable (Rao et al. 2018), disparities across income groups persist (**Figure 10.19**). Upper-middle-income economies are slowly converging with high-income economies in terms of GDP per capita. However, by 2050 their average income would still be less than half of that of the high-income countries. In low-income countries, average GDP per capita as a per cent of that in high-income countries is projected to improve only slightly, from 4 per cent in 2020 to 5 per cent by 2050.

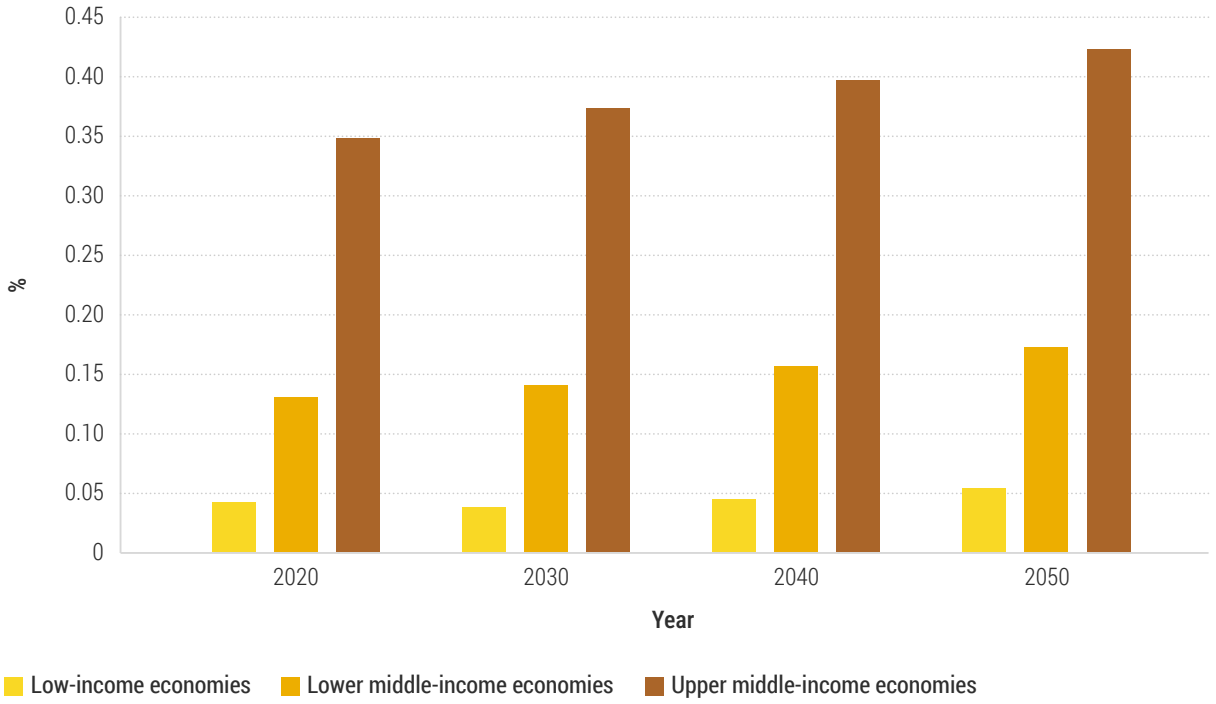
Women and girls are disproportionately affected by poverty, especially as young adults (Marley and Desai 2020). In 2020, the global female poverty rate is 0.6 percentage points higher at US$2.15/day, the extreme poverty line, 5 percentage points higher at US$3.65/day, a poverty line more relevant in lower-middle-income countries, and 10 percentage points higher at US$6.85/day, a poverty line more relevant for upper-middle-income countries. Under the Current Trends scenario, these gaps are projected to narrow in the coming decades, but they are not projected to close. Slower progress will likely also affect Indigenous Peoples and their communities, who often experience worse outcomes compared to non-Indigenous

Box 10.6: Implications of the global environmental crises on the mental health of Indigenous Peoples

For many Indigenous cultures, health and mental well-being are not individual matters, but rather a reflection of respectful, reciprocal relationships with their environment (Redvers 2020; Redvers et al. 2023). Moreover, maintaining a strong attachment to places, preserving cultural practices, institutions, and languages are crucial for effective mental health care in these communities (Redvers 2020; Redvers et al. 2023). However, mental health care of Indigenous Peoples has been neglected globally (Incayawar and Maldonado-Bouchard 2009; Nelson and Wilson 2017; Page et al. 2022; Subica et al. 2024), with many reports identifying colonization and historical trauma as key drivers to the current mental stress challenges (Kirmayer, Brass and Tait 2000; Matthews et al. 2023). The ongoing threats to Indigenous sovereignty and rights, often driven by environmental degradation, further strain mental well-being, especially where healthcare access remains limited (Fernández-Llamazares et al. 2020).

Environmental degradation, industrial resource extraction and pollution on Indigenous lands often harm the mental health of Indigenous communities by eroding Indigenous Knowledge and disrupting their culture (Ninomiya et al. 2023). Climate change stressors and impacts, such as extreme weather events, including storms, flooding, heatwaves, and changes in seasonality, as well as drought, sea ice changes, wildfires, and vegetation shifts, are often linked to feelings of loss, worry, anger, and sadness (Middleton et al. 2020). Long-term exposure to the consequences of climate change among Indigenous populations can affect the fundamental pillars of mental health, including food and water insecurity, community cohesion, and traditional ways of life (Middleton et al. 2020; Brubacher et al. 2024). Among the Shawi people in the Peruvian Amazon, a decline in wild animals in their territory, seen as a disruption of environmental balance or a lack of respect for nature, has led to feelings of anxiety and guilt (Arotoma-Rojas et al. 2022). In the Canadian Arctic, climate-induced displacement among the Inuit leads to the erosion of identity and culture, contributing to environmental emotional distress (Ayeb-Karlsson, Hoad, and Trueba 2024).

Figure 10.19: Relative shares of GDP per capita compared to high-income economies



Source: IFs Model

populations (World Bank 2011; Hall and Patrinos 2012; Anderson et al. 2016).

Global environmental crises are likely to hinder poverty reduction by slowing economic growth and exacerbating inequality, both between countries (Mendelsohn, Dinar, and Williams 2006; Ahmed, Diffenbaugh, and Hertel 2009; Diffenbaugh and Burke 2019) and within countries (Hallegatte and Rozenberg 2017; Paglialunga, Coveri, and Zanfei 2022). Poor households will be especially affected by rising food prices (Hertel, Burke and Lobell 2010; Hallegatte and Rozenberg 2017), while farming and rural households could be hurt by changes in agricultural productivity. Increased health risks could lead to lost working days and higher medical costs (Hallegatte and Rozenberg 2017), while environmental disasters could result in the loss of assets and income, especially for vulnerable populations (Heltberg, Oviedo, and Talukdar 2015). For example, other scenario studies show that climate change alone could push an additional 32 to 132 million people into poverty by 2030 (Jafino et al. 2020), and between 40 and 78 million by 2050 (Moyer et al. 2023).

10.6.4 Human security

Human security measures the presence of violent conflict between groups of people or individuals and includes both intrastate and interstate armed conflict (Hughes et al. 2014). Under the Current Trends scenario, the probability of civil war onset, used here as a proxy for human security, is projected to decrease over time (**Figure 10.17**). This decline is generally attributed to improvements in human development, stronger government institutions, greater international economic integration, and positive neighbourhood effects that underlie this scenario. However, even with this reduced likelihood of conflict, the world is not on track to meet the SDG 16.1 target of eliminating conflict-related deaths.

There are significant uncertainties surrounding these projections – even without considering the global environmental crises (Goldstone et al. 2010; Hegre, Karlesen, and Strand 2013; Cederman and Weidmann 2017; Bowlsby et al. 2019; Hegre, Nygård, and Landsverk 2021). It is essential to acknowledge that models can exhibit varying behaviour over time, and that overreliance on a single model can be misleading. Predicting the onset of conflict is more challenging than estimating the magnitude of conflict. The model used here can be compared with other forecasts of conflict onset, including Goldstone et al. (2010) and Hegre et al. (2013).

Global environmental crises may exacerbate conflict through changes in resource availability and by driving migration, particularly due to the loss of food and livelihoods (7.2). However, evidence of the effects of climate change on the onset of civil war is mixed (Mach et al. 2019). Likewise, projections of armed conflict between states are highly uncertain (Moyer 2024). Changes in socioeconomic patterns and climate change mitigation strategies could lead to geopolitical shifts, either increasing or decreasing the likelihood of interstate armed conflict (Moyer 2024). However, while improvements in human security overall are projected to improve, any armed conflicts have significant negative implications for human development (United Nations Development Programme [UNDP] 2022).

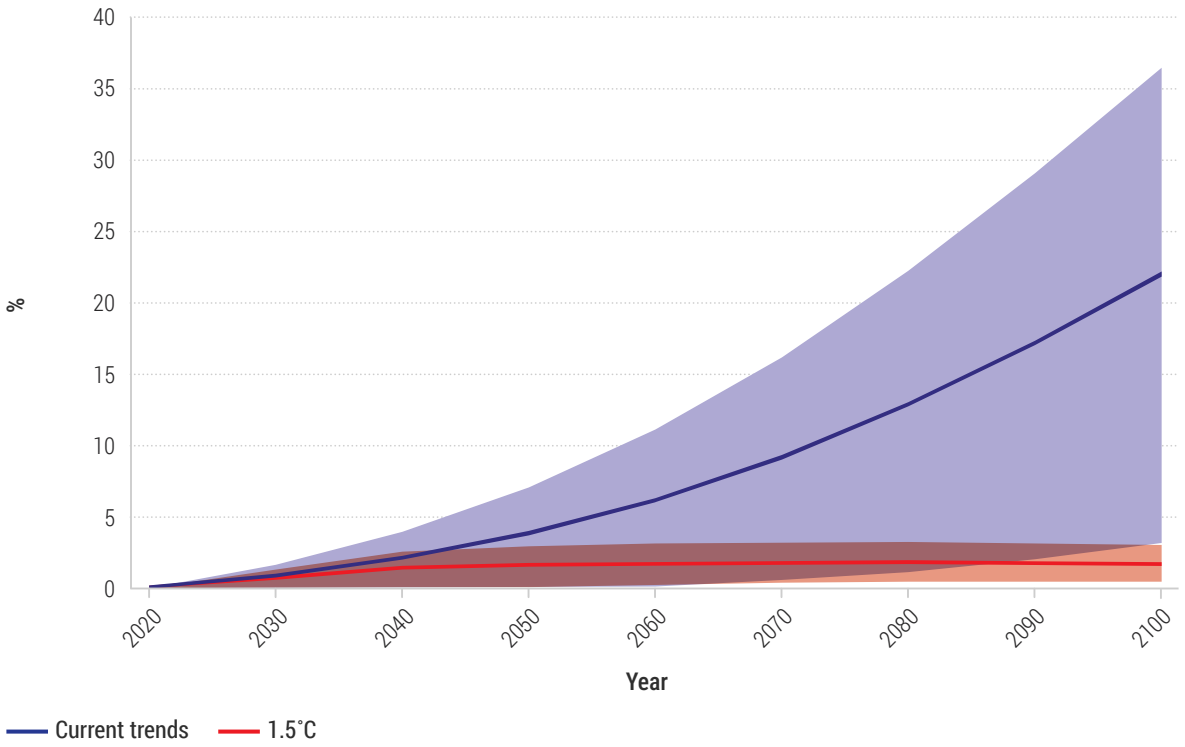
10.6.5 Economic impact

The scientific literature unequivocally emphasize that further worsening of global environmental crises will inevitably lead to rising economic costs (Piontek et al. 2021; IPCC 2022a). The costs of inaction or insufficient action are already evident (Funk et al. 2019; Rimi et al. 2019; Yiou et al. 2020; van Oldenborgh et al. 2021; Tavoni et al. 2024). A range of projections conclude that future GDP growth will be lower than the Current Trends scenario estimates when including the costs of climate change and environmental degradation (Burke et al. 2015; Howard et al. 2017; van der Wijst et al. 2023).

Under the Current Trends scenario, the economic impacts or damage costs from climate change are projected to increase over time (**Figure 10.20**), with a non-linear intensification in the second half of the century. This projection is associated with high uncertainties. The median estimate of global GDP loss is projected to increase to 4 (0-7) per cent in 2050 at US$9.5 trillion per year, growing further to 22 (3-37) per cent in 2100 at US$133 trillion per year. In contrast, a transformation pathway that limits global temperature rise to 1.5°C (11.5), could keep median GDP losses below 2 per cent throughout the century.

These estimates of global GDP loss include, among others, climate-related impacts from agriculture, energy, labour supply, and flooding from rivers and sea-level rise. However, they do not account for other essential aspects, such as climate-change-induced health impacts,

Figure 10.20: Global aggregate GDP losses from climate impacts



Note: Solid lines indicate median estimates of the damage functions. The ranges are the 5th-95th percentiles of the damage functions.

Source: MIMOSA model

biodiversity losses, or tipping points (10.5), which are harder to quantify. Including these factors would likely result in even higher projected GDP losses.

The broad uncertainty range in this projection aligns with the contribution of Working Group 2 to the 6th Assessment report of the IPCC (Rose et al. 2022) and recent studies using empirical data of economic impacts of climate change (Burke et al. 2015; Kalkuhl and Wenz 2020; Piontek et al. 2021). Studies based on empirical GDP growth data and econometric models (Burke et al. 2015) tend to estimate higher economic costs. In contrast, bottom-up studies that account for sector-specific economic damages, such as presented here, tend to estimate lower costs (Takakura et al. 2019).

Beyond climate change, the other global environmental crises are also expected to cause significant economic damage. Johnson et al. (2020) estimate that, under a similar scenario as the Current Trends scenario, the annual GDP loss could reach US$478 billion by 2050, resulting in a total loss of US$9.87 trillion in real GDP by mid-century. The Climate Policy Initiative (2024) estimates cumulative losses of US$1,266 trillion between 2025 and 2100. For biodiversity, a decline in selected ecosystem services could result in a global real GDP loss of US$90-225 billion by 2030 (Johnson et al 2021). Current annual cost of declining ecosystem functionality is estimated at US$5 trillion to US$25 trillion (Costanza et al. 2014; Kurt et al. 2021). Regarding land degradation, the FAO and the Intergovernmental Technical Panel on Soils (2015) highlight that, in response to global soil erosion, annual expenditures range from US$33 billion to US$60 billion for nitrogen and from US$77 billion to US$140 billion for phosphorus applications.

Table 10.1 offers an overview of the cost estimates from the literature related to inaction or inadequate action across various sectors under current

Table 10.1: Cost estimates associated with inaction or inadequate action across various sectors

Sector	Estimated costs	Unit
Agriculture (crop production)	S$80-120 billion lost annually to 2100 (IPCC 2022b; FAO 2023) US$15.3 billion lost annually in real GDP terms due to pollinator habitat reduction and US$19 billion lost annually in real GDP terms due to water scarcity for irrigation alone to mid-century (Johnson et al. 2020)	Value of crop output at risk due to extreme weather events, salt-induced land degradation, pollinator loss, water scarcity for irrigation, increased pests and disease.
Disaster risk reduction	US$327 billion of reduced GDP per year to 2050 (Johnson et al. 2020)	Lost GDP from reduced productivity in coastal areas linked to the loss and depletion of capital and productive assets. This decline results from exposure to inundation due to changes in terrestrial and marine habitats that normally protect the coast from erosion and flooding.
Energy	US$50-80 billion annually to 2100 (IPCC 2022b; IEA 2023) US$12 trillion to 2050 (IRENA 2017)	Value of damage to energy infrastructure and asset stranding following extreme weather events and projected increasing energy demand, in some instances.
Forestry	US$7.5 billion as net annual loss in real GDP to 2050 (Johnson et al. 2020)	Reduced productivity and timber production as a result of changes in biomass linked to land use, temperature and precipitation changes.
Health	US$60-150 billion annually to 2100 (Romanello et al. 2023) US$12.5 trillion by 2050 (World Economic Forum [WEF] 2024) Up to US$18-25 trillion annually by 2060 for air pollution-related deaths and US$2.2 trillion by 2060 for diseases caused by air pollution alone, using constant 2010 US$ and purchasing power parity exchange rates (OECD 2016)	imate-induced productivity loss, due to detrimental health outcomes, and cost of treatment. As for air pollution, costs include the annual economic losses due to premature deaths and costs associated with treating pollution-related illnesses.

Table 10.1: Cost estimates associated with inaction or inadequate action across various sectors (cont.)

Sector	Estimated costs	Unit
Labour	US$2.4 trillion lost by 2030, with limited global warming to 1.5°C above preindustrial levels by the end of the century (International Labour Organization [ILO] 2019)	alue of lost working hours due to heat stress. With further environmental degradation, agricultural workers will be the worst affected and will account for 66 per cent of global work hours lost due to heat stress in 2030 (Montt, Fraga and Harsdorff 2018).
Livestock	US$10-13 billion lost by 2050 due to a 7-10% decrease in livestock numbers at 2°C, in turn, caused by decreased forage productivity (Boone et al. 2018) US$22-38 billion lost annually in dairy and beef production by 2100 under SSP5 (IPCC 2022a)	Direct losses resulting from heat stress affect livestock mortality and productivity, and indirectly impact forage availability and quality.
Tourism	S$80-120 billion lost annually to 2100 (Layne 2017; United Nations World Tourism Organization [UNWTO] 2023)	Value of tourism revenues at risk due to extreme weather events and sea-level rise
Urban areas and infrastructure	S$100-200 billion annually to 2100 (United Nations Office for Disaster Risk Reduction [UNDRR] 2019; IPCC 2022b	Costs of damage repairs due to an increased frequency and intensity of extreme weather and other climate-related events.
Water resources	S$20-40 billion annually to 2100 (IPCC 2022b)	Implication of reduced water availability due to increasing incidences of drought.

trends-like scenarios, primarily SSP2. While these estimates aim to capture the complex economic impacts, uncertainties remain, as reflected in the broad ranges presented. Moreover, differences in metrics and methodologies mean that these studies cannot be directly compared; yet, they unambiguously point to the economic risks of no or inadequate responses to the global environmental crises.

Quantifying the costs of no or insufficient action is a complex task, and estimates vary widely due to differences in the variables being considered, models used, assumptions, and timeframes. Additionally, some costs are not quantified in the literature and are either explored qualitatively or omitted from modelling exercises due to data deficiencies or other challenges. This includes the cost of global environmental crises on Indigenous Peoples and their communities. The literature indicates that as land degradation, pollution, and climate change affect traditional food practices, Indigenous Peoples require more expensive equipment and tools, and increasingly rely on store-bought foods to adapt (Norton-Smith et al. 2016). The economic effect of displacement from Indigenous land remains difficult to model at this time (Ram and Shahzar 2024).

10.7 The need tobreak with current trends

The scenario analysis clearly shows that the world is not on track to achieve the globally agreed goals related to the global environmental crises, including key goals and targets of the Paris Agreement, the Kunming-Montreal Global Biodiversity Framework, and the United Nations Convention to Combat Desertification. The global environmental crises risk triggering major shifts in the Earth's systems, including accelerated rates of change and the potential for tipping points to occur. Furthermore, they hinder progress on socioeconomic SDG targets by impeding food systems, human health, and livelihoods.

The costs of inaction or insufficient action, both economic and social, are already evident and are projected to increase further. Addressing these environmental crises and achieving internationally agreed goals requires a fundamental shift from current trends, including the decoupling of human development from environmental degradation. This requires transformation of the economic and finance, food, energy, and materials/waste systems, as well as changes in the way the environment is managed. Transformation Pathways towards achieving globally agreed goals are discussed in Chapter 11.

References

Agarwal, B. (2018). Gender equality, food security and the sustainable development goals. Current Opinion in Environmental Sustainability 34, 26-32. https://doi.org/10.1016/j.cosust.2018.07.002

Ahmed, S.A., Diffenbaugh, N.S. and Hertel, T.W. (2009). Climate volatility deepens poverty vulnerability in developing countries. Environmental Research Letters 4(3). https://doi.org/10.1088/1748-9326/4/3/034004

Albrecht, J., Peters, M.K., Becker, J.N., Behler, C., Classen, A., Ensslin, A. et al. (2021). Species richness is more important for ecosystem functioning than species turnover along an elevational gradient. Nature Ecology & Evolution 5(12), 1582-1593. https://doi.org/10.1038/s41559-021-01550-9

Alves de Oliveira, B.F., Bottino, M.J., Nobre, P. and Nobre, C.A. (2021). Deforestation and climate change are projected to increase heat stress risk in the Brazilian Amazon. Communications Earth & Environment 2(1) 207. https://doi.org/10.1038/s43247-021-00275-8

Anderson, I., Robson, B., Connolly, M., Al-Yaman, F., Bjertness, E., King, A. et al. (2016). Indigenous and tribal peoples' health (The Lancet-Lowitja Institute Global Collaboration): a population study. Lancet 388(10040), 131-157. https://doi.org/10.1016/S0140-6736(16)00345-7

Armstrong McKay, D.I., Staal, A., Abrams, J.F., Winkelmann, R., Sakschewski, B., Loriani, S. et al. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. Science 377(6611), eabn7950. https://doi.org/10.1126/science.abn7950

Arotoma-Rojas, I., Berrang-Ford, L., Zavaleta-Cortijo, C., Ford, J.D. and Cooke, P. (2022). Indigenous Peoples' Perceptions of Their Food System in the Context of Climate Change: A Case Study of Shawi Men in the Peruvian Amazon. Sustainability 14(24), 16502. https://doi.org/10.3390/su142416502

Aschwanden, A., Fahnestock, M.A., Truffer, M., Brinkerhoff, D.J., Hock, R., Khroulev, C. et al. (2019) Contribution of the Greenland Ice Sheet to sea level over the next millennium. Science Advances 5(6), eaav9396. https://doi.org/10.1126/sciadv.aav9396

Ayeb-Karlsson, S., Hoad, A. and Trueba, M.L. (2024). 'My appetite and mind would go': Inuit perceptions of (im)mobility and wellbeing loss under climate change across Inuit Nunangat in the Canadian Arctic. Humanities and Social Sciences Communications 11(1), 277. https://doi.org/10.1057/s41599-024-02706-1

Balvanera, P., Pfaff, A., Viña, A., Frapolli, E. G., Hussain, S.A. & Merino, L. (2019). Status and Trends – Drivers of Change. In Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Brondízio, E.S., Settele, J., Díaz, S., Ngo, H. T. (ed.). Bonn, Germany: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services Secretariat. https://www.ipbes.net/system/files/2021-06/2020%20IPBES%20GLOBAL%20REPORT(FIRST%20PART)_V3_SINGLE.pdf

Ben-Yami, M., Good, P., Jackson, L.C., Crucifix, M., Hu, A., Saenko, O. et al. (2024). Impacts of AMOC Collapse on Monsoon Rainfall: A Multi-Model Comparison. Earth's Future 12(9), e2023EF003959. https://doi.org/10.1029/2023EF003959

Bezgrebelna, M., McKenzie, K., Wells, S., Ravindran, A., Kral, M., Christensen, J. et al. (2021). Climate Change, Weather, Housing Precarity, and Homelessness: A Systematic Review of Reviews. Int J Environ Res Public Health 18(11). https://doi.org/10.3390/ijerph18115812

Bijl, D.L., Bogaart, P.W., Kram, T., de Vries, B.J.M. and van Vuuren, D.P. (2016). Long-term water demand for electricity, industry and households. Environmental Science & Policy 55, 75-86. https://doi.org/10.1016/j.envsci.2015.09.005

Bleischwitz, R., Spataru, C., VanDeveer, S.D., Obersteiner, M., van der Voet, E., Johnson, C. et al. (2018). Resource nexus perspectives towards the United Nations Sustainable Development Goals. Nature Sustainability 1(12), 737-743. https://doi.org/10.1038/s41893-018-0173-2

Boone, R.B., Conant, R.T., Sircely, J., Thornton, P.K. and Herrero, M. (2018). Climate change impacts on selected global rangeland ecosystem services. Global Change Biology 24(3), 1382-1393. https://doi.org/10.1111/gcb.13995

Boulton, C.A., Lenton, T.M. and Boers, N. (2022). Pronounced loss of Amazon rainforest resilience since the early 2000s. Nature Climate Change 12(3), 271-278. https://doi.org/10.1038/s41558-022-01287-8

Bouwman, A.F., Beusen, A.H.W., Doelman, J.C., Stehfest, E. and Westhoek, H. (2024). Impact of lifestyle, human diet and nutrient use efficiency in food production on eutrophication of global aquifers and surface waters. Global Environmental Change 87, 102874. https://doi.org/10.1016/j.gloenvcha.2024.102874

Box, J.E., Hubbard, A., Bahr, D.B., Colgan, W.T., Fettweis, X., Mankoff, K.D. et al. (2022). Greenland ice sheet climate disequilibrium and committed sea-level rise. Nature Climate Change 12(9), 808-813. https://doi.org/10.1038/s41558-022-01441-2

Bowlsby, D., Chenoweth, E., Hendrix, C. and Moyer, J.D. (2020). The Future is a Moving Target: Predicting Political Instability. British Journal of Political Science 50(4), 1405-1417. https://doi.org/10.1017/S0007123418000443

Brubacher, L.J., Peach, L., Chen, T.T.-W., Longboat, S., Dodd, W., Elliott, S.J. et al. (2024). Climate change, biodiversity loss, and Indigenous Peoples' health and wellbeing: A systematic umbrella review. PLOS Global Public Health 4(3), e0002995. https://doi.org/10.1371/journal.pgph.0002995

Bryson, J.M., Patterson, K., Berrang-Ford, L., Lwasa, S., Namanya, D.B., Twesigomwe, S. et al. (2021). Seasonality, climate change, and food security during pregnancy among Indigenous and non-Indigenous women in rural Uganda: Implications for maternal-infant health. PLoS One 16(3), e0247198. https://doi.org/10.1371/journal.pone.0247198

Burke, M., Hsiang, S.M. and Miguel, E. (2015). Global non-linear effect of temperature on economic production. Nature 527(7577), 235-239. https://doi.org/10.1038/nature15725

Byun, G., Choi, Y., Foo, D., Stewart, R., Song, Y., Son, J.-Y. et al. (2024). Effects of ambient temperature on mental and neurological conditions in older adults: A systematic review and meta-analysis. Environment International 194, 109166. https://doi.org/10.1016/j.envint.2024.109166

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G. and Saba, V. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. Nature 556(7700), 191-196. https://doi.org/10.1038/s41586-018-0006-5

Carmen, A. (2017). Environmental Violence: Impacts on Indigenous Women and Girls. In Indigenous Peoples' Rights and Unreported Struggles: Conflict and Peace. Institute for the Study of Human Rights, Columbia University (ed.). New York City, USA: Institute for the Study of Human Rights, Columbia University. https://doi.org/10.7916/D82R5095

Cederman, L.-E. and Weidmann, N.B. (2017). Predicting armed conflict: Time to adjust our expectations? Science 355(6324), 474-476. https://doi.org/doi:10.1126/science.aal4483

Chaachouay, N. and Zidane, L. (2024). Plant-Derived Natural Products: A Source for Drug Discovery and Development. Drugs and Drug Candidates 3(1), 184-207. https://doi.org/10.3390/ddc3010011

Chambers, C., Greve, R., Obase, T., Saito, F. and Abe-Ouchi, A. (2022). Mass loss of the Antarctic ice sheet until the year 3000 under a sustained late-21st-century climate. Journal of Glaciology 68(269), 605-617. https://www.cambridge.org/core/product/B3D2E5352C999C8702CB3ABDB28CAD75

Chen, L., Jiao, J., Liu, S., Liu, L. and Liu, P. (2023). Mapping the global, regional, and national burden of diarrheal diseases attributable to unsafe water. Frontiers in Public Health 11. https://doi.org/10.3389/fpubh.2023.1302748

Chuwah, C., van Noije, T., van Vuuren, D.P., Stehfest, E. and Hazeleger, W. (2015). Global impacts of surface ozone changes on crop yields and

land use. Atmospheric Environment 106, 11-23. https://doi.org/10.1016/j.atmosenv.2015.01.062

Clarke, L. Wei Y. M. De La Vega Navarro A. Garg A. Hahmann A. N. Khennas S. Azevedo I. M. L. Löschel A. Singh A. K. Steg L. Strbac G. and Wada, K. (2022) Energy systems. In IPCC 2022: Climate Change 2022:Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Shukla, P. R. Skea J. Slade R. Al Khourdajie A. van Diemen R. McCollum D. Pathak M. Some S. Vyas P. Fradera R. Belkacemi M. Hasija A. Lisboa G. Luz S. Malley, J. (eds.). Cambridge University Press, Cambridge, UK and New York, NY, USA. http://ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter06.pdf

Climate Policy Initiative (2024). The Cost of Inaction. https://www.climatepolicyinitiative.org/the-cost-of-inaction. Accessed 24 January 2024.

Cohen, J., Screen, J.A., Furtado, J.C., Barlow, M., Whittleston, D., Coumou, D. et al. (2014). Recent Arctic amplification and extreme mid-latitude weather. Nature Geoscience 7(9), 627-637. https://doi.org/10.1038/ngeo2234

Convention on Biological Diversity (2022). Decision Adopted by the Conference of The Parties to The Convention on Biological Diversity. CBD/COP/DEC/15/4. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf

Convention on Biological, D. (2024). NBSAPs Online Reorting Tool. https://ort.cbd.int/#0.4/0/0. Accessed 2 February 2024.

Cook, S.J., Jouvet, G., Millan, R., Rabatel, A., Zekollari, H. and Dussaillant, I. 2023. Committed ice loss in the European Alps until 2050 using a deep-learning-aided 3D ice-flow model with data assimilation. Geophysical Research Letters, 50(23), p.e2023GL105029.

Costanza, R., Groot, R.W.J.D., Sutton, P.C., Ploeg, S.V.D., Anderson, S.J., Kubiszewski, I. et al. (2014). Changes in the global value of ecosystem services. Global Environmental Change-human and Policy Dimensions 26, 152-158. https://doi.org/10.1016/j.gloenvcha.2014.04.002

Cruz, J., White, P.C.L., Bell, A. and Coventry, P.A. (2020). Effect of Extreme Weather Events on Mental Health: A Narrative Synthesis and Meta-Analysis for the UK. Int J Environ Res Public Health 17(22). https://doi.org/10.3390/ijerph17228581

Dainese, M., Martin, E.A., Aizen, M.A., Albrecht, M., Bartomeus, I., Bommarco, R. et al. (2019). A global synthesis reveals biodiversity-mediated benefits for crop production. Science Advances 5(10), eaax0121. https://doi.org/10.1126/sciadv.aax0121

DeConto, R.M., Pollard, D., Alley, R.B., Velicogna, I., Gasson, E., Gomez, N. et al. (2021). The Paris Climate Agreement and future sea-level rise from Antarctica. Nature 593(7857), 83-89. https://doi.org/10.1038/s41586-021-03427-0

de Graaf, I.E.M., Gleeson, T., van Beek, L.P.H., Sutanudjaja, E.H. and Bierkens, M.F.P. (2019). Environmental flow limits to global groundwater pumping. Nature 574(7776), 90-94. https://doi.org/10.1038/s41586-019-1594-4

Dellink, R., Chateau, J., Lanzi, E. and Magné, B. (2017). Long-term economic growth projections in the Shared Socioeconomic Pathways. Global Environmental Change 42 200-214. https://doi.org/10.1016/j.gloenvcha.2015.06.004

Diffenbaugh, N.S. and Burke, M. (2019). Global warming has increased global economic inequality. Proc Natl Acad Sci U S A 116(20), 9808-9813. https://doi.org/10.1073/pnas.1816020116

Ditlevsen, P. and Ditlevsen, S. (2023). Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. Nature Communications 14(1), 4254. https://doi.org/10.1038/s41467-023-39810-w

Fa, J.E., Watson, J.E., Leiper, I., Potapov, P., Evans, T.D., Burgess, N.D. et al. (2020). Importance of Indigenous Peoples' lands for the conservation of Intact Forest Landscapes. Frontiers in Ecology and the Environment 18(3), 135-140. https://doi.org/10.1002/fee.2148

Faizan, M.A., & Thakur, R. (2019). Association Between Solid Cooking Fuels and Respiratory Disease Across Socio-Demographic Groups in India. Journal of Health & Pollution 9(23), 190911. https://doi.org/10.5696/2156-9614-9.23.190911

Fernández-Llamazares, Á., Garteizgogeascoa, M., Basu, N., Brondizio, E.S., Cabeza, M., Martínez-Alier, J. et al. (2020). A State-of-the-Art Review of Indigenous Peoples and Environmental Pollution. Integrated Environmental Assessment and Management 16(3), 324-341. https://doi.org/10.1002/ieam.4239

Fernández-Llamazares, Á., Lepofsky, D., Lertzman, K., Armstrong, C.G., Brondizio, E.S., Gavin, M.C. et al. (2021). Scientists' Warning to Humanity on Threats to Indigenous and Local Knowledge Systems. Journal of Ethnobiology 41(2), 144-169, 126. https://doi.org/10.2993/0278-0771-41.2.144

Flores, B.M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R.A. et al. (2024). Critical transitions in the Amazon forest system. Nature 626(7999), 555-564. https://doi.org/10.1038/s41586-023-06970-0

Food and Agriculture Organization of the United Nations (2023). The State of Food and Agriculture 2023. Revealing the true cost of food to transform agrifood systems. Rome, Italy: FAO. https://doi.org/10.4060/cc7724en

Food and Agriculture Organization and Intergovernmental Technical Panel on Soils (2015). Status of the World's Soil Resources (SWSR)—Main Report. Rome, Italy: FAO and ITPS. http://www.fao.org/3/a-i5199e.pdf

Food and Agriculture Organization and United Nations Economic Commission for Europe (2023). Forest Products Annual Market Review 2021-2022. https://unece.org/sites/default/files/2023-02/2228765E_Inside_final_signa_red.pdf

Forster, P., T. Storelvmo, K. Armour, W. Collins, J.-L. Dufresne, D. Frame, D.J. Lunt, T. Mauritsen, M.D. Palmer, M. Watanabe, M. Wild, and H. Zhang (2021). The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [(eds.)]. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (ed.). Cambridge, UK, and New York City, USA Cambridge University Press. https://doi.org/10.1017/9781009157896.009

Fu, B. and Zhang, J. (2024). Progress and challenges of Sustainable Development Goals (SDGs). Bulletin of Chinese Academy of Sciences (Chinese Version) 39(2). https://doi.org/10.16418/j.issn.1000-3045.20240221004

Fuller, R., Landrigan, P.J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M. et al. (2022). Pollution and health: a progress update. The Lancet Planetary Health 6(6), e535-e547. https://doi.org/10.1016/S2542-5196(22)00090-0

Funk, C., Pedreros, D., Nicholson, S., Hoell, A., Korecha, D., Galu, G. et al. (2019). Examining the Potential Contributions of Extreme "Western V" Sea Surface Temperatures to the 2017 March–June East African Drought. Bulletin of the American Meteorological Society 100(1), S55-S60. https://doi.org/10.1175/BAMS-D-18-0108.1

Fuso Nerini, F., Tomei, J., To, L.S., Bisaga, I., Parikh, P., Black, M. et al. (2017). Mapping synergies and trade-offs between energy and the Sustainable Development Goals. Nature Energy 3(1), 10-15. https://doi.org/10.1038/s41560-017-0036-5

Galway, L.P., Esquega, E. and Jones-Casey, K. (2022). "Land is everything, land is us": Exploring the connections between climate change, land, and health in Fort William First Nation. Social Science & Medicine 294, 114700. https://doi.org/10.1016/j.socscimed.2022.114700

GLOBAÏA (2025). Planetary Tipping Systems. https://globaia.org/tipping

Goldstone, J.A., Bates, R.H., Epstein, D.L., Gurr, T.R., Lustik, M.B., Marshall, M.G. et al. (2010). A Global Model for Forecasting Political Instability. American Journal of Political Science 54(1), 190-208. https://doi.org/10.1111/j.1540-5907.2009.00426.x

González, R. (2024). Left in Dust. Communities living near mine wastes breathe air laden with potentially toxic dust. Health effects are now emerging. Science. https://www.science.org/content/article/mine-waste-contaminates-air-potentially-toxic-dust-threatening-nearby-communities Accessed 24 April 2025.

Green, H., Bailey, J., Schwarz, L., Vanos, J., Ebi, K. and Benmarhnia, T. (2019). Impact of heat on mortality and morbidity in low and middle income countries: A review of the epidemiological evidence and considerations for future research. Environ Res 171, 80-91. https://doi.org/10.1016/j.envres.2019.01.010

Haagsma, J.A., James, S.L., Castle, C.D., Dingels, Z.V., Fox, J.T., Hamilton, E.B. et al. (2020). Burden of injury along the development spectrum: associations between the Socio-demographic Index and disability-adjusted life year estimates from the Global Burden of Disease Study 2017. Injury Prevention 26(Suppl 2), i12. https://doi.org/10.1136/injuryprev-2019-043296

Hall, G.H. and Patrinos, H.A. (2012). Indigenous Peoples, Poverty, and Development. Cambridge, UK: Cambridge University Press. https://www.cambridge.org/bo/universitypress/subjects/economics/economic-development-and-growth/indigenous-peoples-poverty-and-development?format=HB&isbn=9781107020573

Hallegatte, S. and Rozenberg, J. (2017). Climate change through a poverty lens. Nature Climate Change 7(4), 250-256. https://doi.org/10.1038/nclimate3253

Hanna, E., Topál, D., Box, J.E., Buzzard, S., Christie, F.D.W., Hvidberg, C. et al. (2024). Short- and long-term variability of the Antarctic and Greenland ice sheets. Nature Reviews Earth & Environment 5(3), 193-210. https://doi.org/10.1038/s43017-023-00509-7

Hansen, J.E., Sato, M., Simons, L., Nazarenko, L.S., Sangha, I., Kharecha, P. et al. (2023). Global warming in the pipeline. Oxford Open Climate Change 3(1), kgad008. https://doi.org/10.1093/oxfclm/kgad008

Harrison, S., Kargel, J.S., Huggel, C., Reynolds, J., Shugar, D.H., Betts, R.A. et al. (2018). Climate change and the global pattern of moraine-dammed glacial lake outburst floods. The Cryosphere 12(4), 1195-1209. https://tc.copernicus.org/articles/12/1195/2018/

Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B.L., Doelman, J.C. et al. (2018). Risk of increased food insecurity under stringent global climate change mitigation policy. Nature Climate Change 8(8), 699-703. https://doi.org/10.1038/s41558-018-0230-x

Hasegawa, T., Sakurai, G., Fujimori, S., Takahashi, K., Hijioka, Y. and Masui, T. (2021). Extreme climate events increase risk of global food insecurity and adaptation needs. Nat Food 2(8), 587-595. https://doi.org/10.1038/s43016-021-00335-4

Hegre, H., Karlsen, J., Nygård, H.M., Strand, H. and Urdal, H. (2013). Predicting Armed Conflict 2010–20501. International Studies Quarterly 57(2), 250-270. https://doi.org/10.1111/isqu.12007

Hegre, H., Nygård, H.M. and Landsverk, P. (2021). Can We Predict Armed Conflict? How the First 9 Years of Published Forecasts Stand Up to Reality. International Studies Quarterly 65(3), 660-668. https://doi.org/10.1093/isq/sqaa094

Heltberg, R., Oviedo, A.M. and Talukdar, F. (2015). What do Household Surveys Really Tell Us about Risk, Shocks, and Risk Management in the Developing World? The Journal of Development Studies 51(3) 209-225. https://doi.org/10.1080/00220388.2014.959934

Hertel, T.W., Burke, M.B. and Lobell, D.B. (2010). The poverty implications of climate-induced crop yield changes by 2030. Global Environmental Change 20(4), 577-585. https://doi.org/10.1016/j.gloenvcha.2010.07.001

Hoffman, K.M., Davis, E.L., Wickham, S.B., Schang, K., Johnson, A., Larking, T. et al. (2021). Conservation of Earth's biodiversity is embedded in Indigenous fire stewardship. Proc Natl Acad Sci U S A 118(32). https://doi.org/10.1073/pnas.2105073118

Howard, P.H. and Sterner, T. (2017). Few and Not So Far Between: A Meta-analysis of Climate Damage Estimates. Environmental and Resource Economics 68(1), 197-225. https://doi.org/10.1007/s10640-017-0166-z

Hughes, B. B., Joshi, D. K., Moyer, J. D., Sisk, T. D., & Solorzano, J. R. (2014). PPHP 5: Strengthening Governance Globally: Forecasting the next 50 years (Vol. 5). Pardee Center for International Futures, University of Denver; Paradigm; Oxford University Press. https://korbel.du.edu/sites/default/files/2021-12/PPHP5%20Full%20Volume.pdf

Incayawar, M. and Maldonado-Bouchard, S. (2009). The forsaken mental health of the Indigenous Peoples - a moral case of outrageous exclusion in Latin America. BMC Int Health Hum Rights 9, 27. https://doi.org/10.1186/1472-698x-9-27

IK & LK Dialogues (2025). Indigenous Knowledge and Local Knowledge Dialogues. Global Environment Outlook 7. Mexico City: CopIt-arXives https://copitarxives.fisica.unam.mx/SC0011EN/SC0011EN.php

Intergovernmental Panel on Climate Change (2018). Global Warming of 1.5°C.An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. https://www.ipcc.ch/sr15/

Intergovernmental Panel on Climate Change (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. H.-O. Pörtner, D.C.R., V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (ed.). Cambridge, UK, and New York City, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157964

Intergovernmental Panel on Climate Change (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B. (ed.). Cambridge, UK, and New York City, USA: Cambridge University Press. https://doi.org/10.1017/9781009157896

Intergovernmental Panel on Climate Change (2022a). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926

Intergovernmental Panel on Climate Change (2022b). Climate Change 2022: Impacts, adaptation and vulnerability. Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Rama, B. (ed.). Cambridge, UK, and New York City, USA: Cambridge University Press. https://doi.org/10.1017/9781009325844

Intergovernmental Panel on Climate Change (2022c). Land degradation. In Climate Change and Land: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Intergovernmental Panel on Climate Change (ed.). Cambridge, UK: Cambridge University Press. https://www.cambridge.org/core/product/47C1BEABC8A0A7C4E08B5AB6DD4C20CE

Intergovernmental Panel on Climate Change (2023a). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Lee, H., Romero, J. (ed.). Geneva, Switzerland: Intergovernmental Panel on Climate Change. https://doi.org/10.59327/IPCC/AR6-9789291691647

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Brondizio, E.S., Settele, J., Díaz, S., Ngo, H.T. (ed.). Bonn, Germany: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services Secretariat. https://www.ipbes.net/node/35274

International Energy Agency (2023). Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach. Paris, France: IEA. https://iea.blob.core.windows.net/assets/9a698da4-4002-4e53-8ef3-631d8971bf84/NetZeroRoadmap_AGlobalPathwaytoKeepthe1.5CGoalinReach-2023Update.pdf

International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, World Bank, World Health Organization, (2024). Tracking SDG 7: The Energy Progress Report 2024. Washington D.C., USA: World Bank. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Jun/IRENA_Tracking_SDG7_energy_progress_2024.pdf

International Institute for Applied Systems Analysis (2019). Global emission fields of air pollutants and GHGs. https://iiasa.ac.at/models-tools-data/global-emission-fields-of-air-pollutants-and-ghgs. Accessed 19 October 2024

International Labour Organization (2019). Working on a warmer planet: The impact of heat stress on labour productivity and decent work. Geneva, Switzerland: International Labour Office. https://www.ilo.org/sites/

default/files/wcmsp5/groups/public/@dgreports/@dcomm/@publ/documents/publication/wcms_711919.pdf

International Renewable Energy Agency (2017). Stranded assets and renewables: how the energy transition affects the value of energy reserves, buildings and capital stock. Abu Dhabi, UAE: International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Jul/IRENA_REmap_Stranded_assets_and_renewables_2017.pdf?rev=169eb7d8d20e42baadf8a96a8dc91880

Jafino, B.A., Walsh, B., Rozenberg, J. and Hallegatte, S. (2020). Revised estimates of the impact of climate change on extreme poverty by 2030. World Bank Working Paper. Washington, D.C.. https://openknowledge.worldbank.org/handle/10986/34555

Jägermeyr, J., Müller, C., Ruane, A.C., Elliott, J., Balkovic, J., Castillo, O. et al. (2021). Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. Nature Food 2(11), 873-885. https://doi.org/10.1038/s43016-021-00400-y

Jaureguiberry, P., Titeux, N., Wiemers, M., Bowler, D.E., Coscieme, L., Golden, A.S. et al. (2022). The direct drivers of recent global anthropogenic biodiversity loss. Science Advances 8(45), eabm9982. https://doi.org/10.1126/sciadv.abm9982

Jessel, S., Sawyer, S. and Hernandez, D. (2019). Energy, Poverty, and Health in Climate Change: A Comprehensive Review of an Emerging Literature. Front Public Health 7, 357. https://doi.org/10.3389/fpubh.2019.00357

Jiang, L. and O'Neill, B.C. (2017). Global urbanization projections for the Shared Socioeconomic Pathways. Global Environmental Change 42, 193-199. https://doi.org/10.1016/j.gloenvcha.2015.03.008

Johnson, J.A., Baldos, U., Hertel, T., Liu, J., Nootenboom, C., Polasky, S., and Roxburgh, T. (2020). Global Futures: modelling the global economic impacts of environmental change to support policy-making. https://files.worldwildlife.org/wwfcmsprod/files/Publication/file/75p5cvk0ul_Summary_Report.pdf

Johnson, J.A., Ruta G., Baldos, U., Cervigni, R., Chonabayashi, S., Corong, E., Gavryliuk, O., Gerber, J., Hertel, T., Nootenboom, C., Polasky, S., Gerber, J., Ruta, G., Polasky, S., (2021). The Economic Case for Nature: A Global Earth-Economy Model to Assess Development Policy Pathways. Washington, D.C., USA. https://hdl.handle.net/10986/35882

Kalkuhl, M. and Wenz, L. (2020). The impact of climate conditions on economic production. Evidence from a global panel of regions. Journal of Environmental Economics and Management 103, 102360. https://doi.org/10.1016/j.jeem.2020.102360

Kayser, G.L., Rao, N., Jose, R. and Raj, A. (2019). Water, sanitation and hygiene: measuring gender equality and empowerment. Bull World Health Organ 97(6), 438-440. https://doi.org/10.2471/blt.18.223305

KC, S. and Lutz, W. (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Global Environmental Change 42, 181-192. https://doi.org/10.1016/j.gloenvcha.2014.06.004

Kirmayer, L.J., Brass, G.M. and Tait, C.L. (2000). The mental health of Aboriginal peoples: transformations of identity and community. Can J Psychiatry 45(7), 607-616. https://doi.org/10.1177/070674370004500702

Kok, M., Marques, A., Bakkenes, M., Doelman, J., Hilbers, J., Immerzeel, R., Krüger, C., & Schipper, A. (2024). A prospective evaluation of the ambition of the Kunming-Montreal Global Biodiversity Framework: A contribution to the CBD review process. The Hague, the Netherlands: PBL Netherlands Environmental Assessment Agency. https://www.pbl.nl/downloads/pbl-2024-policy-brief-cop-16-5361pdf

Kok, M.T.J., Meijer, J.R., van Zeist, W.-J., Hilbers, J.P., Immovilli, M., Janse, J.H. et al. (2023). Assessing ambitious nature conservation strategies in a below 2-degree and food-secure world. Biological Conservation 284, 110068. https://doi.org/10.1016/j.biocon.2023.110068

Krause, A., Pugh, T.A.M., Bayer, A.D., Li, W., Leung, F., Bondeau, A. et al. (2018). Large uncertainty in carbon uptake potential of land-based climate-change mitigation efforts. Global Change Biology 24(7), 3025-3038. https://doi.org/10.1111/gcb.14144

Kuhn, R., Rothman, D.S., Turner, S., Solórzano, J. and Hughes, B. (2016). Beyond Attributable Burden: Estimating the Avoidable Burden of Disease Associated with Household Air Pollution. PLOS ONE 11(3), e0149669. https://doi.org/10.1371/journal.pone.0149669

Lapola, D.M., Pinho, P., Quesada, C.A., Strassburg, B.B.N., Rammig, A., Kruijt, B. et al. (2018). Limiting the high impacts of Amazon forest dieback with no-regrets science and policy action. Proceedings of the National Academy of Sciences 115(46), 11671-11679. https://doi.org/10.1073/pnas.172177011

Layne, D. (2017). Impacts of Climate Change on Tourism in the Coastal and Marine Environments of Caribbean Small Island Developing States (SIDS), Caribbean Marine Climate Change Report Card: Science Review. Science Review 2017 174-184. https://assets.publishing.service.gov.uk/media/5a82a85840f0b6230269c051/12._Tourism.pdf

Lenton, T.M. (2013). Environmental Tipping Points. Annual Review of Environment and Resources 38(Volume 38 2013), 1-29. https://doi.org/10.1146/annurev-environ-102511-084654

Lenton, T.M., Armstrong McKay, D.I., Loriani, S., Abrams, J. F., Lade, S. J., Donges, J. F. et al. (2023). The Global Tipping Points Report 2023. Exeter, UK. https://pure.iiasa.ac.at/id/eprint/19228/1/GTP-Full-Document.pdf

Lenton, T.M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W. et al. (2019). Climate tipping points — too risky to bet against. Nature 575, 592-595. https://doi.org/10.1038/d41586-019-03595-0

Li, D., Lu, X., Walling, D.E., Zhang, T., Steiner, J.F., Wasson, R.J. et al. (2022). High Mountain Asia hydropower systems threatened by climate-driven landscape instability. Nature Geoscience 15(7), 520-530. https://doi.org/10.1038/s41561-022-00953-y

Liu, W., Liu, X., Yang, H., Ciais, P. and Wada, Y. (2022). Global Water Scarcity Assessment Incorporating Green Water in Crop Production. Water Resources Research 58(1), e2020WR028570. https://doi.org/10.1029/2020WR028570

Lucas, P.L., Hilderink, H.B.M., Janssen, P.H.M., Kc, S., van Vuuren, D.P. and Niessen, L. (2019). Future impacts of environmental factors on achieving the SDG target on child mortality—A synergistic assessment. Global Environmental Change 57, 101925. https://doi.org/10.1016/j.gloenvcha.2019.05.009

Ma, Q., Shi, X., Scholz, P., Sidorenko, D., Lohmann, G. and Ionita, M. (2024). Revisiting climate impacts of an AMOC slowdown: dependence on freshwater locations in the North Atlantic. Science Advances 10(47), eadr3243. https://doi.org/10.1126/sciadv.adr3243

Mach, K.J., Kraan, C.M., Adger, W.N., Buhaug, H., Burke, M., Fearon, J.D. et al. (2019). Climate as a risk factor for armed conflict. Nature 571(7764), 193-197. https://doi.org/10.1038/s41586-019-1300-6

Magney, T.S. and Pierrat, Z.A. (2025). Shifting equilibria in a warming boreal forest. Proceedings of the National Academy of Sciences 122(3), e2424669122. https://doi.org/10.1073/pnas.2424669122

Malekpour, S., Allen, C., Sagar, A., Scholz, I., Persson, Å., Miranda, J. J., Bennich, T., Dube, O. P., Kanie, N., Madise, N., Shackell, N., Montoya, J. C., Pan, J., Hathie, I., Bobylev, S. N., Agard, J., & Al-Ghanim, K. (2023). What scientists need to do to accelerate progress on the SDGs. Nature, 621(7978), 250-254. https://doi.org/10.1038/d41586-023-02808-x. Accessed 24 April 2025

Marley, J., Desai, H. (2020). Fragility and Agenda 2030: Navigating shocks and pressures in fragile contexts. OECD Development Co-operation Working Papers(82). https://doi.org/10.1787/65d5cb9c-en

Martin, W.J., II, Hollingsworth, J. W., & Ramanathan, V. (2014). Household air pollution from cookstoves: Impacts on health and climate. In Global climate change and public health Pinkerton, K.E. and Rom, W.N. (ed.). New York City, USA: Springer Science+Business Media. https://doi.org/10.1007/978-1-4614-8417-2_13

Matthews, V., Vine, K., Atkinson, A.R., Longman, J., Lee, G.W., Vardoulakis, S. et al. (2023). Justice, culture, and relationships: Australian Indigenous prescription for planetary health. Science 381(6658), 636-641. https://doi.org/10.1126/science.adh9949

McPherson, G.R., Sirmacek, B.K., Massa, J.R., Kallfelz, W. and Vinuesa, R. (2023). The commonly overlooked environmental tipping points. Results in Engineering 18, 101118. https://doi.org/10.1016/j.rineng.2023.101118

Meccia, V.L., Simolo, C., Bellomo, K. and Corti, S. (2025). The impact of a weakened AMOC on European heatwaves. Environmental Research Letters 20(2), 024005. https://dx.doi.org/10.1088/1748-9326/ada3e7

Mendelsohn, R., Dinar, A., & Williams, L. (2006). The distributional impact of climate change on rich and poor countries. Environment and Development Economics 11(2), 159–178. https://doi.org/10.1017/S1355770X05002755

Middleton, J., Cunsolo, A., Jones-Bitton, A., Wright, C.J. and Harper, S.L. (2020). Indigenous mental health in a changing climate: a systematic scoping review of the global literature. Environmental Research Letters 15(5), 053001. https://doi.org/10.1088/1748-9326/ab68a9

Millar, C.I. and Stephenson, N.L. (2015). Temperate forest health in an era of emerging megadisturbance. Science 349(6250), 823-826. https://doi.org/10.1126/science.aaa9933

Miner, K.R., Turetsky, M.R., Malina, E., Bartsch, A., Tamminen, J., McGuire, A.D. et al. (2022). Permafrost carbon emissions in a changing Arctic. Nature Reviews Earth & Environment 3(1), 55-67. https://doi.org/10.1038/s43017-021-00230-3

Mistry, J., Bilbao, B.A. and Berardi, A. (2016). Community owned solutions for fire management in tropical ecosystems: case studies from Indigenous communities of South America. Philosophical Transactions of the Royal Society B: Biological Sciences 371(1696) 20150174. https://doi.org/10.1098/rstb.2015.0174

Moyer, J.D. (2024). A double-edged sword into a plowshare: Analyzing geopolitical implications of alternative socioeconomic development pathways. One Earth 7(2), 336-347. https://doi.org/10.1016/j.oneear.2024.01.002

Moyer, J.D. and Hedden, S. (2020). Are we on the right path to achieve the sustainable development goals? World Development 127, 104749. https://doi.org/10.1016/j.worlddev.2019.104749

Moyer, J.D., Pirzadeh, A., Irfan, M., Solórzano, J., Stone, B., Xiong, Y. et al. (2023). How many people will live in poverty because of climate change? A macro-level projection analysis to 2070. Climatic Change 176(10). https://doi.org/10.1007/s10584-023-03611-3

Moyer, J.D., Verhagen, W., Mapes, B., Bohl, D.K., Xiong, Y., Yang, V. et al. (2022). How many people is the COVID-19 pandemic pushing into poverty? A long-term forecast to 2050 with alternative scenarios. PLOS ONE 17(7), e0270846. https://doi.org/10.1371/journal.pone.0270846.

Muhammad, A., Seale, J. L., Meade, B., & Regmi, A. (2011). International evidence on food consumption patterns: an update using 2005 international comparison program data. TB-1929. U.S. Dept. of Agriculture, Econ. Res. Serv. March 2011. Revised February 2013. https://www.ers.usda.gov/webdocs/publications/47579/7637_tb1929.pdf?v=8728.3

Mutton, H., Chadwick, R., Collins, M., Lambert, F.H., Taylor, C.M., Geen, R. et al. (2024). The impact of a uniform ocean warming on the West African monsoon. Climate Dynamics 62(1), 103-122. https://doi.org/10.1007/s00382-023-06898-1

Nath, D., Nath, R. and Chen, W. (2024). Faster dieback of rainforests altering tropical carbon sinks under climate change. npj Climate and Atmospheric Science 7(1), 235. https://doi.org/10.1038/s41612-024-00793-0

National Snow and Ice Data Center (2024). Why it Matters. https://nsidc.org/learn/parts-cryosphere/sea-ice/why-sea-ice-matters. Accessed 23 October 2024.

Naughten, K.A., Holland, P.R. and De Rydt, J. (2023). Unavoidable future increase in West Antarctic ice-shelf melting over the twenty-first century. Nature Climate Change 13(11), 1222-1228. https://doi.org/10.1038/s41558-023-01818-x

Nelson, S.E. and Wilson, K. (2017). The mental health of Indigenous peoples in Canada: A critical review of research. Soc Sci Med 176, 93-112. https://doi.org/10.1016/j.socscimed.2017.01.021

Ninomiya, M.E.M., Burns, N., Pollock, N.J., Green, N.T.G., Martin, J., Linton, J. et al. (2023). Indigenous communities and the mental health impacts of land dispossession related to industrial resource development: a systematic review. The Lancet Planetary Health 7(6), e501-e517. https://doi.org/10.1016/S2542-5196(23)00079-7

Nkuba, M.R., Chanda, R., Mmopelwa, G., Mangheni, M.N., Lesolle, D. and Kato, E. (2020). Indigenous Knowledge Systems and Indicators of Rain: Evidence from Rwenzori Region, Western Uganda. Weather, Climate, and Society 12(2), 213-234. https://doi.org/10.1175/WCAS-D-19-0027.1

Norton-Smith, K., Lynn, K., Chief, K., Cozzetto, K., Donatuto, J., Hiza Redsteer, M. et al. (2016). Climate change and indigenous peoples: a synthesis of current impacts and experiences. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. http://dx.doi.org/10.2737/PNW-GTR-944

Nounkeu, C.D. and Dharod, J.M. (2021). Integrated Approach in Addressing Undernutrition in Developing Countries: A Scoping Review of Integrated Water Access, Sanitation, and Hygiene (WASH) + Nutrition Interventions. Current Developments in Nutrition 5(7). https://doi.org/10.1093/cdn/nzab087

O'Bryan, C.J., Garnett, S.T., Fa, J.E., Leiper, I., Rehbein, J.A., Fernández-Llamazares, Á., Jackson, M.V., Jonas, H.D., Brondizio, E.S., Burgess, N.D., Robinson, C.J., Zander, K.K., Molnár, Z., Venter, O. and Watson, J.E.M. (2021), The importance of Indigenous Peoples' lands for the conservation of terrestrial mammals. Conservation Biology, 35: 1002-1008. https://doi.org/10.1111/cobi.13620

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S. et al. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change 42, 169-180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

Ogar, E., Pecl, G. and Mustonen, T. (2020). Science Must Embrace Traditional and Indigenous Knowledge to Solve Our Biodiversity Crisis. One Earth 3(2), 162-165. https://doi.org/10.1016/j.oneear.2020.07.006

Organisation for Economic Co-operation and Development (2016). The Economic Consequences of Outdoor Air Pollution. OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264257474-en

Organisation for Economic Co-operation and Development (2019). Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences. Paris, France. https://doi.org/10.1787/9789264307452-en

Orr, B.J., A.L. Cowie, V.M. Castillo Sanchez, P. Chasek, N.D. Crossman, A. Erlewein, G. Louwagie, M. Maron, G.I. Metternicht, S. Minelli, A.E. Tengberg, S. Walter, and S. Welton (2017) Scientific Conceptual Framework for Land Degradation Neutrality. A Report of the Science-Policy Interface. United Nations Convention to Combat Desertification (UNCCD), Bonn, Germany. https://www.unccd.int/sites/default/files/documents/2017-08/LDN_CF_report_web-english.pdf

Otosaka, I.N., Shepherd, A., Ivins, E.R., Schlegel, N.J., Amory, C., van den Broeke, M.R. et al. (2023). Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. Earth Syst. Sci. Data 15(4), 1597-1616. https://doi.org/10.5194/essd-15-1597-2023

Pacetti, T., Caporali, E. and Rulli, M.C. (2017). Floods and food security: A method to estimate the effect of inundation on crops availability. Advances in Water Resources 110, 494-504. https://doi.org/10.1016/j.advwatres.2017.06.019

Page, I.S., Ferrari, A.J., Slade, T., Anderson, M., Santomauro, D. and Diminic, S. (2022). Estimating the difference in prevalence of common mental disorder diagnoses for Aboriginal and Torres Strait Islander peoples compared to the general Australian population. Epidemiol Psychiatr Sci 31, e44. https://doi.org/10.1017/s2045796022000233

Page, I.S., Ferrari, A.J., Slade, T., Anderson, M., Santomauro, D. and Diminic, S. (2022). Estimating the difference in prevalence of common mental disorder diagnoses for Aboriginal and Torres Strait Islander peoples compared to the general Australian population. Epidemiol Psychiatr Sci 31, e44. https://doi.org/10.1017/S2045796022000233

Paglialunga, E., Coveri, A. and Zanfei, A. (2022). Climate change and within-country inequality: New evidence from a global perspective. World Development 159, 106030. https://doi.org/10.1016/j.worlddev.2022.106030

Palacios-Abrantes, J., Frolicher, T.L., Reygondeau, G., Sumaila, U.R., Tagliabue, A., Wabnitz, C.C.C. et al. (2022). Timing and magnitude of climate-driven range shifts in transboundary fish stocks challenge their management. Glob Chang Biol 28(7), 2312-2326. https://doi.org/10.1111/gcb.16058

Panteli, M. and Mancarella, P. (2015). Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies. Electric Power Systems Research 127, 259-270. https://doi.org/10.1016/j.epsr.2015.06.012

Pearce-Kelly, P., Altieri, A.H., Bruno, J.F., Cornwall, C.E., McField, M., Muñiz-Castillo, A.I. et al. (2025). Considerations for determining warm-water

coral reef tipping points. Earth Syst. Dynam. 16(1), 275-292. https://doi.org/10.5194/esd-16-275-2025

Pereira, H.M., Martins, I.S., Rosa, I.M.D., Kim, H., Leadley, P., Popp, A. et al. (2024). Global trends and scenarios for terrestrial biodiversity and ecosystem services from 1900 to 2050. Science 384(6694), 458-465. https://doi.org/10.1126/science.adn3441

Pesantes, M.A., Bazán Macera, M., Mercier, S. and Katic, P.G. (2024). Healthy food, unhealthy food: Indigenous perspectives on the nutrition transition. Glob Public Health 19(1), 2329210. https://doi.org/10.1080/17441692.2024.2329210

Piontek, F., Drouet, L., Emmerling, J., Kompas, T., Méjean, A., Otto, C. et al. (2021). Integrated perspective on translating biophysical to economic impacts of climate change. Nature Climate Change 11(7), 563-572. https://doi.org/10.1038/s41558-021-01065-y

Popp A, Calvin K, Fujimori S, Havlik P, Humpenöder F, Stehfest E, Bodirsky BL, Dietrich JP, Doelmann JC, Gusti M. (2017). Land-use futures in the shared socio-economic pathways. Global Environmental Change 42: 331–345. https://www.pbl.nl/en/publications/the-global-potential-for-land-restoration-scenarios-for-the-global-land-outlook-2

Potter, E., Fyffe, C., Orr, A., Quincey, D., Ross, A., Rangecroft, S. et al. (2023). A future of extreme precipitation and droughts in the Peruvian Andes. npj Climate and Atmospheric Science 6. http://dx.doi.org/10.1038/s41612-023-00409-z

Pouramin, P., Nagabhatla, N. and Miletto, M. (2020). A Systematic Review of Water and Gender Interlinkages: Assessing the Intersection With Health. Frontiers in Water 2. https://doi.org/10.3389/frwa.2020.00006

Pratiti, R., Vadala, D., Kalynych, Z. and Sud, P. (2020). Health effects of household air pollution related to biomass cook stoves in resource limited countries and its mitigation by improved cookstoves. Environ Res 186, 109574. https://doi.org/10.1016/j.envres.2020.109574

Previdi, M., Smith, K.L. and Polvani, L.M. (2021). Arctic amplification of climate change: a review of underlying mechanisms. Environmental Research Letters 16(9), 093003. https://doi.org/10.1088/1748-9326/ac1c29

Prüss-Ustün, A., Bartram, J., Clasen, T., Colford Jr, J.M., Cumming, O., Curtis, V. et al. (2014). Burden of disease from inadequate water, sanitation and hygiene in low- and middle-income settings: a retrospective analysis of data from 145 countries. Tropical Medicine & International Health 19(8), 894-905. https://doi.org/10.1111/tmi.12329

Prüss-Ustün, A., Wolf, J., Bartram, J., Clasen, T., Cumming, O., Freeman, M.C. et al. (2019). Burden of disease from inadequate water, sanitation and hygiene for selected adverse health outcomes: An updated analysis with a focus on low- and middle-income countries. Int J Hyg Environ Health 222(5), 765-777. https://doi.org/10.1016/j.ijheh.2019.05.004

Rahman, M.S. and Di, L. (2020). A Systematic Review on Case Studies of Remote-Sensing-Based Flood Crop Loss Assessment. Agriculture 10(4). https://doi.org/10.3390/agriculture10040131

Rao, N.D. and Min, J. (2018). Decent Living Standards: Material Prerequisites for Human Wellbeing. Social Indicators Research 138(1), 225-244. https://doi.org/10.1007/s11205-017-1650-0

Rao, M.P., Davi, N.K., Magney, T.S., Andreu-Hayles, L., Nachin, B., Suran, B. et al. (2023). Approaching a thermal tipping point in the Eurasian boreal forest at its southern margin. Communications Earth & Environment 4(1), 247. https://doi.org/10.1038/s43247-023-00910-6

Ram A., L. and Shahzar, E. (2024) Land, loss and liberation: Indigenous struggles amid the climate crisis. World Economic Forum. https://www.weforum.org/stories/2024/02/indigenous-challenges-displacement-climate-change/. Accessed 24 April 2025.

Rataj, E., Kunzweiler, K. and Garthus-Niegel, S. (2016). Extreme weather events in developing countries and related injuries and mental health disorders - a systematic review. BMC Public Health 16(1), 1020. https://doi.org/10.1186/s12889-016-3692-7

Redvers, J. (2020). "The land is a healer": Perspectives on land-based healing from Indigenous practitioners in northern Canada. International Journal of Indigenous Health 15(1), 90-107. https://doi.org/10.32799/ijih.v15i1.34046

Redvers, N., Aubrey, P., Celidwen, Y. and Hill, K. (2023). Indigenous Peoples: Traditional knowledges, climate change, and health. PLOS Global Public Health 3(10), e0002474. https://doi.org/10.1371/journal.pgph.0002474

Reyes-García, V., García-del-Amo, D., Álvarez-Fernández, S., Benyei, P., Calvet-Mir, L., Junqueira, A.B. et al. (2024). Indigenous Peoples and local communities report ongoing and widespread climate change impacts on local social-ecological systems. Communications Earth & Environment 5(1), 29. https://doi.org/10.1038/s43247-023-01164-y

Rhoades, O.K., Brandt, M. and Witman, J.D. (2023). La Niña-related coral death triggers biodiversity loss of associated communities in the Galápagos. Marine Ecology 44(5), e12767. https://doi.org/10.1111/maec.12767

Rimi, R.H., Haustein, K., Allen, M.R. and Barbour, E.J. (2019). Risks of Pre-Monsoon Extreme Rainfall Events of Bangladesh: Is Anthropogenic Climate Change Playing a Role? Bulletin of the American Meteorological Society 100(1), S61-S65. https://doi.org/10.1175/BAMS-D-18-0152.1

Rocklov, J. and Dubrow, R. (2020). Climate change: an enduring challenge for vector-borne disease prevention and control. Nat Immunol 21(5), 479-483. https://doi.org/10.1038/s41590-020-0648-y

Romanello, M., Napoli, C.d., Green, C., Kennard, H., Lampard, P., Scamman, D. et al. (2023). The 2023 report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. The Lancet 402(10419), 2346-2394. https://doi.org/10.1016/S0140-6736(23)01859-7

Rose, S., Diaz, D., Carleton, T., Drouet, L., Guivarch, C., Méjean, A. and Piontek, F. (2022). Cross-Working Group Box ECONOMIC | Estimating Global Economic Impacts from Climate Change. In Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A. and Rama, B. (ed.). Cambridge, UK, and New York City, NY, USA: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_CCB-CWGB_Compilation.pdf

Rounce, D.R., Hock, R., Maussion, F., Hugonnet, R., Kochtitzky, W., Huss, M. et al. (2023). Global glacier change in the 21st century: Every increase in temperature matters. Science 379(6627), 78-83. https://doi.org/10.1126/science.abo1324

Sachs, J.D., Lafortune, G. and Fuller, G. (2024). The SDGs and the UN Summit of the Future. Sustainable Development Report 2024. Dublin: Dublin University Press. https://doi.org/10.25546/108572

Savo, V., Lepofsky, D., Benner, J.P., Kohfeld, K.E., Bailey, J. and Lertzman, K. (2016). Observations of climate change among subsistence-oriented communities around the world. Nature Climate Change 6(5), 462-473. https://doi.org/10.1038/nclimate2958

Schipper, E.L.F., Tanner, T., Dube, O.P., Adams, K.M. and Huq, S. (2020). The debate: Is global development adapting to climate change? World Development Perspectives 18, 100205. https://doi.org/10.1016/j.wdp.2020.100205

Shugar, D.H., Jacquemart, M., Shean, D., Bhushan, S., Upadhyay, K., Sattar, A. et al. (2021). A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. Science 373(6552), 300-306. https://doi.org/10.1126/science.abh4455

Schuur, E.A., McGuire, A.D., Schädel, C., Grosse, G., Harden, J.W., Hayes, D.J. et al. (2015). Climate change and the permafrost carbon feedback. Nature 520(7546), 171-179. https://doi.org/10.1038/nature14338

Secretariat of the Convention on Biological Diversity (2020). Global Biodiversity Outlook 5 Montreal, Canada: Secretariat of the Convention on Biological Diversity. https://www.cbd.int/gbo/gbo5/publication/gbo-5-en.pdf

Seitzinger, S. P., et al. (2010), Global river nutrient export: A scenario analysis of past and future trends, Global Biogeochem. Cycles, 24, GB0A08. https://doi.org/10.1029/2009GB003587

Sellers, S. (2020). Cause of death variation under the shared socioeconomic pathways. Climatic Change 163(1), 559-577. https://doi.org/10.1007/s10584-020-02824-0

Sen, K.K., Karmaker, S.C., Hosan, S., Chapman, A.J. and Saha, B.B. (2023). Thinking of the children: Energy poverty and acute respiratory

infections among young children in South Asia. Energy Research & Social Science 105, 103271. https://doi.org/10.1016/j.erss.2023.103271

Seppelt, R., Arndt, C., Beckmann, M., Martin, E.A. and Hertel, T.W. (2020). Deciphering the Biodiversity–Production Mutualism in the Global Food Security Debate. Trends in Ecology & Evolution 35(11), 1011-1020. https://doi.org/10.1016/j.tree.2020.06.012

Seth, A., Giannini, A., Rojas, M., Rauscher, S., Bordoni, S., Singh, D. et al. (2019). Monsoon Responses to Climate Changes—Connecting Past, Present and Future. Current Climate Change Reports 5. https://doi.org/10.1007/s40641-019-00125-y

Sewell, A., van der Esch, S. and Löwenhardt, H. (2020). Goals and Commitments for the Restoration Decade A global overview of countries' restoration commitments under the Rio Conventions and other pledges. The Hague, the Netherlands: PBL Netherlands Environmental Assessment Agency. https://www.pbl.nl/uploads/default/downloads/pbl-2020-goals-and-commitments-for-the-restoration-decade-3906.pdf

Shugar, D.H., Jacquemart, M., Shean, D., Bhushan, S., Upadhyay, K., Sattar, A. et al. (2021). A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. Science 373(6552), 300-306. https://doi.org/10.1126/science.abh4455

Solé, R. and Levin, S. (2022). Ecological complexity and the biosphere: the next 30 years. Philosophical Transactions of the Royal Society B: Biological Sciences 377(1857) 20210376. https://doi.org/10.1098/rstb.2021.0376

Springmann, M., Mason-D'Croz, D., Robinson, S., Garnett, T., Godfray, H.C., Gollin, D. et al. (2016). Global and regional health effects of future food production under climate change: a modelling study. Lancet 387(10031), 1937-1946. https://doi.org/10.1016/S0140-6736(15)01156-3

Stroeve, J.C., Serreze, M.C., Holland, M.M., Kay, J.E., Malanik, J. and Barrett, A.P. (2012). The Arctic's rapidly shrinking sea ice cover: a research synthesis. Climatic Change 110(3), 1005-1027. https://doi.org/10.1007/s10584-011-0101-1

Subica, A.M., Soakai, L., Tukumoeatu, A., Johnson, T. and Aitaoto, N. (2024). Trauma and mental health in Pacific Islanders. Int J Soc Psychiatry 70(5), 861-873. https://doi.org/10.1177/00207640241236109

Takakura, J.y., Fujimori, S., Hanasaki, N., Hasegawa, T., Hirabayashi, Y., Honda, Y. et al. (2019). Dependence of economic impacts of climate change on anthropogenically directed pathways. Nature Climate Change 9(10), 737-741. https://doi.org/10.1038/s41558-019-0578-6

Tavoni, M., Andreoni, P., Calcaterra, M., Calliari, E., Deubelli-Hwang, T., Mechler, R. et al. (2024). Economic quantification of Loss and Damage funding needs. Nature Reviews Earth & Environment 5(6), 411-413. https://doi.org/10.1038/s43017-024-00565-7

Tian, C., Huang, G., Lu, C., Song, T., Wu, Y. and Duan, R. (2023). Northward Shifts of the Sahara Desert in Response to Twenty-First-Century Climate Change. Journal of Climate 36(10), 3417-3435. https://doi.org/10.1175/JCLI-D-22-0169.1

Tollefson, J. (2025). Earth breaches 1.5 °C climate limit for the first time: what does it mean? Nature 637, 769-770. https://doi.org/10.1038/d41586-025-00010-9

Torsten, K., Wübbels, G., Portafaix, A., Meyer zum Felde, A. and Zielcke, S. (2021). The Biodiversity Crisis Is a Business Crisis. Boston Consulting Group. https://web-assets.bcg.com/fb/5e/74af5531468e9c1d4dd5c9fc0bd7/bcg-the-biodiversity-crisis-is-a-business-crisis-mar-2021-rr.pdf

Turetsky, M.R., Abbott, B.W., Jones, M.C., Walter Anthony, K., Olefeldt, D., Schuur, E.A. et al. (2020). Carbon release through abrupt permafrost thaw. Nature Geoscience 13, 138-143. https://doi.org/10.1038/s41561-019-0526-0

Turnock, S.T., Allen, R.J., Andrews, M., Bauer, S.E., Deushi, M., Emmons, L. et al. (2020). Historical and future changes in air pollutants from CMIP6 models. Atmos. Chem. Phys. 20(23), 14547-14579. https://doi.org/10.5194/acp-20-14547-2020

United Nations Children's Fund and World Health Organization (2023). Progress on household drinking water, sanitation and hygiene 2000–2022: special focus on gender. New York City, NY, USA: United Nations Children's Fund and World Health Organization. https://washdata.org/report/jmp-2023-wash-households

United Nations Department of Economic and Social Affairs (2014). Electricity and education: The benefits, barriers, and recommendations for achieving the electrification of primary and secondary schools. New York City, USA: United Nations Department of Economic and Social Affairs. https://sustainabledevelopment.un.org/content/documents/1608Electricity%20and%20Education.pdf

United Nations Department of Economic and Social Affairs (2024). World Population Prospects 2024: Summary of Results. New York City, USA: United Nations Department of Economic and Social Affairs. https://desapublications.un.org/file/20622/download

United Nations Development Programme (2022). Special Report on Human Security. New York City, USA. https://hs.hdr.undp.org/pdf/srhs2022.pdf

United Nations Environment Programme (2024a). Food Waste Index Report 2024. Think Eat Save: Tracking Progress to Halve Global Food Waste. Nairobi: United Nations Environment Programme. https://wedocs.unep.org/20.500.11822/45230

United Nations Environment Programme (2024b). Global Resources Outlook 2024: Bend the Trend – Pathways to a liveable planet as resource use spikes. Nairobi: United Nations Environment Programme. https://www.resourcepanel.org/sites/default/files/documents/document/media/gro24_full_report_1mar_final_for_web.pdf

United Nations Environment Programme (2024c). Emissions Gap Report 2024: No more hot air … please! Nairobi: United Nations Environment Programme. https://wedocs.unep.org/bitstream/handle/20.500.11822/46404/EGR2024.pdf?sequence=3&isAllowed=y

United Nations Office for Disaster Risk Reduction (2019). Global Assessment Report on Disaster Risk Reduction 2019. https://doi.org/10.18356/f4ae4888-en

van der Esch, S., Sewell, A., Bakkenes, M., Berkhout, E., Doelman, J., Stehfest, E., Langhans, C., Fleskens, L., Bouwman, A. and Ten Brink, B. (2022). The global potential for land restoration: Scenarios for the Global Land Outlook 2. The Hague, the Netherlands: PBL Netherlands Environmental Assessment Agency. https://www.pbl.nl/uploads/default/downloads/pbl-2022-the-global-potential-for-land-restoration-glo2-4816_0.pdf

van der Esch, S., ten Brink, B., Stehfest, E., Bakkenes, M., Sewell, A., Bouwman, A., Meijer, J., Westhoek, H., van den Berg, M., van den Born, G. J., Doelman, J., Berkhout, E., Klein Goldewijk, K., Bouwman, A. F., Beusen, A., van Zeist, W.-J., Stoorvogel, J. J., Schut, A. G. T., Biemans, H., ... Mantel, S. (2017). Exploring future changes in land use and land condition and the impacts on food, water, climate change and biodiversity: Scenarios for the UNCCD Global Land Outlook. The Hague, the Netherlands. http://www.pbl.nl/en/publications/exploring-future-changes-in-land-use

van der Wijst, K.-I., Bosello, F., Dasgupta, S., Drouet, L., Emmerling, J., Hof, A. et al. (2023). New damage curves and multimodel analysis suggest lower optimal temperature. Nature Climate Change 13(5), 434-441. https://doi.org/10.1038/s41558-023-01636-1

van Oldenborgh, G.J., Krikken, F., Lewis, S., Leach, N.J., Lehner, F., Saunders, K.R. et al. (2021). Attribution of the Australian bushfire risk to anthropogenic climate change. Nat. Hazards Earth Syst. Sci. 21(3), 941-960. https://doi.org/10.5194/nhess-21-941-2021

van Vuuren, D.P., Zimm, C., Busch, S., Kriegler, E., Leininger, J., Messner, D. et al. (2022). Defining a sustainable development target space for 2030 and 2050. One Earth 5(2), 142-156. https://doi.org/10.1016/j.oneear.2022.01.003

Vecchio, E.A., Dickson, M. and Zhang, Y. (2022). Indigenous mental health and climate change: A systematic literature review. The Journal of Climate Change and Health 6. https://doi.org/10.1016/j.joclim.2022.100121

Vermeulen, S.J., Campbell, B.M. and Ingram, J.S.I. (2012). Climate Change and Food Systems. Annual Review of Environment and Resources 37(1), 195-222. https://doi.org/10.1146/annurev-environ-020411-130608

Wada, Y., Flörke, M., Hanasaki, N., Eisner, S., Fischer, G., Tramberend, S. et al. (2016). Modeling global water use for the 21st century: the Water Futures and Solutions (WFaS) initiative and its approaches. Geosci. Model Dev. 9(1), 175-222. https://doi.org/10.5194/gmd-9-175-2016

Watts, N., Amann, M., Arnell, N., Ayeb-Karlsson, S., Beagley, J., Belesova, K. et al. (2021). The 2020 report of The Lancet Countdown on health and

climate change: responding to converging crises. Lancet 397(10269), 129-170. https://doi.org/10.1016/S0140-6736(20)32290-X.

World Bank (2011). Still among the poorest of the poor. Indigenous Peoples country brief. Washington, D.C.: World Bank Group. http://documents.worldbank.org/curated/en/144831468330276370/Still-among-the-poorest-of-the-poor

World Bank (2024). Pathways Out of the Polycrisis. Washington D.C.: World Bank Group. https://openknowledge.worldbank.org/bitstreams/8f505de6-d365-4f10-aa5a-353c39616895/download

World Economic Forum (2024). Quantifying the Impact of Climate Change on Human Health. Geneva, Switzerland: World Economic Forum. https://www3.weforum.org/docs/WEF_Quantifying_the_Impact_of_Climate_Change_on_Human_Health_2024.pdf

World Health Organization (2023). 'Traditional medicine has a long history of contributing to conventional medicine and continues to hold promise'. https://www.who.int/news-room/feature-stories/detail/traditional-medicine-has-a-long-history-of-contributing-to-conventional-medicine-and-continues-to-hold-promise. Accessed 10 April 2025.

World Health Organization and Secretariat of the Convention on Biological Diversity (2015). Connecting global priorities: biodiversity and human health: a state of knowledge review. Geneva, Switzerland: WHO Press. https://iris.who.int/bitstream/handle/10665/174012/9789241508537_eng.pdf?sequence=1

World Tourism Organization (2023). Climate Action in Tourism – An overview of methodologies and tools to measure greenhouse gas emissions. Madrid: World Tourism Organization (UNWTO). https://doi.org/10.18111/9789284423927

Yaduvanshi, A., Nkemelang, T., Bendapudi, R. and New, M. (2021). Temperature and rainfall extremes change under current and future global warming levels across Indian climate zones. Weather and Climate Extremes 31, 100291. https://doi.org/10.1016/j.wace.2020.100291

Yiou, P., Cattiaux, J., Faranda, D., Kadygrov, N., Jézéquel, A., Naveau, P. et al. (2020). Analyses of the Northern European Summer Heatwave of 2018. Bulletin of the American Meteorological Society 101(1), S35-S40. https://doi.org/10.1175/BAMS-D-19-0170.1

Zavaleta-Cortijo, C., Ford, J.D., Arotoma-Rojas, I., Lwasa, S., Lancha-Rucoba, G., García, P.J. et al. (2020). Climate change and COVID-19: reinforcing Indigenous food systems. The Lancet Planetary Health 4(9), e381-e382. https://doi.org/10.1016/S2542-5196(20)30173-X

Zemp, M., Jakob, L., Dussaillant, I., Nussbaumer, S.U., Gourmelen, N., Dubber, S. et al. (2025). Community estimate of global glacier mass changes from 2000 to 2023. Nature 639(8054), 382-388. https://doi.org/10.1038/s41586-024-08545-z

Zhu, C., Liu, Z., Zhang, S. and Wu, L. (2023). Likely accelerated weakening of Atlantic overturning circulation emerges in optimal salinity fingerprint. Nature Communications 14(1), 1245. https://doi.org/10.1038/s41467-023-36288-4

11 Transformation Pathways Towards Achieving Global Goals: Global Implications

Coordinating Lead Authors: Vassilis Daioglou (PBL Netherlands Environmental Assessment Agency, Utrecht University), Ana Paula Aguiar (INPE, Brazilian Institute for Space Research) and Detlef van Vuuren (PBL Netherlands Environmental Assessment Agency, Utrecht University)

Lead Authors: Alaa Al Khourdajie (Imperial College London), Lindsay Beevers (University of Edinburgh), Claudio Belis (European Commission, Joint Research Centre), Hester Biemans (Wageningen University), Edward Byers (International Institute for Applied Systems Analysis), Jonathan Doelman (PBL Netherlands Environmental Assessment Agency), Panagiotis Fragkos (E3 Modelling), Shinichiro Fujimori(Kyoto University), Taylor Hanna (Pardee Institute University of Denver), Jiang Kejun (Environment Research Institute), Yolanda López-Maldonado (Independent Scientist), Paul Lucas (PBL Netherlands Environmental Assessment Agency), Jonathan Moyer (Pardee Institute University of Denver), Leonidas Paroussos (E3 Modelling), Heinz Schandl (CSIRO), Audrone Telesiene (Kaunas University of Technology) and Carol Zavaleta-Cortijo (Universidad Peruana Cayetano Heredia)

Contributing Authors: Rob Alkemade (PBL Netherlands Environmental Assessment Agency) , Michel Bakkenes (PBL Netherlands Environmental Assessment Agency), Arthur Beusen (PBL Netherlands Environmental Assessment Agency), Dimitris Fragkiadakis (E3 Modelling), Yingying Lu (CSIRO), Stephen Maycock (PBL Netherlands Environmental Assessment Agency), Kaj-Ivar van der Wijst (Utrecht University), Laszlo Vreedenburgh (PBL Netherlands Environmental Assessment Agency), Michaela Werning (International Institute for Applied Systems Analysis)

Fellow: Michael Ruggeri (University of Oxford)

Image credit: baliukhpavlo/Envato

Chapter summary

Credit: image Envato

The GEO-7 target-seeking scenarios illustrate that achieving the ambitious environmental and societal goals as agreed upon in multilateral agreements is possible, but only if immediate, unprecedented and coordinated transformations take place across the economy and finance, energy, food, materials/waste, and environmental systems (*well established*) {11.2}. The scenarios describe a complete transformation of systems for supply, demand, consumption, and provision of services. The different pathways show a range of possible and coherent strategies across the systems to achieve the goals {11.6}. Challenges lie in rapid implementation, in coordinating with actors across diverse systems, sectors, and regions, and in gaining societal acceptance of specific solutions, such as carbon dioxide removal, changes in consumption patterns and human behaviour, among others, without exacerbating existing or creating new forms of inequality and injustice {11.7}.

There are still several pathways to achieving the intended goals. The GEO-7 *Behaviour-focused Transformation Pathway* and the *Technology-focused Transformation Pathway* assessed here achieve the goals based on different combinations of social and technical shifts, but both have major implications for energy, materials/waste and food systems. Both Transformation Pathways depend on effective governance and strong institutions at multiple levels {11.5, 11.7}, high levels of technology development, and well-regulated markets where prices reflect the true environmental and social cost of goods and services. However, they differ in the relative importance of regulation and pricing instruments, type and purpose of technological development, and the overall emphasis on behavioural changes towards sufficiency, or technological solutions towards efficiency. Aligned to these overall emphases, specific solutions or strategies are adopted in the transformation of each system {11.2, 11.3}. By elaborating on the results of these two pathways, it is possible to identify similarities and contrasts between them, highlighting important synergies and trade-offs between the different systems.

Abandoning inefficient and unnecessary use of resources creates multiple synergies across the systems, helping to address the global environmental crises and improve human well-being (*well established*) {11.6}. For instance, reducing overall energy demand makes it significantly easier to decarbonize the energy system {11.3.1} and meet climate goals {11.4.1}. This can be aided by lowering energy and material demands for shelter, mobility and other goods and services. This also reduces

the requirement for vast amounts of renewable energy technologies, and related critical materials {11.3.3}, as well as the dependence on large-scale negative emission technologies {11.4.1}. Less need for biomass and bioenergy also reduces pressures on land, biodiversity and water. Shifting dietary patterns away from excessive amounts of animal products towards plant-based foods, cultured meat, and healthy food-intake levels also reduces pressure on the land system {11.3.2}. This can free up large areas currently dedicated to animal feed production, while also reducing greenhouse gas emissions related to industrial-scale livestock production. This makes it easier to achieve climate, biodiversity, land degradation and pollution goals, and helps make the land system a net carbon dioxide sink, further mitigating climate change and land degradation {11.4.1, 11.4.3}.

Transforming human systems to address the global environmental crises has multiple benefits for people, but additional measures are necessary to fully achieve well-being goals (*established but incomplete*). Ending hunger and establishing universal access to clean water, mobility, adequate housing, clean energy, clean air, and appropriate changes in diets have significant benefits for human health, poverty reduction and human security {11.5}. However, to achieve the full range and depth of socioeconomic goals, societal transformations are necessary. For example, eliminating hunger will require direct support for the poorer parts of society. Addressing global environmental crises without simultaneously addressing unacceptable levels of inequality and inequity, regional disparities, and failures in social security and health provision may lead to significant trade-offs and social strife. Thus, all system transformations must occur in an equitable and inclusive manner, including Indigenous populations and local communities. Social, political and cultural change must necessarily accompany the transformations {11.5, 11.6, 11.7}.

An immediate, sustained and just transformation of the energy system is necessary to meet climate goals and will enable the required transformations of other systems {11.3.1}. A sustained increase in renewables and a substantial reduction of unabated fossil fuel technologies by 2050 are a prerequisite for meeting climate goals {11.4.1}. The electrification of final energy demand by 2050 forms part of both *Transformation Pathways*, more than doubling from approximately 20 per cent to almost 50 per cent by 2050. This highlights the importance of investing in reliable and interconnected infrastructure, combined with massive investment in renewable energy capacities, power storage, and new energy consumption technologies, such as electrified transport and heat pumps, among others. Given the urgency of meeting climate goals, both pathways also rely on some form of carbon dioxide removal techniques, but to differing extents. Reducing energy demand, by changing consumption patterns and increasing efficiency, makes increased electrification rates easier to achieve. It also reduces dependence on technologies such as carbon capture and storage, whose large-scale deployment is both uncertain and expensive and may pose significant risks. The presented transformation in the energy system limits energy demand, reduces resource use and contributes to meeting air pollution, food access, biodiversity and water scarcity goals {11.3.2, 11.3.3, 11.4.2, 11.4.4, 11.4.6}.

Food system measures such as improved agricultural practices, diet change, and food-waste reductions can prevent continued natural land conversion and degradation (*well established*) {11.3.2}. Possible food system transformations range from highly intensified systems in line with the land-sparing paradigm, to mixed systems combining Indigenous Knowledge, Local Knowledge and scientific knowledge. Reduced demand for agricultural products through changes in dietary patterns and less food waste can alleviate pressure on the agricultural system, decreasing agricultural land use. Curtailing the consumption of meat has the greatest effect, vastly reducing the use of land for pasture and feed, improving biodiversity {11.4.4}, reducing surplus manure and associated pollution {11.4.5}, and providing significant health benefits {11.5.2}. These changes, together with improved irrigation management, can also vastly reduce water stress while still providing adequate irrigation {11.4.6}. Furthermore, the abatement of agricultural methane and ammonia emissions helps reduce atmospheric pollution {11.4.2}.

Protection of existing ecosystems, restoration of degraded lands and improved land management are crucial to preserving biodiversity and increasing carbon storage (*established but incomplete*) {11.3.4}. Both pathways envision an increase in protected areas, ranging from 30 per cent with strict protection, called land-sparing, to 50 per cent with more mutually beneficial relations between humans and nature, called land-sharing. Increasing protected areas helps prevent the conversion of natural land and improves the possibilities of tackling biodiversity loss {11.4.4}. Furthermore, preserving and expanding natural lands allows them to act as important carbon sinks,

Credit: vectorfusionart/Envato

which helps to mitigate climate change {11.4.1}. However, this protection needs to be supported by improvements in agricultural production, including agroecology and agroforestry, and in distribution. This will help avoid food deprivation in vulnerable populations, which may arise from increased competition for land {11.3.2, 11.5, 11.6}.

The benefits of transformation vastly outweigh the upfront costs due to the avoided damages from climate change, with benefits surpassing US$ 20 trillion per year by 2070 (*established but incomplete*). Changes in consumption and production due to the transformations needed across all systems will cost approximately US$ 1 trillion to US$ 3 trillion per year until 2050, equivalent to a loss of approximately 1.5 per cent of projected global economic activity. However, after 2050, the economic damage from climate change becomes increasingly severe {10.6.5}, leading to a loss of 6 per cent of potential future gross domestic product by 2070 and increasing to over 25 per cent by 2100. This is equivalent to the benefits of the transformation being approximately US$ 20 trillion per year in 2070, to over US$ 100 trillion per year by 2100 {11.5.5}. Additional economic benefits of the transformation can be expected from improved access to food and energy services and positive effects on work, productivity and social well-being, as well as benefits from improved ecosystem services.

The associated transformations present a number of important synergies. However, to avoid potential trade-offs, the correct enabling conditions need to be identified and implemented (*established but incomplete*) {11.6}. While the presented pathways can meet multiple goals across environmental and human systems, bringing them to fruition will require broad negotiation on potential trade-offs. Given the scale of the transformation needed, inevitably there will be segments of society and interests that will be significantly affected. This makes it particularly important to ensure that the opportunities that arise are harnessed and distributed equitably and that the costs are shared in a just manner. The transformation depends on the presence of specific conditions including effective governance and policymaking; appropriate legal frameworks; increased predictability of policies to ensure adequate engagement of stakeholders including industry, civil society, and others; and inclusion of various forms of knowledge such as Indigenous, local and scientific. Furthermore, protecting those who are energy and food-insecure and fostering legitimate and well-functioning institutions to mediate social and political friction when implementing the proposed solutions is also required.

Credit: iiMOHAMMEDii/Envato

11.1 Introduction

As the *Current Trends Scenario* demonstrates, continuing current trends across the economic and financial, energy, food, resource, and environmental systems is failing to achieve many internationally agreed environmental goals and related SDGs. This pathway is even amplifying negative trends in the global environmental crises towards 2050 (Chapter 10). In this chapter we will explore two target-seeking scenarios, the *Behaviour-focused Transformation* and the *Technology-focused Transformation*. They represent alternative Transformation Pathways that could meet a set of internationally agreed environmental goals while guaranteeing food security and universal access to energy and water. The goals and adopted targets are indicated in **Table 9.1** and discussed in more detail in Chapter 9.

Importantly, these deliberately constrained target-seeking scenarios are not predictions, and no likelihood is attached to them, nor do they present or evaluate specific policy measures. Instead, they are archetypes of different possible transformations. As such, they illustrate – in general terms – the type and extent of action needed to meet the goals, the critical choices involved, the associated synergies and trade-offs, and the possible challenges and opportunities.

Section 11.2 presents the narratives for the target-seeking scenarios, following the methodology and general assumptions detailed in Section 9.4. Section 11.3 presents quantitative results for each system, while Sections 11.4 and 11.5 present, respectively, the environmental and socioeconomic implications of the two pathways. Finally, Sections 11.6 and 11.7 discuss some considerations about the synergies, challenges and opportunities presented. This chapter does not discuss the social or political feasibility of the Transformation Pathways. Instead, it aims to present quantitative and qualitative context on the extent of the required transformation and important underlying dynamics. Subsequently, Chapters 12–18 build upon the insights presented here and detail specific "solution pathways" that describe how to implement the transformation of each system, such as the necessary conditions, actors, policies and measures. Then Chapters 19 and 20 further explore the Transformation Pathways from a regional perspective. Chapter 21 synthesizes the work of these chapters and assesses how to accelerate the required transformations.

11.2 Two narratives of transformation

The two narratives are individually coherent stories rooted in the general assumptions for each Transformation Pathway, as defined in Section 9.4 and presented in **Boxes 11.1** and **11.2**. The two pathways differ mainly in terms of the focus on behaviour versus technology solutions:

- The *Behaviour-focused* transformation describes a world in which society transforms its core values towards sufficiency, placing less emphasis on material consumption and status, and reducing the pressure on natural systems.
- The *Technology-focused* transformation describes a highly globalized and market-driven world that relies primarily on technological development and efficiency gains in both supply and demand to overcome the global environmental crises.

Both pathways move beyond gross domestic product (GDP) as a measure of well-being, instead focusing more on the well-being of nature and society (Jansen et al. 2024). It is important to stress that the pathways are not mutually exclusive, as technology improvements and consumption changes are parts of both scenarios (Mosca et al. 2024; Strefler et al. 2024), but each pathway relies on them to differing extents. Analysing such archetypal pathways together provides a broader understanding of possible solutions and of the associated synergies and trade-offs. In reality, elements of both pathways can already be found in different contexts, as discussed in Chapter 9.

11.2.1 Solutions presented by each pathway

Each narrative combines coherent strategies and solutions across five systems – economy and finance, energy, food, materials/waste, and environment – to achieve internationally agreed goals (**Table 9.1**). They were constructed at the solution level within the Goal, Solution, Lever framework introduced in Chapter 13 (13.6). As a result, the narratives provide sufficient detail to support the scenario quantification process, while maintaining consistency with Chapters 14–18.

The definition of the adopted solutions for each system was based on an analysis of similar scenario exercises conducted recently (Kok et al. 2023; Soergel et al. 2024; Strefler et al. 2024; van Heerden et al. 2024) and refined by an internal consultation with expert authors from the GEO-7 Systems and Regional chapters (9.4). Alternative solutions in each pathway reflect key debates about sustainability and intend to foster discussion at multiple levels (Aguiar et al. 2020). The food and environment systems are entangled via land use and practices, and their solutions relate to the land-sparing and land-sharing and the Half-Earth approaches (Bennett 2017; Ellis and Mehrabi 2019), as well as the debate on agricultural practices and intensification (Struik et al. 2014; Tittonell 2014; Duru et al. 2015; Newell and Taylor 2018). As the *Behaviour-focused* transformation pathway assumes deeper value changes, it explores a paradigm shift towards land-sharing, in which no clear separation exists between humans and nature (Pereira et al. 2020). For this pathway, shared-use protected areas cover 50 per cent of the world, moving away from the contested Half-Earth proposal of fully protected areas for conservation (Büscher et al. 2016; Büscher and Fletcher 2020). There is also a focus on ecological intensification, with an increase in agroecological or biodiversity-based practices (Tittonell 2014; Duru et al. 2015).

The *Technology-focused* pathway follows the current dominant sustainability paradigm of efficiency and profit, exploring the land-sparing solution (Phalan et al. 2011) that assumes a clear division between human uses and natural areas. It envisions a highly concentrated spatial model for food production, achieved through developing more efficient and less harmful agricultural practices. This approach aims to promote large-scale sustainable agricultural production on a reduced area (Cassman and Grassini 2020).

The food system transformation in each pathway also diverges in relation to future diets, particularly in relation to protein sources, to mitigate the impacts of cattle ranching (Godfray et al. 2018). While the *Behaviour-focused* pathway prioritizes a shift towards plant-based diets, following the EAT Lancet report (Willett et al. 2019), the *Technology-focused* pathway explores a partial substitution with cultured meat (Chen et al. 2022; Cassman and Grassini 2025; Hocquette et al. 2025).

Likewise, comparable differences apply to the energy system. A key distinction between the pathways relates to the degree of energy production centralization (Burke and Stephens 2018; Fuss et al. 2018; Waller et al. 2020). The *Technology-focused* pathway assumes centralized production and distribution, while in the Behaviour-focused pathway, it is mostly decentralized. The pathways have different configurations in relation

Box 11.1 The Behaviour-focused Transformation Narrative

Behaviour-focused transformation pathway

In the Behaviour-focused transformation, goals are achieved through lifestyle, behavioural and value changes. It envisions a future where increased societal awareness of global environmental crises drives a shift toward a sufficiency worldview. This transformation is guided by principles of sharing, reciprocity, responsibility and care, local-to-global outlooks, and aiming to reconcile human well-being with ecosystem health. Multiple forms of knowledge are combined, including mainstream science and Indigenous and Local Communities (ILC)'s philosophies, practices and values. Examples include climate change adaptation measures, regeneration of abandoned lands, and governing fisheries and rivers. Aligned with these general assumptions, coherent solutions are adopted for each system:

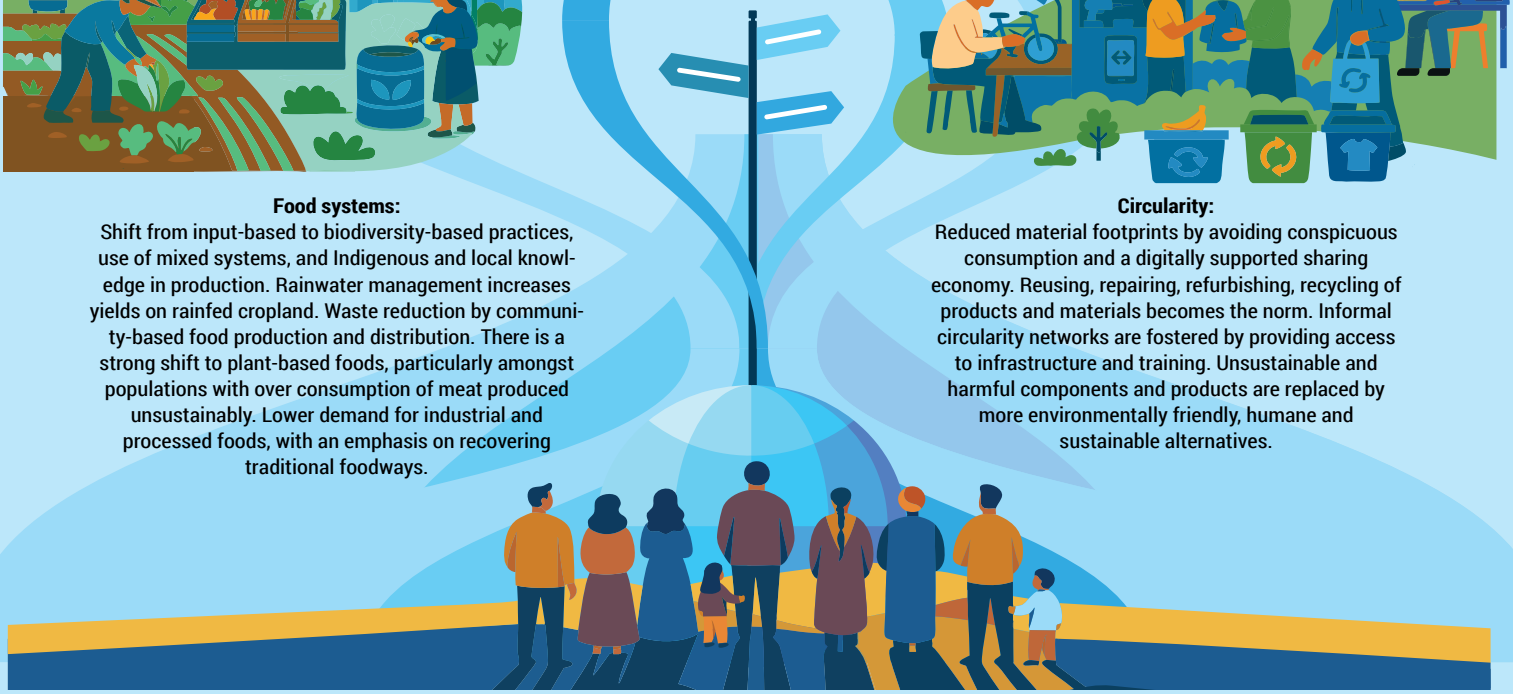
Economic systems:
Beyond economic growth and GDP as a measure of well-being. Reduction of externalities through a combination of pricing and non-pricing instruments. Investments in technological and social solutions oriented towards enabling human and nature wellbeing.

Environmental systems:
Guided by principles of land sharing, there is an increase in symbiotic/sustainable use of protected areas (terrestrial, freshwater, marine), aiming for 50% of the world in 2050. Natural regrowth/restoration on abandoned agricultural lands due to changes in the food system provides carbon removal service.

Energy systems:
Behavioural and lifestyle changes lead to reductions in energy demand in rich regions, while middle-and lower-income gain access to basic energy services. Emergence of "prosumers" facilitated through small-scale decentralized electricity generation. Micro-grids, demand-side management, and distributed storage are scaled up.

Food systems:
Shift from input-based to biodiversity-based practices, use of mixed systems, and Indigenous and local knowledge in production. Rainwater management increases yields on rainfed cropland. Waste reduction by community-based food production and distribution. There is a strong shift to plant-based foods, particularly amongst populations with over consumption of meat produced unsustainably. Lower demand for industrial and processed foods, with an emphasis on recovering traditional foodways.

Circularity:
Reduced material footprints by avoiding conspicuous consumption and a digitally supported sharing economy. Reusing, repairing, refurbishing, recycling of products and materials becomes the norm. Informal circularity networks are fostered by providing access to infrastructure and training. Unsustainable and harmful components and products are replaced by more environmentally friendly, humane and sustainable alternatives.



Box 11.2 The Technology-focused Transformation Narrative

Technology-focused transformation pathway

In the Technology-focused transformation, the goals are achieved through innovation and technological solutions. It envisions a future characterized by an urbanized world with significant global trade and technological spill-over and leapfrogging, in which society relies on price-mediated and technological solutions together with expert and scientific knowledge:

Environmental systems:
Guided by the principle of sparing, biodiversity hotspots are protected, and the efficient use of non-protected areas allowing the regeneration of large areas of natural vegetation. Natural vegetation covering more than 30% is pursued together with significant afforestation via planted forests.

Economic systems:
Reduction of externalities through pricing mechanisms and efficiency gains. High investments in technical solutions to environmental and social problems, while valuing multiple ecosystem services and human capabilities as a metric of well-being.

Energy systems:
Supply-side investments with a focus on efficiency, clean energy, interconnectivity, and high levels of electrification. The electricity system is built around centralized distribution networks, large-scale supply and storage of electricity, and large-scale grid interconnections. Technological solutions, including power-to-liquids, advanced biofuels, hydrogen, and carbon capture and storage are made mainstream.

Food systems:
Aligned to the land-sparing principle, i.e., producing more in less area, freeing land for nature restoration, biodiversity protection, and conservation. Adoption of efficient irrigation, automated agricultural production, and the substitution of animal products by novel foods such as cultured meat. Technical means are adopted to tackle food waste and losses.

Circularity:
Design driven by cradle-to-cradle concerns, increased efficiency, and reduced waste. Monitoring, reviewing, and redesigning of products and implementation of necessary infrastructure, improves recyclability and enables high recycling rates. Efficient modular design in buildings and goods reduces their material footprint and increases their longevity and ability to be refurbished. Technological solutions including machine learning contribute to waste management and circular supply chains.

to the energy matrix, including the use of contested technologies such as nuclear plants and bioenergy (Fuss et al. 2018; Waller et al. 2020). Concerning energy demand, the *Technology-focused* pathway prioritizes efficiency, while the *Behaviour-focused* pathway limits energy demand via lifestyle changes.

For the materials/waste system, the Transformation Pathways reflect the sharing and circular economy debate (Henry et al. 2021). The main difference is that the *Behaviour-focused* pathway relies on a sharing economy (Curtis and Lehner 2019) combined with decreased consumption, while the *Technology-focused* pathway relies on the efficient design of products and reduced waste. The two pathways involve different levels of reuse, repairing, refurbishing and recycling. Finally, in the case of the economic and finance system, the difference is in the importance of regulatory or market instruments to reduce environmental externalities.

In the solutions for the *Behaviour-focused* pathway, a basic assumption is that integrating sources of knowledge results in a type of co-creation. A widely-recognized example of such co-creation, where Indigenous Knowledge informs conventional approaches, supports biodiversity preservation through the use of fire knowledge in the Amazon region, Australia, and other parts of the world (**Box 3.2**) (Burrows, Burbidge and Fuller 2004; Mistry, Bilbao and Berardi 2016; Hoffman et al. 2021; Ruscalleda-Alvarez et al. 2023). Other examples include implementing climate change adaptation measures such as climate risk communication and green infrastructure (Petzold et al. 2020); regenerating abandoned land in the Amazon with medicinal and food species (Levis et al. 2018); and governing fisheries and restoring rivers in the European Arctic (Brattland and Mustonen 2018; Ogar, Pecl and Mustonen 2020).

11.2.2 Quantification of the narratives

The first step for building model-based projections of the Transformation Pathways consists of translating the qualitative narratives into appropriate parameterization for the model framework described in Section 9.5. The table in Appendix 11.1 presents an overview of how the narratives were translated into quantitative parameters for the models. The Appendix also maps the broad strategies outlined in

Credit: biletskiy/Envato

the narratives to the solutions presented in the section describing the solution pathways for each system in Chapters 14–18.

The quantitative results of the target-seeking scenarios are compared to the *Current Trends* scenario detailed in Chapters 9 and 10 using the same activity and population drivers as the middle of the road scenario of the Shared Socioeconomic Pathways (SSP2) (O'Neil et al. 2017). However, our scenarios differ from each other in the technological and behavioural assumptions as outlined in the boxes. This comparison helps highlight the different transformations each system may undergo to bring them in line with the goals detailed in **Table 9.1**.

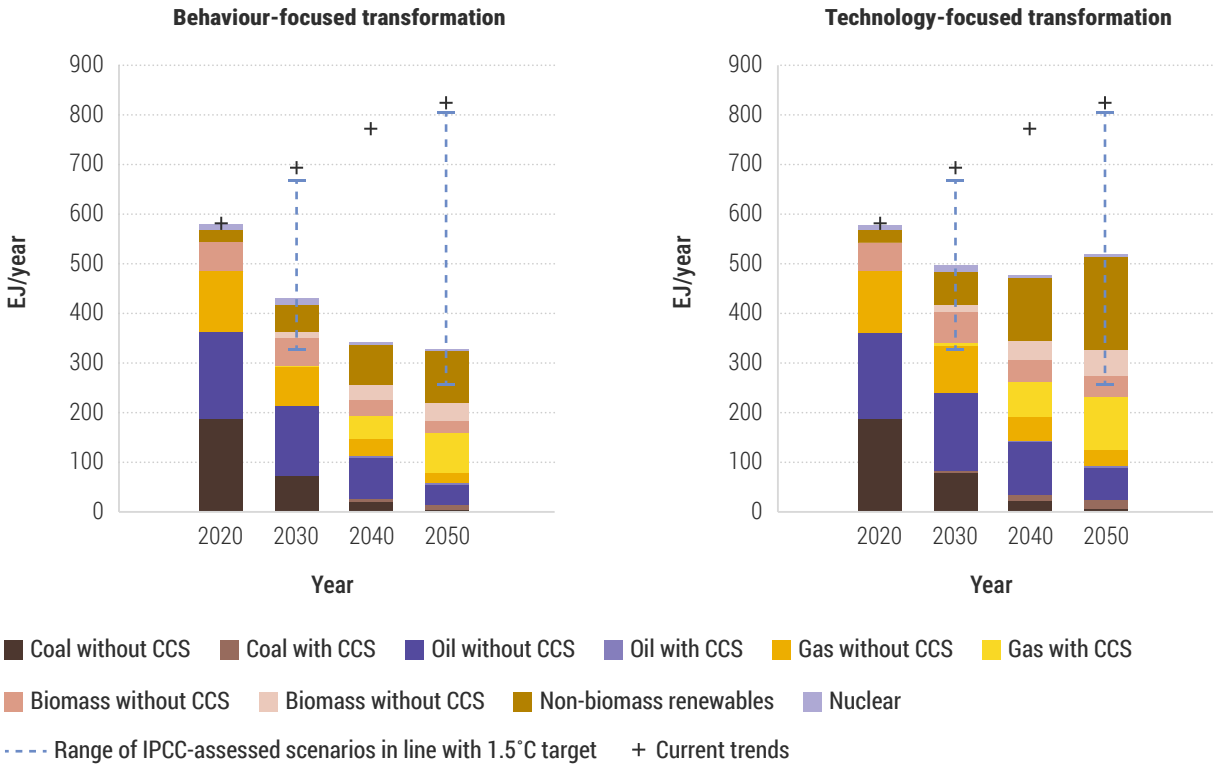
11.3 Systems transformations

The following sections describe the transformation each system undergoes to make it consistent with the goals set out in Section 9.3. Contrasting the results of the two pathways illustrates that there are multiple routes towards achieving these goals, each with their associated system transformations, challenges and opportunities.

11.3.1 Energy

Both pathways show a clear break from the *Current Trends* scenario concerning energy supply and demand. **Figure 11.1** shows a decrease in the short term, arising from the use of energy-efficient technologies in both supply and demand as in the *Technology-focused* pathway, and in structural changes and reduced demand for energy services in the *Behaviour-focused* pathway. By 2050, both pathways show lower energy demand than today while also meeting energy access goals and lowering primary energy demand compared to the *Current Trends*, by 40 per cent and 60 per cent for the *Behaviour-focused* and *Technology-focused* pathways, respectively. These projections may differ across different regions based on their socioeconomic situation, with Chapters 19 and 20 providing further details.

Figure 11.1: Primary energy disaggregated across energy resources for the *Behaviour-focused* and *Technology-focused* transformation pathways



Note: The range of the results from the IPCC-assessed scenarios as shown in dashed lines are in line with the 1.5°C target (>50 per cent probability, with no or low overshoot, immediate action after 2020). The scenarios from the IPCC-AR6 have a primary focus on climate change goals only. CCS refers to Carbon Capture and Storage.

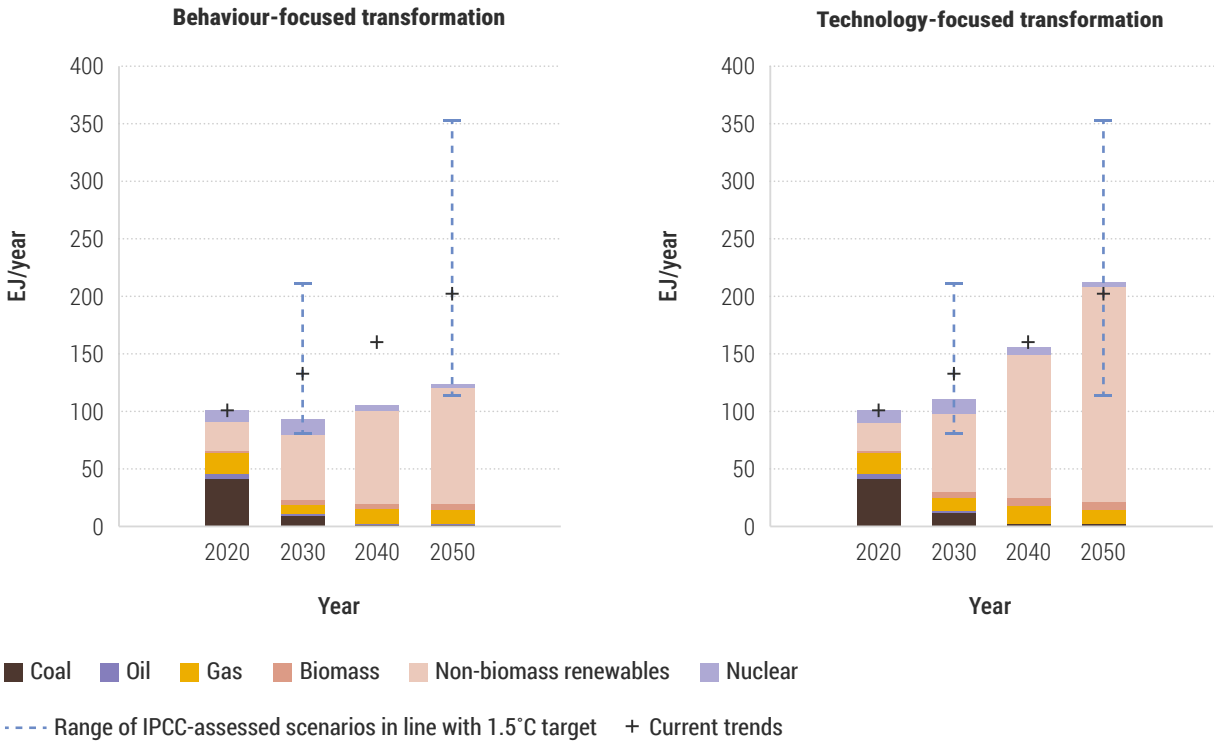
Source: IMAGE 3.3 Model (transformation pathways) and AIM Model (current trends)

As highlighted in **Table 9.1**, both Transformation Pathways are consistent with the goals of the Paris Agreement, as well as goals concerning access to clean energy (11.4.1; 11.5.1). This implies an immediate and rapid reduction in the extraction and use of fossil resources, with total fossil fuel consumption in 2050 at less than 50 per cent of 2020 and most of the remaining fossil fuel emissions addressed by Carbon Capture and Storage (CCS). Remaining fossil fuel use is focused on sectors that are particularly difficult to completely decarbonize by 2050, such as heavy industry and transport (Edelenbosch et al. 2024). Bioenergy also contributes to decarbonizing these sectors and contributing to climate goals (11.4.1), especially forms of transport that cannot be electrified. Approximately two-thirds of the bioenergy supply is projected to come from agricultural and forestry residues, reducing the need for extra agricultural land (11.3.2).

The use of zero-carbon energy options needs to increase rapidly, building upon and beyond the recent growth in these energy resources, with an annual growth rate of around 8–11 per cent from 2020 to 2030. Zero-carbon energy resources play an obvious role in the power generation sector, where renewable energy is projected to constitute more than 85 per cent of electricity production by 2050, increasing from approximately 25 per cent in 2020 (**Figure 11.2**). Nuclear power is projected to play a smaller role due to its high costs compared to renewables.

This decarbonization of power generation is crucial since both Transformation Pathways highlight the importance of increased electrification. In 2020, electricity constituted approximately 20 per cent of total final energy use. In the *Current Trends* scenario, this increases to approximately 26 per cent by 2050, and the Transformation Pathways both show an important shift, with electrification rates more than doubling to up to 45 per cent. Despite this vast increase in the share of final energy supplied by electricity, due to the described changes in total energy demand, total electricity production is projected to be lower than the *Current Trends* scenario. This highlights that a lower overall demand for energy makes it easier and less

Figure 11.2: Electricity generation disaggregated across primary energy sources for the *Behaviour-focused* and *Technology-focused* transformation pathways



Note: The range of results from the IPCC-assessed scenarios as shown in dashed lines are in line with the 1.5°C target (>50 per cent probability, with no or low overshoot, immediate action after 2020). The scenarios from the IPCC-AR6 have a primary focus on climate change goals only.

Source: IMAGE 3.3 (transformation pathways) and AIM (current trends)

costly to scale up the required infrastructure for an effective decarbonization of the electricity supply and the overall energy system (11.6).

The Transformation Pathways indicate that recent technological progress leading to lower costs for renewables compared to fossil-fuel power generation could strongly support the transition (Way et al. 2022). However, the Transformation Pathways also highlight that the high rates of electrification will require expanding electricity generation, driven by the growth in zero-carbon generation capacity (van Heerden et al. 2024), and ensuring universal, reliable and just access through the expansion of interconnected electricity networks. This requires policy frameworks to support positive effects for all populations, including Indigenous Peoples and diverse local communities (Hoicka, Savic and Campney 2021; Vega-Araújo and Heffron 2022; Owen et al. 2023) (16.2.1).

Development and distribution of keystone technologies that also enable behavioural and lifestyle choices for a reduction in energy demand – and associated infrastructure – is vital (Sugiyama et al. 2024). Examples include demand-side management; efficiency-improving technologies in the built environment, including heat pumps and rooftop photovoltaics; and provision of reliable electrified public transport. Others are increased efficiency in energy conversion and use, energy storage options enabling high penetration of intermittent renewable energy, and the development of advanced fuels and energy carriers to decarbonize hard-to-abate sectors. Further details on options and important actors for transforming the energy system are discussed in Chapter 16.

It is noteworthy that more than 50 per cent of minerals necessary for the energy transition are situated adjacent to or within Indigenous Peoples' lands and rural communities (Owen et al. 2023), highlighting the importance of ensuring a just and equitable energy transition. In this context, centring Indigenous perspectives concerning the relational connection among humans, other beings and lands can help to create effective, ethical and sustainable polices to achieve energy goals (Sankaran and McIntyre-Mills 2022; Kennedy et al. 2023; Loginova et al. 2025).

11.3.2 Food

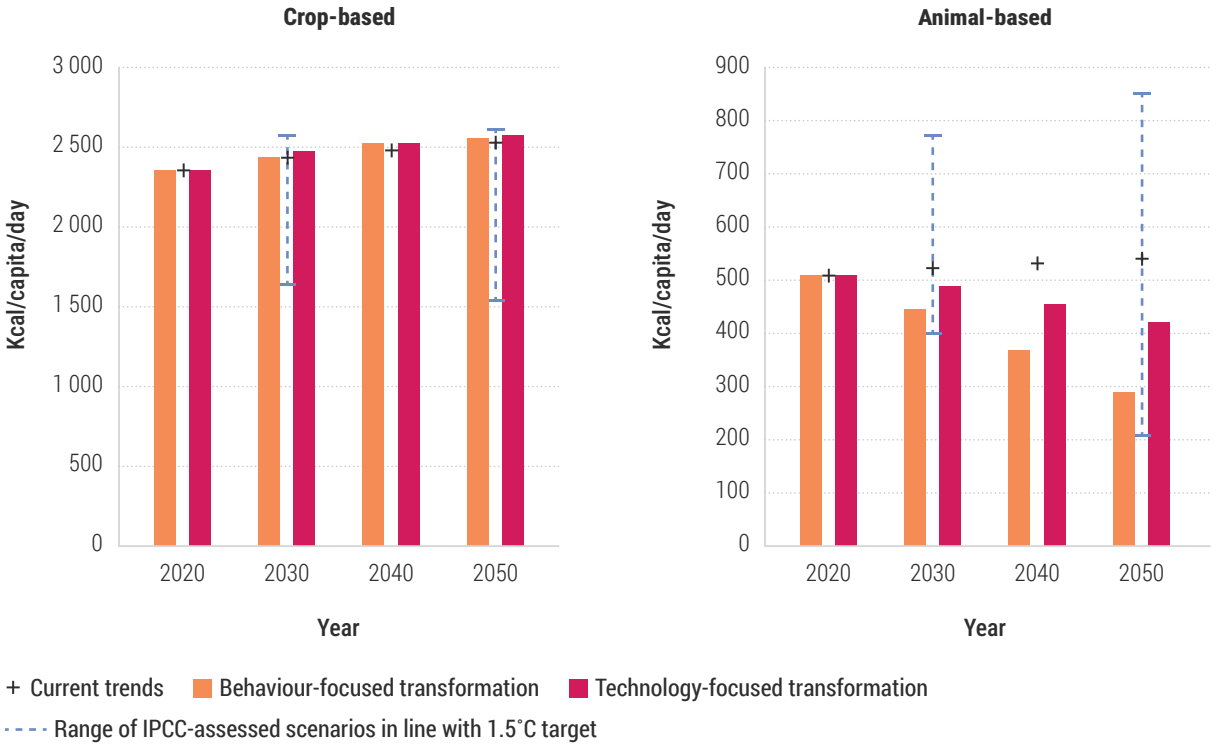
The global food system is responsible for approximately one-third of greenhouse gas (GHG) emissions (Crippa et al. 2021), drives land degradation through the expansion of agriculture that also leads to biodiversity loss and causes pollution through fertilizer use and large-scale livestock production (4.3, 17.2.5). The *Current Trends* scenario presented in Chapter 10 shows that further exacerbation of these issues is expected. Both selected Transformation Pathways present changes that put the food system on a different track.

Ensuring adequate nutrition for a growing population leads to modest continued increases in food demand in both Transformation Pathways, but a strong reduction in the consumption of livestock-based products (**Figure 11.3**). In the *Technology-focused* transformation, meat substitutes replace traditional meat. In the Behaviour-focused transformation, the overconsumption of animal products is reduced most notably in high- and middle-income regions due to higher awareness of the health and environmental consequences, in line with the EAT-Lancet diet (Willett et al. 2019).

Figure 11.4 highlights that in both the Transformation Pathways, livestock production decreases substantially due to dietary shifts, as also shown by Springmann et al. (2018) and Kozicka et al. (2023). This transformation also delivers a substantial decrease in feed requirements, from both grazing and crop harvests – resulting in lower demand for crop production. Furthermore, any increase in crop production is mitigated by reductions in food waste, with high-tech solutions and community-based solutions driving the transformations in the *Technology-focused* and the *Behaviour-focused* pathways, respectively. However, relative increases in crop production are also accounted for: cultured meat itself requires substantial amounts of crop as feedstock, while the transition to healthy, plant-based diets results in strong production increases in protein-rich crops, such as legumes, as well as fruits and vegetables. Accounting for all these dynamics, compared to the *Current Trends*, the *Behaviour-focused* pathway shows a modest decrease while the *Technology-focused* pathway shows a modest increase in total crop production.

Technological developments, including widespread automation of farm practices and genetic improvements of crop varieties, lead to strong yield and livestock efficiency increases in the *Technology-focused* pathway, where cereal yields are about 30 per cent higher in 2050 compared to today (**Figure 11.5**). In the *Behaviour-*

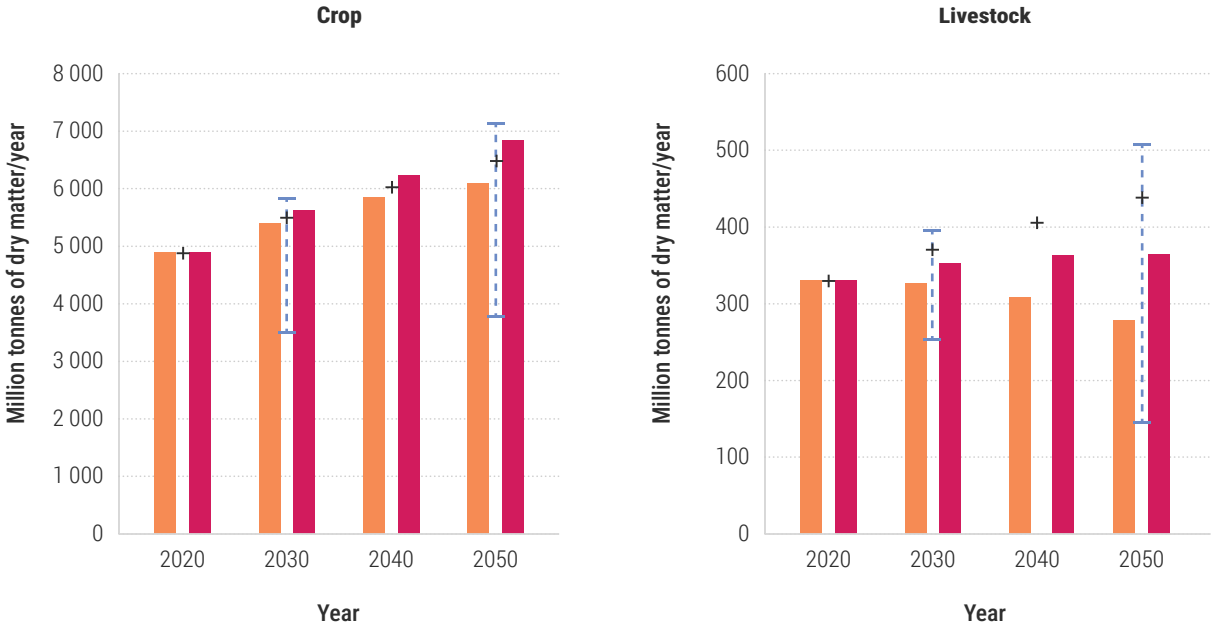
Figure 11.3: Consumption of crop-based products and animal-based products per capita per day



Note: The range of the results from the IPCC-assessed scenarios as shown in dashed lines are in line with the 1.5°C target (>50 per cent probability, with no or low overshoot, immediate action after 2020). The scenarios from the IPCC-AR6 have a primary focus on climate change goals only.

Source: IMAGE 3.3 Model (transformation pathways) and AIM Model (current trends)

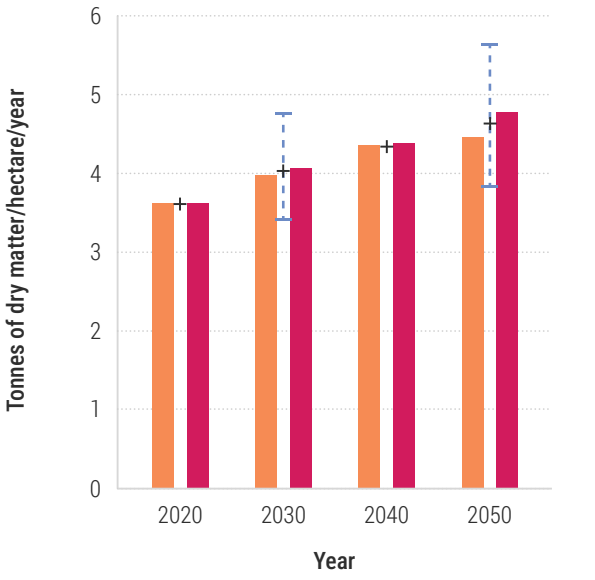
Figure 11.4: Projections of food crop and livestock production



Note: The range of the results from the IPCC-assessed scenarios as shown in dashed lines are in line with the 1.5°C target (>50 per cent probability, with no or low overshoot, immediate action after 2020). The scenarios from the IPCC-AR6 have a primary focus on climate change goals only.

Source: IMAGE 3.3 Model (transformation pathways) and AIM Model (current trends)

Figure 11.5: Projections of aggregate cereal crop yields



Note: The range of the results from the IPCC-assessed scenarios as shown in blue dashed lines are in line with the 1.5°C target (>50 per cent probability, with no or low overshoot, immediate action after 2020). The scenarios from the IPCC-AR6 have a primary focus on climate change goals only.

Source: IMAGE 3.3 (transformation pathways) and AIM (current trends

focused pathway, nature-focused practices, including mixed cropping and integrated systems, are assumed to become dominant. Improved land management allows for continued yield improvement, albeit at a lower level than the other pathways as there is less focus on agricultural intensification.

Mixed cropping and integrated systems could be aligned with the diversity of Indigenous food systems (Baena et al. 2023), with implications for new policies that recognize and protect the foods typically consumed by Indigenous communities, but which are still considered neglected plants (Baldermann et al. 2016; Melash et al. 2023) or wild foods (Carvalho et al. 2015; Kenny et al. 2018). The prioritization of Indigenous food systems and diets could also reduce the introduction of ultraprocessed foods into Indigenous territories, which Indigenous Peoples and scientists have identified as harmful for health, livelihoods and cultures (Kuhnlein and Receveur 1996; Kuhnlein et al. 2006).

These developments have massive implications for land use (**Figure 11.6**). In the *Behaviour-focused* pathway, the reduction in livestock production results in major decreases in grazing land, up to 780 Mha – half of total cropland area today – from 2020 to 2050. This allows for large increases in natural land, contributing to the achievement of climate, land degradation and biodiversity goals (11.4.1; 11.4.3; 11.4.4). Cropland continues to increase in all cases to achieve the food access goal, but also partly due to increased demand for bioenergy (11.3.1). However, a focus on residue-based bioenergy means that cropland requirements do not surpass 80 Mha or 5 per cent of projected cropland.

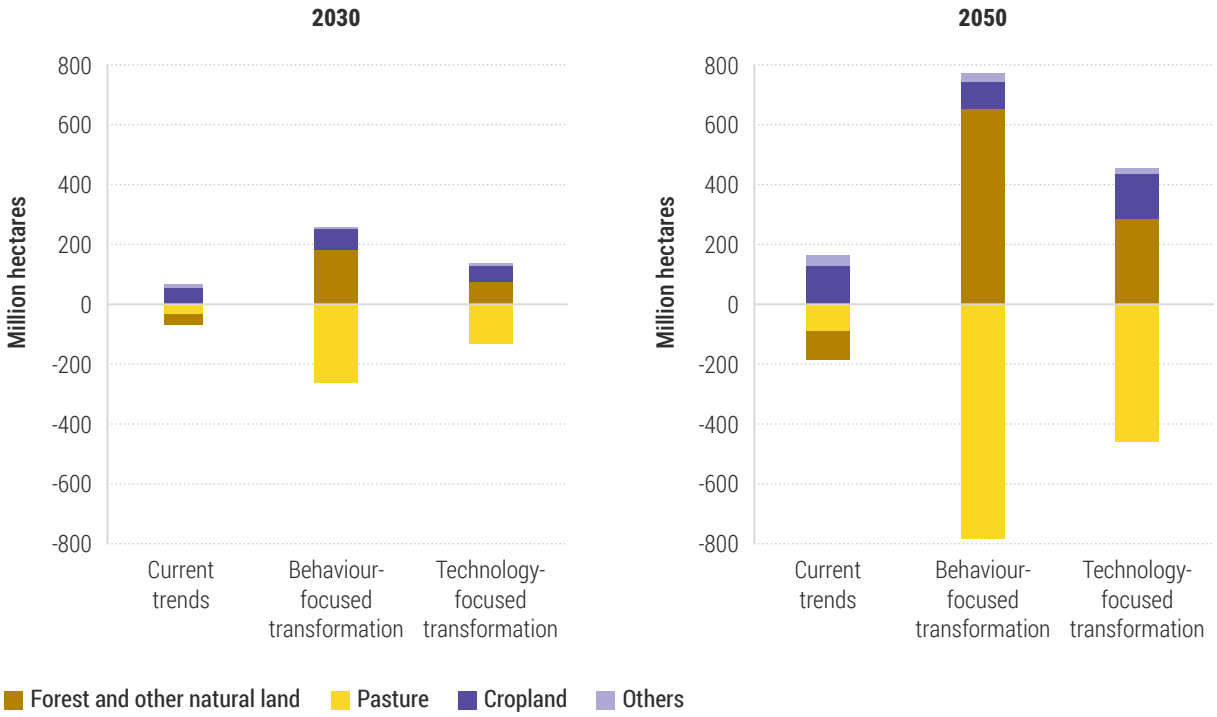
11.3.3 Material resources

Materials are crucial for meeting multiple goals, including energy system transformation, adequate housing and mobility, among other services. All pathways show a short-term increase in material demand, however innovation and technological change bring it back to current levels by 2050 on the *Technology-focused* pathway, while behavioural change can lead to reductions in global material demand of over 20 per cent by 2050, compared to 2020 (**Figure 11.7**). Global material demand is projected to peak at around 115 billion tons by 2030 for both *Transformation Pathways*, with the *Current Trends* increasing beyond 160 billion tons by 2050. This also translates into per capita material savings globally, reducing to 11.1 tons per capita on the *Technology-focused* pathway and 8.6 tons per capita on the *Behaviour-focused* pathway by 2050 from 17.6 tons per capita in the Current Trends. However, it is important to note that there are significant differences across regions and socioeconomic groups (Chapters 19 and 20).

These results align with the Global Resource Outlook 2024, which conducts a similar analysis with a specific focus on resource use (United Nations Environment Programme 2024). However, the Transformation Pathways presented here demonstrate a more radical shift in material supply and demand systems and recycling rates, leading to lower material intensities than the Global Resource Outlook.

Under both Transformation Pathways, fossil fuel extraction reduces by more than 70 per cent by 2050, showing the highest reduction in material demand relative to the *Current Trends*. The reduction in the Technology-focused pathway is driven by technological change and the *Behaviour-focused* pathway benefits from changes in energy consumption patterns, as

Figure 11.6: Changes, compared to 2020, in land areaby land-use classification in 2030 and 2050



Source: IMAGE 3.3 model (transformation pathways), AIM model (current trends).

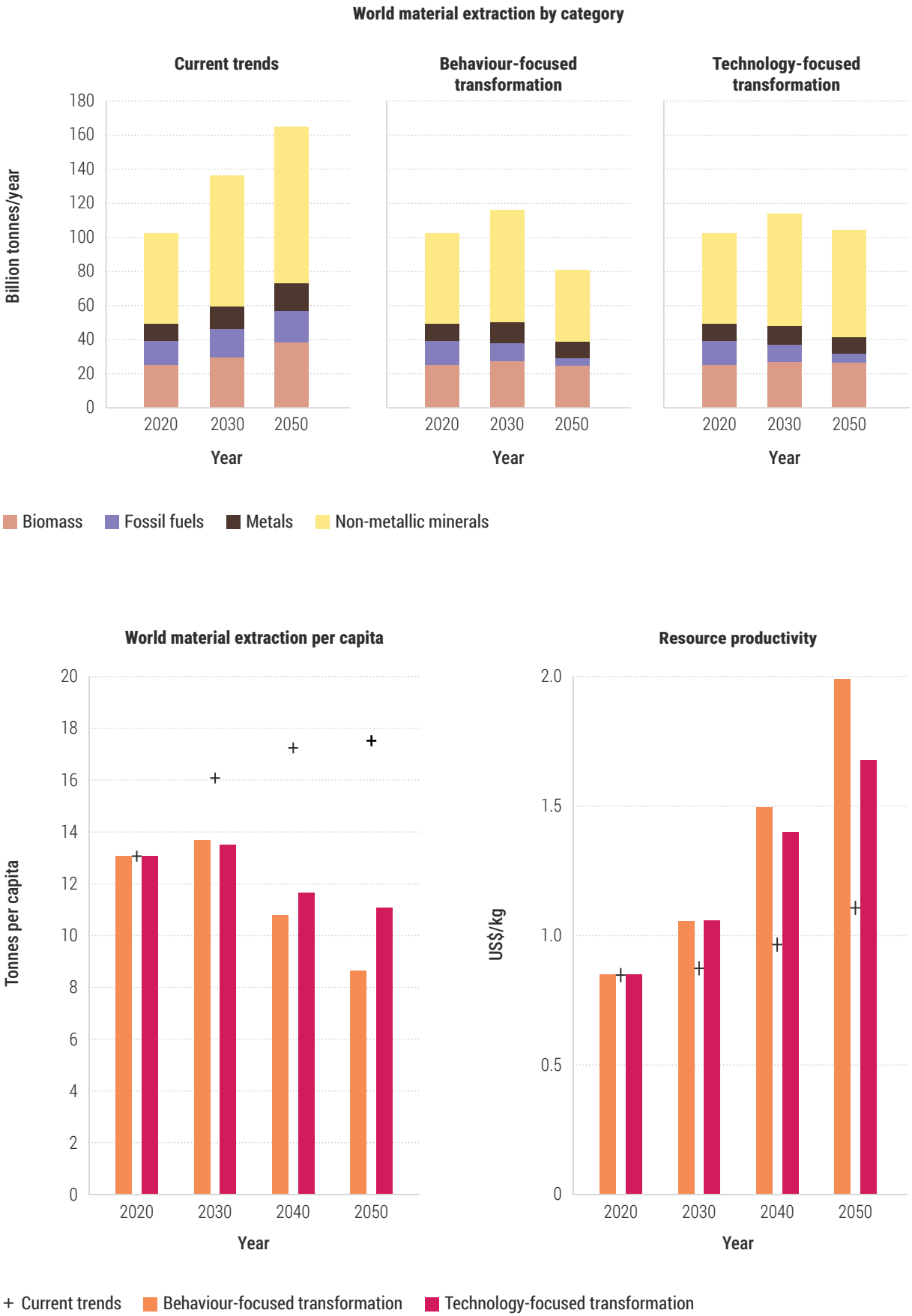
described in Section 11.3.1. The second largest percentage reduction, minus 40 per cent, is related to metal extraction, driven by the resource efficiency policies from both the demand side and the supply side. However, for certain metals such as copper, there is still increasing demand until 2050 due to its importance for energy transformation. In the *Behaviour-focused* pathway, the percentage reduction of non-metallic minerals, minus 54 per cent, highlights the importance of behavioural change in housing patterns, reflected by lower floorspace demand compared to the *Current Trends*. These reductions in material demand help reduce environmental damage and pollution arising from mining and transporting bulk materials.

11.3.4 Environment

To achieve the twin goals of reversing biodiversity loss and halting land degradation, both Transformation

Credit: Mumemories/Envato

Figure 11.7: Material extraction and resource productivity



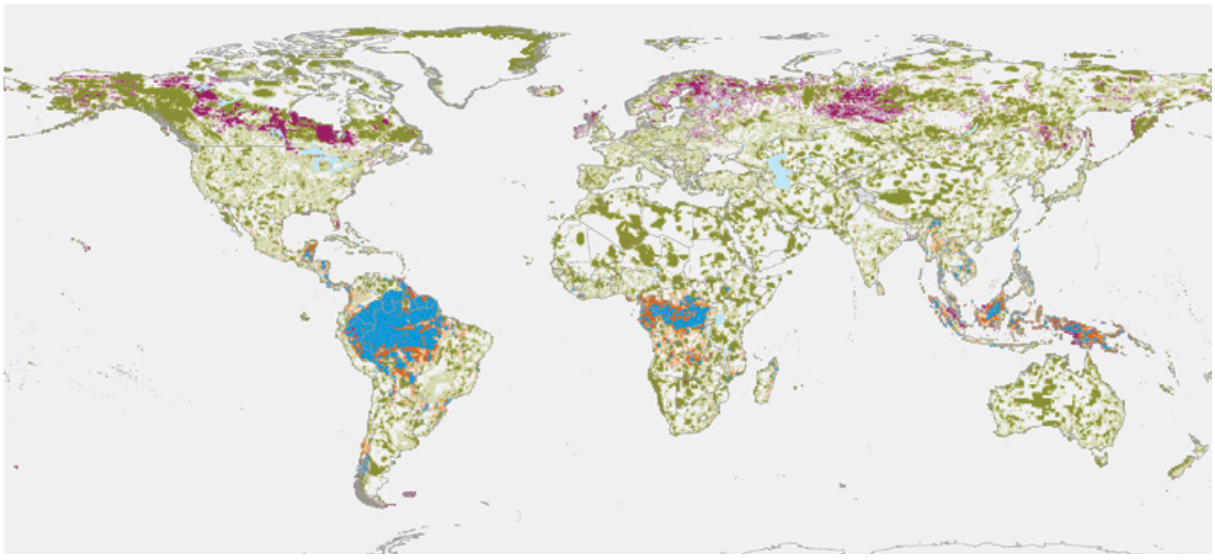
Source: GTEM

Pathways diverge strongly from the *Current Trends*, which entail continued conversion of natural land and intensification of agricultural production (10.3; 10.4). The required transition in environmental management includes expanding protected areas, increasing restoration of degraded ecosystems, sustainable land and sea use, reforestation and rewilding, and improved agricultural land management.

Protection of natural lands is common for both Transformation Pathways. In the *Technology-focused* pathway, 30 per cent of all terrestrial land is protected, in line with the Kunming-Montreal Global Biodiversity Framework (**Figure 11.8**). In addition, forests with high carbon stocks are protected in Annex II countries under the Reducing Emissions from Deforestation and Forest Degradation (REDD+) framework. In the *Behaviour-focused* pathway, an even more ambitious protected-area effort is introduced where 50 per cent of all terrestrial land has its natural capital protected (Wilson 2016; Kok et al. 2023), explicitly assuming that all ecosystems are considered equally valuable. Small-scale land use is allowed in these areas in line with the mutually beneficial use of nature, including agroforestry and other integrated production systems. In both pathways, natural peatlands are strictly protected. Total protected areas increase from approximately 2100 Mha in 2020, to 5500 and 6900 Mha in 2050 in the *Technology-focused* and *Behaviour-focused* pathway, respectively.

Furthermore, former agricultural lands and degraded forest areas undergo restoration, showing an increase in forest area (**Figure 11.6**). In the *Technology-focused* pathway, this is mainly achieved through reforestation and afforestation with monocultures, leading to relatively fast growth and carbon uptake. In the *Behaviour-focused* pathway, forests and other vegetation types are restored through natural regeneration providing slower carbon uptake, with some rapid-growth afforestation in high-income regions allowed to provide adequate carbon storage for the climate targets (11.4.1). Indigenous Knowledge and practices can provide guidance in ecosystem restoration, including cosmogonies and traditions that recognize all ecosystem elements as

Figure 11.8: Protected areas in the technology-focused transformation pathway



Note: The values indicate the percentage fraction of each grid-cell that is protected from conversion to human use. Each grid-cell is 30 arc-minute or approximately 50 km by 50 km at the equator. The colours indicate the primary reason for protection, distinguishing between biodiversity (green), carbon storage (orange), peatland (purple) or both biodiversity and carbon storage (blue). Protection of a given location may lead to synergies across biodiversity and carbon storage

Source: IMAGE 3.3

Credit: JuiceFlair/Envato

alive, making regeneration an integral part of life (IK & LK Dialogues 2025).

Improved land management is an important part of the required transition since in all pathways, agricultural production continues to use large areas. In the Behaviour-focused pathway, small-scale measures proliferate; by 2050, 50 per cent of all agricultural land would be under improved management, with a 40 per cent increase in residues left on the field and measures in place to store rainwater for the dry season. In the Technology-focused pathway, high-tech solutions include the expansion of irrigated areas, with a simultaneous increase in irrigation efficiency through the widespread implementation of drip irrigation to limit overall water consumption (11.4.6).

11.3.5 Economy and finance system

The Transformation Pathways require rapid changes both in the demand and supply of goods and services, with important implications for economic growth, and different financing needs. The deployment of required technologies necessitates accelerated technical progress, capacity expansion and extension and upgrade of energy and transport infrastructure (11.3.1), and sufficient financial resources to support investment growth. From the demand side, changes in behaviour towards environmentally sound lifestyles and circular patterns of consumption (11.3.1; 11.3.2; 11.3.3) are also required, which in many cases come at a low cost or even with gains for the households and firms adopting them.

The economic and financial effects of the transformation are also dependent on the relevant choice of instruments. Carbon pricing is a key instrument for carbon neutrality, as it internalizes the damages from climate change into the decisions of households, firms and governments, leading to emissions reductions. It can also generate revenues to finance clean energy innovation and research and development, support low-income households and reduce labour costs to firms through reduction of social security contributions.

The projected carbon prices consistent with the *Transformation Pathways* range from US$ 200–400/tCO_2 in 2050, with **Figure 11.9** showing the resultant revenues. The *Technology-focused* pathway requires higher carbon prices than the *Behaviour-focused* pathway to meet the climate goal due to increased demand for energy and land use, but it also has slightly higher carbon revenues that can aid with investments in technologies. It should be noted that these carbon prices do not reflect the potential costs of achieving technological innovations or behavioural changes, which are assumed a priori in the pathways. The economic and financial systems are affected by opposing forces in both Transformation Pathways. **Table 11.1** presents the main channels through which the economy and finance systems are affected. The possible role of different policy levers and different

actors in the transformation of the financial system is further explored in Chapter 14.

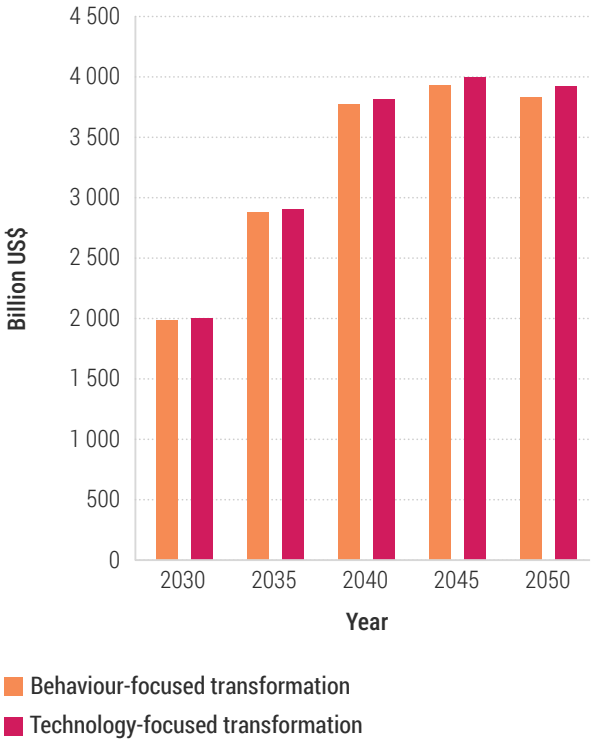
11.4 Environmental implications

This section discusses the effects of the transformation of the five systems on the global environmental crises. It also explores both the positive and negative implications of issues that are not directly included, including water stress and freshwater pollution.

11.4.1 Greenhouse gas emissions and climate change

In the two Transformation Pathways, CO_2 emissions decline immediately and rapidly, reaching net zero around mid-century, with total GHG emissions following a similar pattern (**Figure 11.10**). Other major GHGs, particularly CH_4 and N_2O, are also significantly reduced, but do not reach net zero. Thus, both *Transformation Pathways* present a complete break with the *Current Trends*.

Figure 11.9: Revenues from carbon pricing, used to accelerate R&D and support low-income households



Source: GEM-E3 model

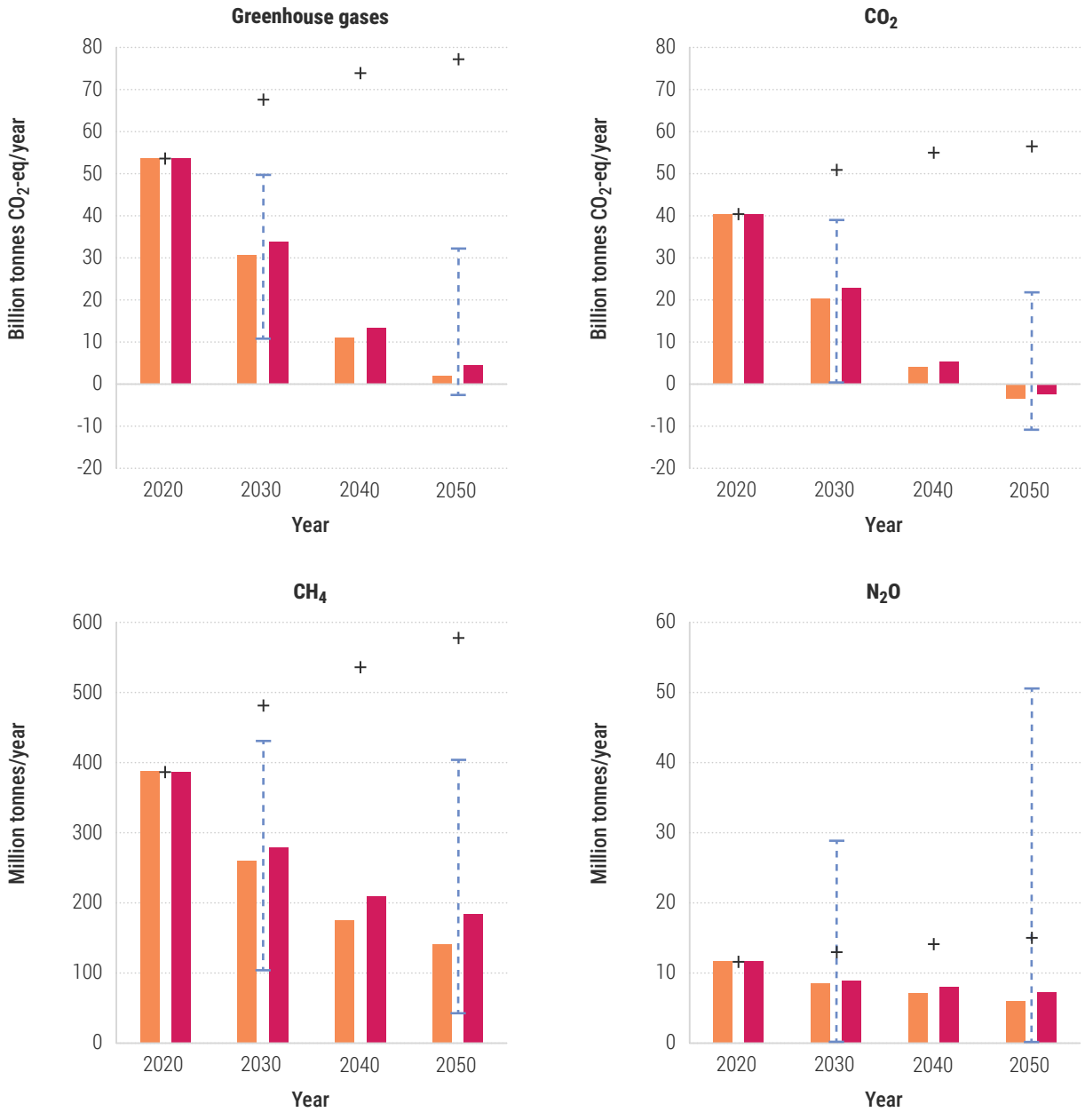
Table 11.1: Decomposition of GDP impact on key factors per Transformation pathway compared to the current trends

Factor	Behaviour-focused transformation pathway	Technology-focused transformation pathway
Technical progress for clean technologies	(-) Moderate impact on technology progress as most substitutions are driven by behavioural changes	(+) Accelerated technological progress, enhanced diffusion, lower capital costs
Finance	(+) No significant requirements for financing/ freeing up capital/lowering interest rates	(+) Lower capital costs due to technical progress, lower financing needs and stress on capital markets (-) Significant dependence on technology and capital/different costs of capital per country and technology/stress on capital markets
Resource availability	(+) Climate change mitigation lowers the cost of climate inaction (10.6.5) (+) Productivity infrastructure (+) Improved health and working hours	
Skills	Neutral impact on skills	(+) High-skilled labour, higher wages and income (-) Human capital availability potentially a barrier as it may not be available in time to support the rapid transformation required

Note: decomposition of GDP effect on key factors per Transformation Pathway compared to the Current Trends, which shows an average annual global GDP growth of approximately 3 per cent in the period 2020–2050. A (+) sign signifies a positive impact on GDP, and the (-) sign signifies a negative impact on GDP.

While the emission trajectories of the two Transformation Pathways are very similar, as they both reach the same climate goal, they do highlight the different possible routes. Besides the large differences in the energy, land use and materials/waste systems described in Sections 11.3.1 to 11.3.4, there are important differences regarding the sectoral emissions and when net-zero CO_2 is reached (**Figure 11.11**). Looking at the *Current Trends*, while overall emissions in 2050 are higher, the relative contribution of different sectors is similar compared to 2020. The *Behaviour-focused* pathway shows a very rapid emission reduction in the energy demand and supply sectors, with remaining positive emissions at

Figure 11.10: Global emissions of greenhouse gases, CO_2, CH_4 and N_2O



Note: All panels show the current trends and the two transformation pathways. The range of the results from the IPCC-assessed scenarios as shown in dashed lines are in line with the 1.5°C target (>50 per cent probability, with no or low overshoot, immediate action after 2020). The scenarios from the IPCC-AR6 have a primary focus on climate change goals only

Source: IMAGE 3.3 (transformation pathways) and AIM (current trends)

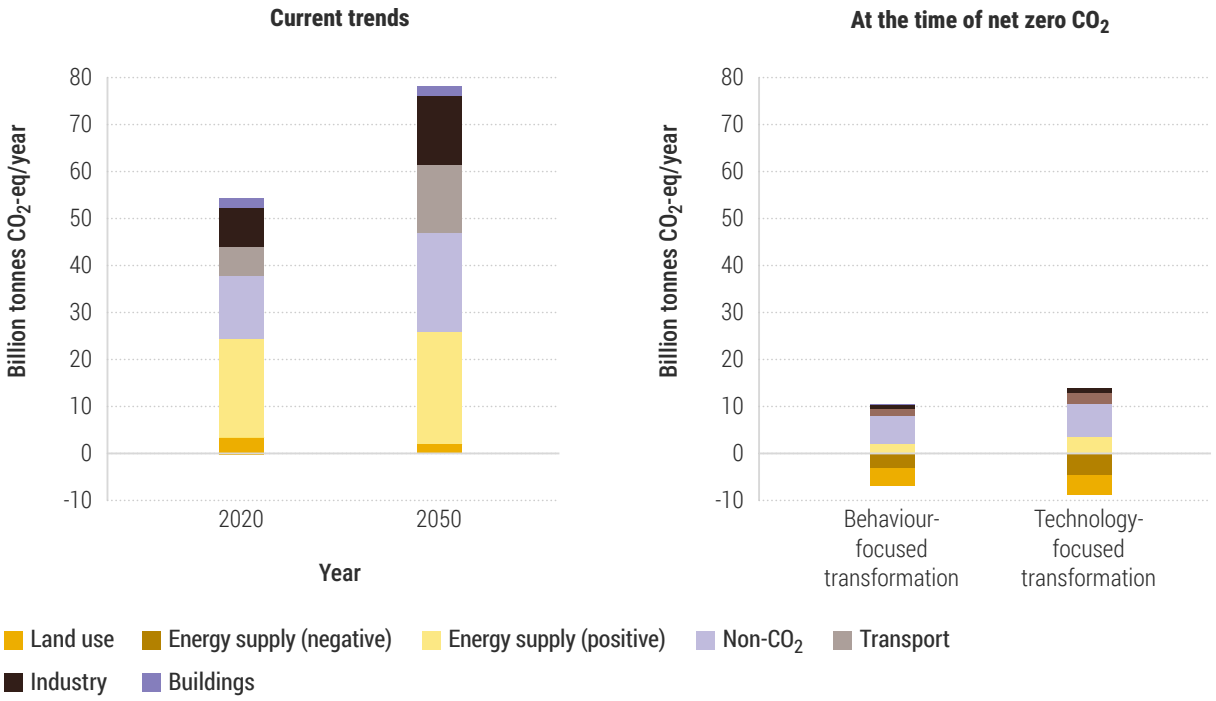
the time of net zero mostly made of non-CO_2 gases and hard-to-abate emissions in heavy transport and power production. The *Technology-focused* pathway shows a slightly higher aggregate level of positive emissions, requiring more negative emissions using CO_2 removal measures to compensate for remaining emissions from hard-to-abate sectors (Edelenbosch et al. 2024).

Carbon dioxide removal (CDR) options such as afforestation, bioenergy with carbon capture and storage or direct air capture of atmospheric carbon, and carbon capture and storage in general, can help with meeting strict climate targets (Pathak et al. 2022). These technologies play three important roles in meeting the climate targets (Babiker et al. 2022). They contribute to rapid reduction in overall emissions by decarbonizing the energy system; CDR can counterbalance residual emissions from hard-to-abate sectors (**Figure 11.11**); and CDR technologies can ensure climate goals are met after potential overshoot by providing net-negative emissions. Meeting targets on climate change without the use of CDR is extremely difficult, as it would imply reducing all GHG emissions to zero within a very tight time frame.

While both Transformation Pathways rely on CDR, the level of net-negative emissions is higher in the case of *Technology-focused*, increasing further towards the end of the century. This higher dependence of on CDR is due to the *Technology-focused* pathway permitting increased use and rapid adoption of these advanced technologies. The *Behaviour-focused* pathway reduces this dependency, lowering the need for carbon removal by having lower energy and land-use demand (11.3.1; 11.3.2).

Dependence on CDR poses risks for land-use competition, if it leads to upscaling of crop-based bioenergy with carbon capture and storage (BECCS) as well as land-based mitigation in the form of rapid-growth afforestation. The *Behaviour-focused* pathway poses a lower risk, with a 30 per cent and 50 per cent lower need for CDR in 2050 and 2100, respectively, compared to the *Technology-focused*. Both pathways aim to minimize the use of crop-based bioenergy by prioritizing bioenergy supply from agricultural and forestry residues (11.3.1). Concerning land-based mitigation, the *Behaviour-focused* pathway has a bias towards natural regrowth on abandoned lands that tend to have a slower uptake of CO_2, rather than

Figure 11.11: Sectoral GHG emissions in the year 2050 under the current trends, and at the respective year of net zero CO_2 for the two transformation pathways, compared to 2020 emissions



Note: For Transport, Industry and Buildings, only emissions from combustion are shown. Indirect emissions are covered under Energy supply.

Source: IMAGE 3.3 model (transformation pathways) and AIM model (current trends)

active use of the land for carbon management. The Technology-focused pathway focuses on planted forests that have a rapid uptake of CO_2 but may pose risks for biodiversity and land management. Notably, direct air carbon capture and storage is projected to become cost-competitive only after 2050, significantly later than other CDR methods.

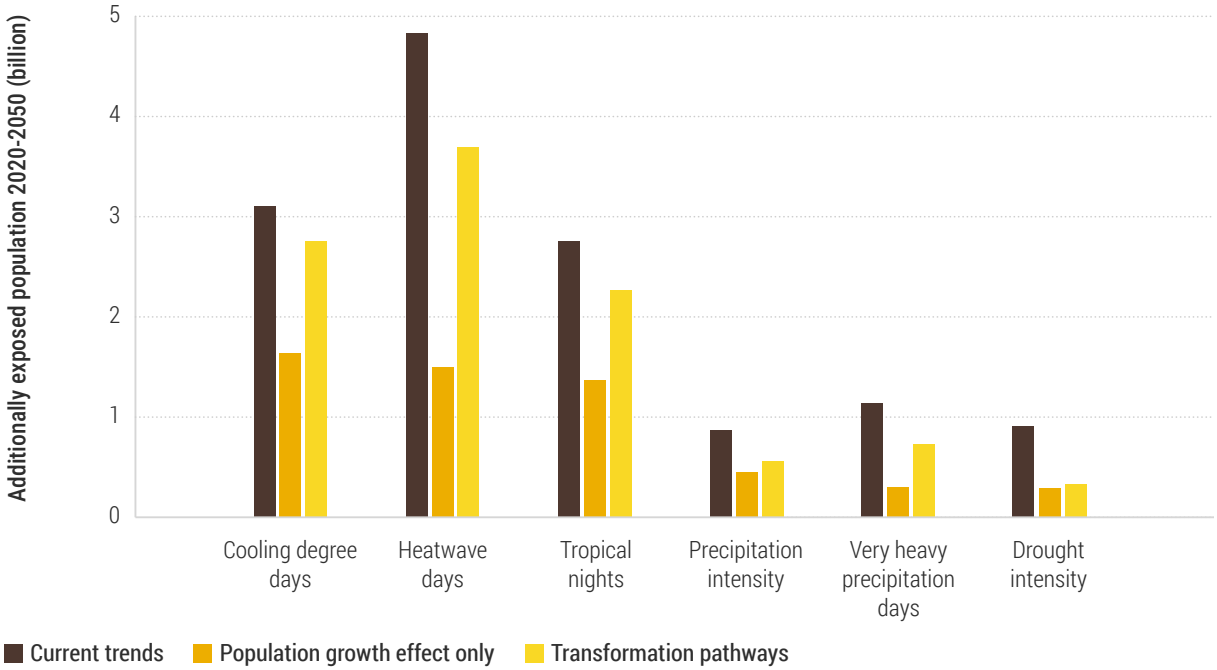
The *Transformation Pathways* present a vastly improved situation compared to the *Current Trends* concerning climate impacts by tracking six climate impact indicators: cooling degree days, heatwave days, tropical nights, precipitation intensity, very heavy precipitation days and drought intensity (**Figure 11.12**). By 2050, global population exposures across the six indicators are projected to increase compared to 2020 levels. Temperature-based indicators show the most substantial increases, with the Transformation Pathways presenting a marked reduction compared to the *Current Trends*. Hydrological indicators also show increases in exposure, although this is less pronounced than in the temperature-based ones, with the Transformation Pathways again presenting the best outcomes. For both the precipitation-intensity and drought-intensity indices, the Transformation Pathways significantly mitigate climate impacts, nearly bringing the exposure levels down to what would be expected from population growth alone. This highlights the potential of the Transformation Pathways to completely mitigate certain climate change impacts.

Overall, the Transformation Pathways reduce population exposure to climate risks compared to the *Current Trends* by 200 million to 1 billion people, depending on the indicator. Importantly, while the Transformation Pathways significantly reduce exposure across indicators compared to *Current Trends*, they do not eliminate increased exposure entirely. This illustrates the importance of adopting adaptation measures in parallel.

11.4.2 Air pollution

The ambient air quality projections are shown in **Figure 11.13**, with both Transformation Pathways depicting comparable ambient air pollutant concentration trends. The average global $PM_{2.5}$ decreases by 25 per cent

Figure 11.12: Additional population exposed to climate impacts in 2050



Note: Bars show additional population exposure levels relative to 2020 (see Figure 10.7 for 2020 levels), due to population growth, and further exposure under both the current trends warming (2.2°C by 2050) and the transformation pathways warming (1.55°C) for six climate indicators. Both Transformation pathways have identical climate outcomes, dictated by the goals of the Paris Agreement.

Source: RIME Model

between 2020 and 2050, with most of the decrease happening in the short term. Both Transformation Pathways represent an improvement compared with the *Current Trends* pathway where concentrations increase between 2020 and 2030 (10.4.2). This improvement is mainly due to the abatement of SO_2 with minus 80 per cent and NOx with minus 70 per cent emissions in the energy and transport sectors, as well as NH_3 with a reduction of 40 per cent in the agricultural sector. The reduction in $PM_{2.5}$ is higher than other published scenarios with similar climate targets (Turnock et al. 2020), indicating the added benefits of transforming multiple systems simultaneously. Global ozone levels fall by 8 per cent in 2050 compared with 2020, due to the combined effect of NOx and VOC emissions abatement. Such concentration reduction is comparable with the one projected for the same time window in a scenario exploring maximum feasible reduction (Bessagnet et al. 2024).

Both transformations show an improvement in global population exposure to $PM_{2.5}$ compared to the *Current Trends* pathway, mainly observed in Eastern and Southern Asia, Eastern Europe and Africa, while comparable or slightly lower levels are observed in the rest of the world (**Figure 11.14**). Global ozone summer exposure is lower in the Transformation Pathways compared to the Current Trends everywhere, with the maximum improvements of minus 1000–2000 ppb·day in the Persian Gulf and Eastern Asia, due to changes in fossil fuel production and use.

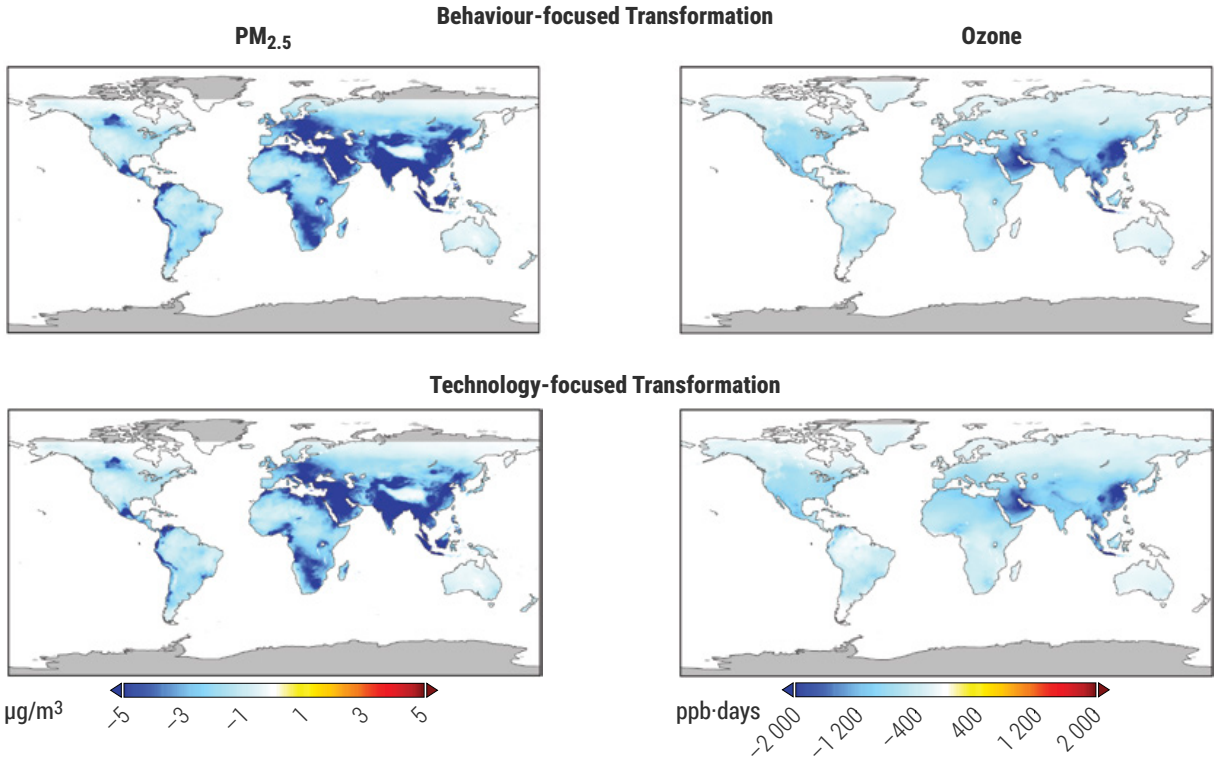
These differences result in decreased mortality due to air quality (**Figure 11.15**). Between 2030 and 2040, almost 1.2 million premature deaths per year are prevented due to lower $PM_{2.5}$ exposure. Both Transformation Pathways show that by 2050 the prevented premature deaths reduce to 0.9 million as the *Current Trends* pathway also shows a benefit in the longer term, reducing the overall positive impact of the Transformation Pathways. A similar situation is observed in the mortality attributable to ozone exposure, with a maximum benefit of 220,000 prevented premature deaths annually in 2040.

These results are in line with those reported in the literature for a scenario with similar climate targets (Yue et al. 2024). However, while the air pollution

Figure 11.13: Global trends of $PM_{2.5}$ and ozone from 2020 to 2050 in the *Behaviour-focused* and *Technology-focused* transformation pathways compared to the current trends

Source: JRC-FASST model

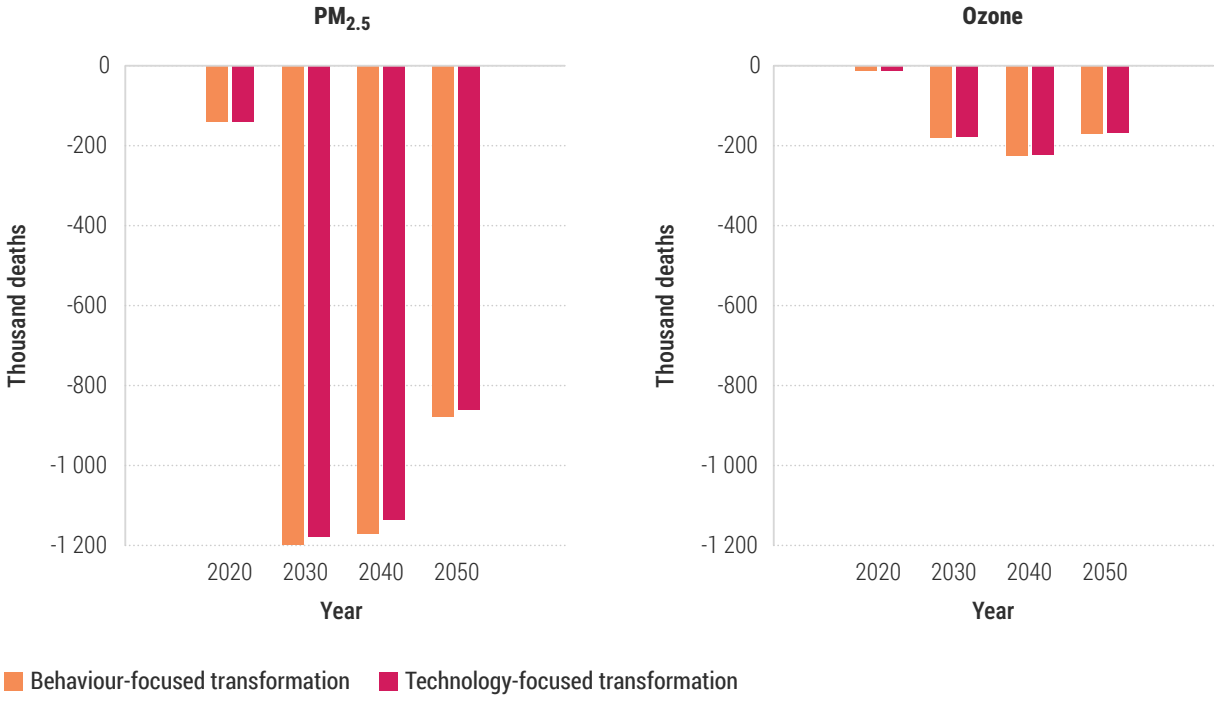
Figure 11.14: Difference in exposure to ambient air pollution in the Transformation Pathways compared to the Current Trends in 2050



Note: the population-weighted exposure indicators are $PM_{2.5}$ (µg/m^3) annual average while for ozone is reported the 6-month SOMO 35 (ppb•days)

Source: JRC-FASST

Figure 11.15: Prevented premature deaths from air pollution in transformation pathways compared to current trends



Source: JRC-FASST model

goal of reducing population exposed to $PM_{2.5}$ to less than 10 per cent by 2050 is met for most regions, it is not achieved in Africa with 47 per cent by 2050, nor Asia and the Pacific with 39 per cent by 2050. This is despite improvement compared to both 2020 and the *Current Trends* pathway and highlights the difficulties in achieving this goal in these regions.

11.4.3 Land degradation

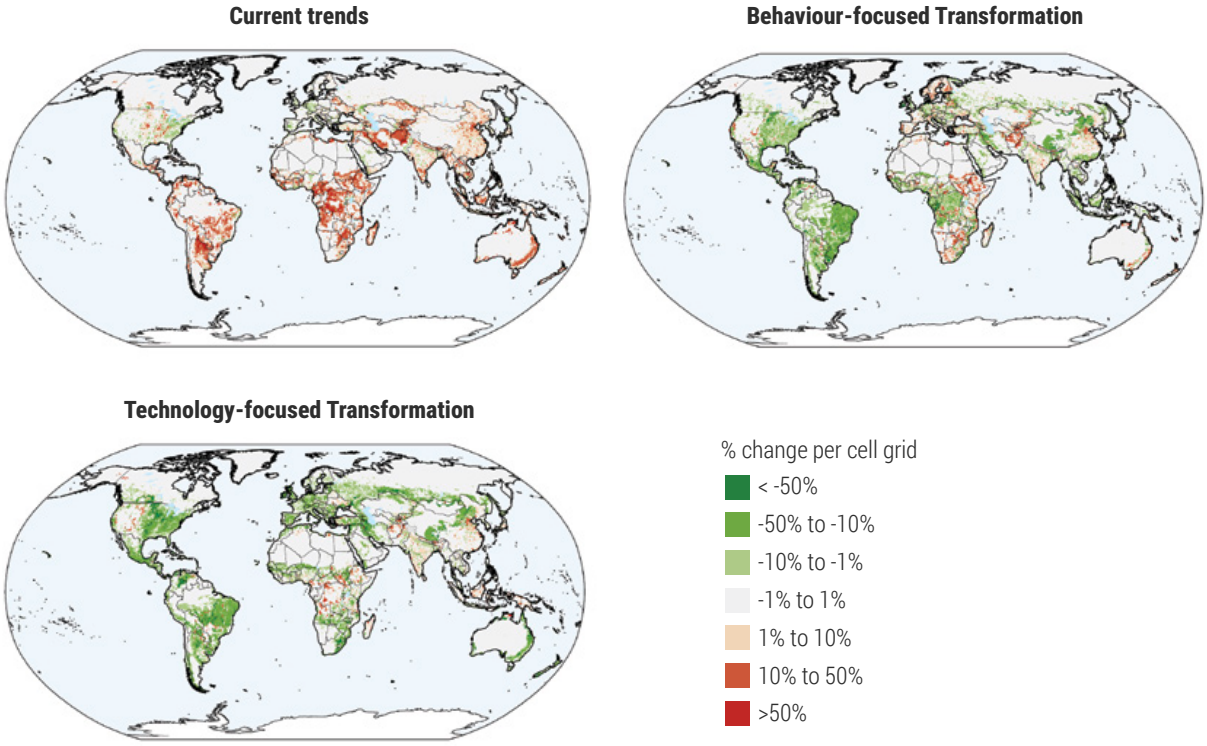
In both Transformation Pathways, the continued loss of natural land observed in *Current Trends* is mostly prevented, largely due to reductions in grazing land driven by dietary shifts (**Figure 11.16**). This allows for a large-scale expansion of forests and other natural land. In the near term of 2025–2030, Sub-Saharan Africa still experiences some land-use change for food production, but the extent varies across the pathways. As the *Technology-focused* pathway includes strict protection of all forests with high carbon stocks, conversion mostly takes place in non-forest ecosystems such as the Savannah. In the *Behaviour-focused* pathway, synergistic use of forest and non-forest ecosystems implies some conversion of natural land to food production in Sub-Saharan Africa.

Both Transformation Pathways preserve substantially more carbon stocks in above-ground vegetation compared to the *Current Trends* (**Figure 11.17**). Forest expansion also allows for additional sequestration of carbon, with faster uptake in the *Technology-focused* pathway due to large-scale planting of managed forests. Soil carbon stocks are also affected by different agricultural management methods. Most notably in the *Behaviour-focused* pathway, the use of residues on fields fosters soil organic carbon levels, increasing by 2.9 tons carbon per hectare (tC/ha) on average from 2020 to 2050.

11.4.4 Biodiversity loss

Figure 11.18 breaks down the characteristics of the Transformation Pathways leading to improved biodiversity outcomes, highlighting the very important role of climate change mitigation and the land-use changes outlined in Sections 11.4.1 and 11.4.3. Limiting

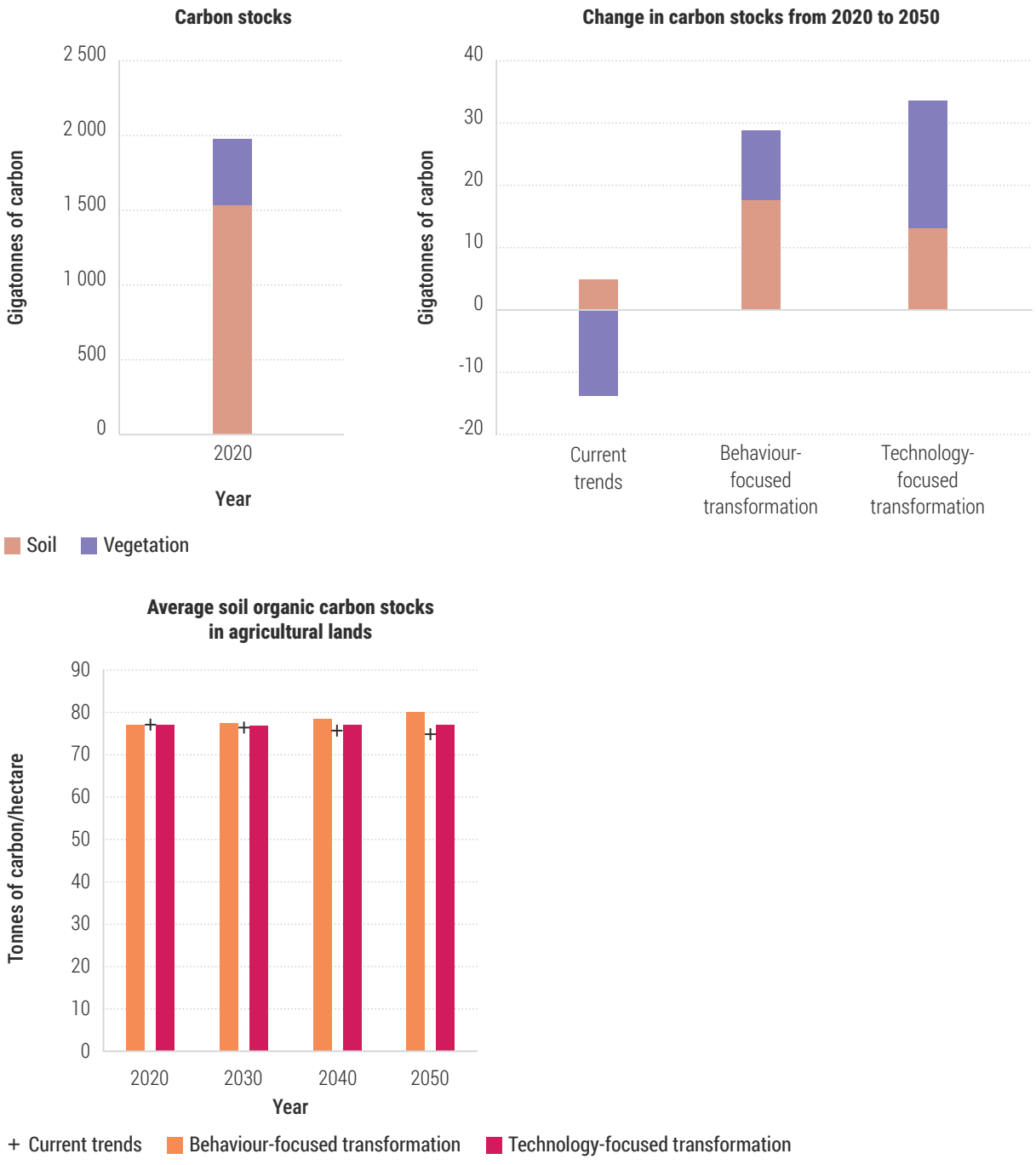
Figure 11.16: Natural land conversion in the Current Trends, Technology-focused and Behaviour-focused Transformation Pathways from 2020 to 2050



Note: An increase (red colour) indicates deforestation or use of other natural land, while a decrease (green colour) indicates reforestation or restoration of other natural ecosystems

Source: IMAGE 3.3

Figure 11.17: Carbon stocks in soils and vegetation in 2020, and changes in total soil and vegetation carbon stocks from 2020 to 2050

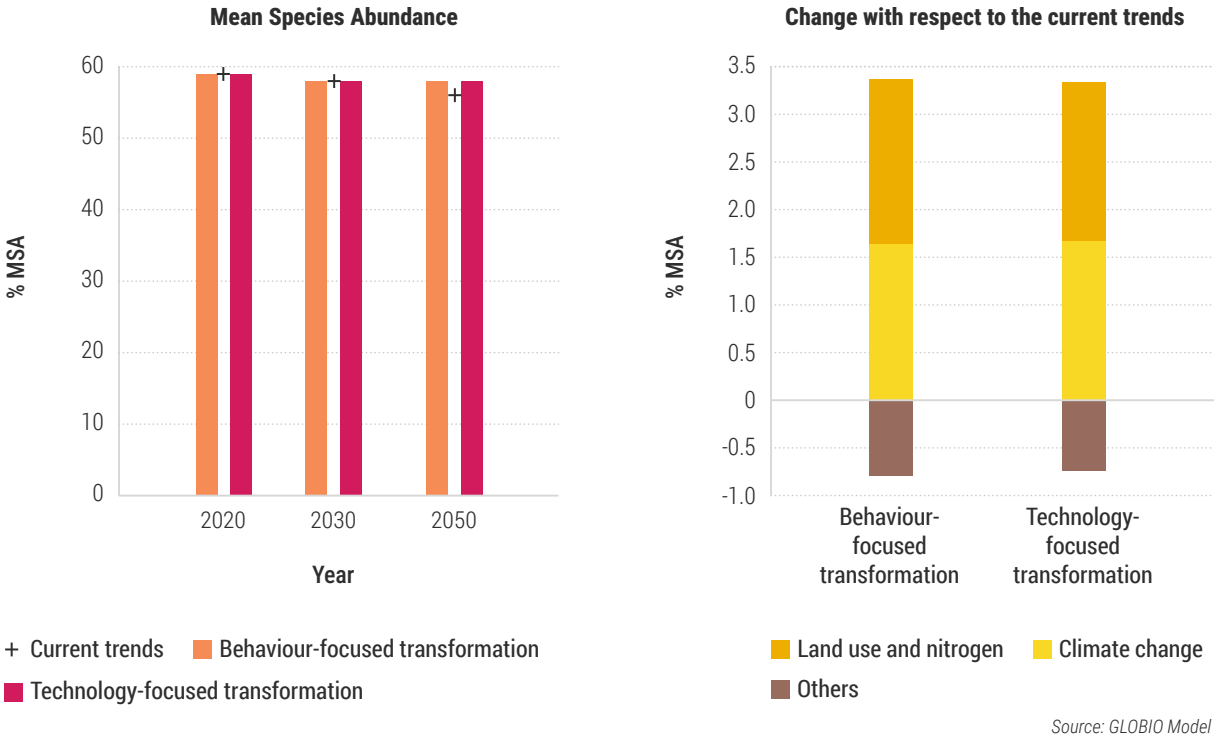


Source: IMAGE 3.3 model

global mean temperature increase to 1.5°C improves mean species abundance, a measure of biodiversity intactness, by more than 1.6 per cent. Differences in land-use projections and nutrient pollution lead to a further improvement of 1–2 per cent, depending on the Transformation Pathway.

The different transformations of the energy and food systems contribute to improving biodiversity compared to the Current Trends via their implications for climate change and land use. In both Transformation Pathways, while cropland increases slightly, reductions in pastureland result in improved biodiversity outcomes. The impacts of climate change increase slightly up to 2050, but less so than the Current Trends, stabilizing biodiversity loss. This highlights that mitigating climate change, while avoiding additional land use, is important in achieving biodiversity targets.

Figure 11.18: Projections of Mean Species Abundance (MSA), and factors contributing the MSA difference in the transformation pathways with respect to the current trends in 2050



Source: GLOBIO Model

Halting biodiversity loss also requires addressing other factors, including introducing biodiversity-friendly forestry (Kok et al. 2018); reducing direct harvest from ecosystems, including hunting and collection of plant products at unsustainable levels, whether legal or illegal; reducing pollution and reducing habitat fragmentation. However, although these transformations are an important prerequisite, they need to be supplemented by appropriate land protection and conservation measures. Indigenous Peoples' practices and their knowledge related to food production and regeneration are vital to consider

Credit: thananit_s/Envato

in addressing the impacts of these transformations on biodiversity (Argumedo et al. 2021; FAO, Alliance of Bioversity International and CIAT 2021). The implications of the Transformation Pathways for global biodiversity are comparable to other studies (Kok et al. 2023; Leclère et al. 2020), which include a similar set of measures as those employed in the Transformation Pathways, albeit at different levels and combinations.

11.4.5 Nutrient pollution

In both Transformation Pathways, water quality improves through lower nitrogen and phosphorus concentration levels. The key driver for this is increased nitrogen-use efficiency in agriculture, implying a lower fertilizer input to produce the same amount of crops, and lower losses to the environment. Additionally, dietary changes mean less livestock, which reduces manure production, thereby limiting nutrient release into surface waters (**Figure 11.19**). Wastewater from human activities also affects water quality, particularly the degree of sanitation and wastewater treatment (van Puijenbroek et al. 2023). Substantial improvements in wastewater treatment in both Transformation Pathways are assumed, reducing the effects of wastewater on surface water quality. Finally, high levels of nutrient production can also lead to the acidification of soils, degradation of coastal ecosystems and eutrophication, with associated impacts on biodiversity (Guo et al. 2010; Zhu et al. 2018; Zhu et al. 2020; Norwegian Meteorological Institute 2024). All these impacts are mitigated in the Transformation Pathways by reducing the discharge of nutrients.

To assess improvements in water quality, the areas exceeding threshold concentration values for surface and groundwater are compared (10.4.5). **Figure 11.20** shows that surpassing the threshold for both nitrogen and phosphorous in surface and groundwater is projected to be substantially lower in the Transformation Pathways when compared to both the Current Trends pathway and 2020 values. These improvements are focused on high-income regions. In middle- and low-income regions, water quality improvements are more difficult to achieve due to strong increases in population, consumption and agricultural production.

11.4.6 Water scarcity

As shown in **Figure 11.21**, both Transformation Pathways project lower water use than the Current Trends. Interestingly, in the Technology-focused pathway, the Sahel region of Sub-Saharan Africa shows an increase in water use compared to Current Trends due to efforts to increase agricultural production through irrigation. This highlights a potential trade-off between water scarcity and agricultural production, even with efficient irrigation. In contrast, the Behaviour-focused pathway focuses more on increasing rain-fed yields with small-scale decentralized improvements to save rainwater, and applying mulch to prevent evaporative losses and increase infiltration (Jägermeyr et al. 2017; He and Rosa 2023). Furthermore, decarbonizing the energy system is also beneficial due to less water demand from thermal power plants, which have very high cooling water needs.

While both pathways show a decrease in blue water consumption compared to the Current Trends, in the Technology-focused pathway, this is driven by increased irrigation efficiency, whereas the Behaviour-focused pathway benefits from fewer irrigated areas. The Behaviour-focused pathway sees a strong increase in green water consumption through better rainwater management. This highlights the different ways in which both pathways increase their water productivity and decrease total cropland compared to the Current Trends. Especially in the Behaviour-focused pathway, the rainwater management options applied in small-scale agriculture contribute to a large decrease in the water yield gaps on rain-fed cropland (**Figure 11.22**).

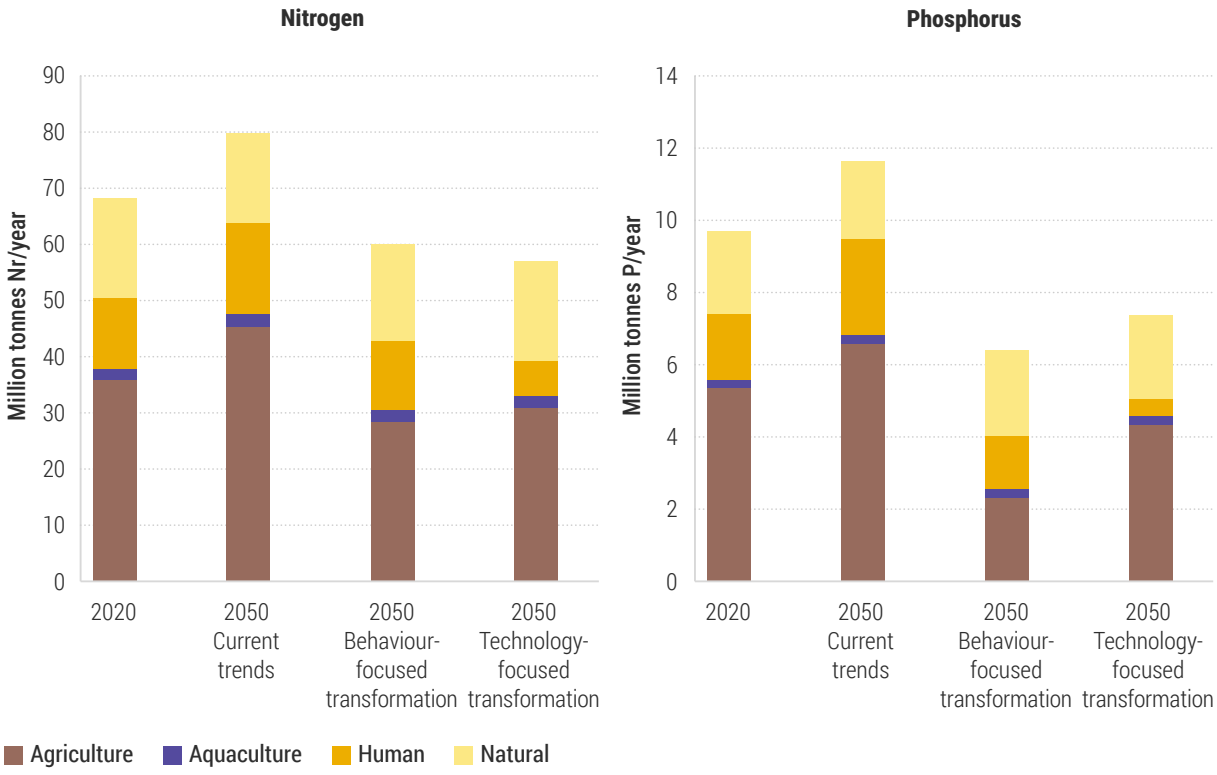
11.5 Socioeconomic implications

Environmental and social systems are intimately connected. This section focuses on the implications of the Transformation Pathways on socioeconomic outcomes and human well-being, mainly at a broad, global level. However, meeting the included targets requires addressing disparities across regions and populations, including addressing gender-specific needs and the effects of environmental crises (Pirzadeh et al. 2023).

11.5.1 Basic material needs

The Transformation Pathways assume the ability to meet basic human material needs, including hunger, as well as access to key infrastructure like electricity, water, and sanitation (9.3). Both Transformation Pathways lift almost 200 million people out of

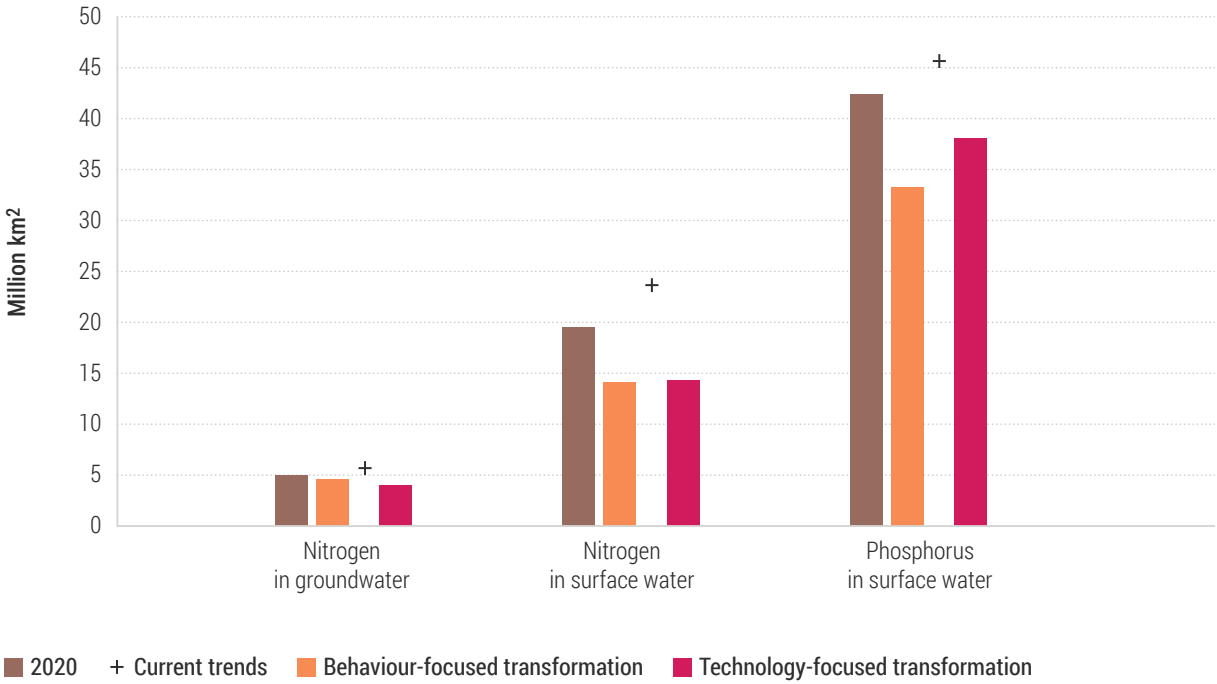
Figure 11.19: Delivery of nitrogen and phosphorus to surface water from the different sources for 2020 and 2050



Note: Nr refers to reactive nitrogen.

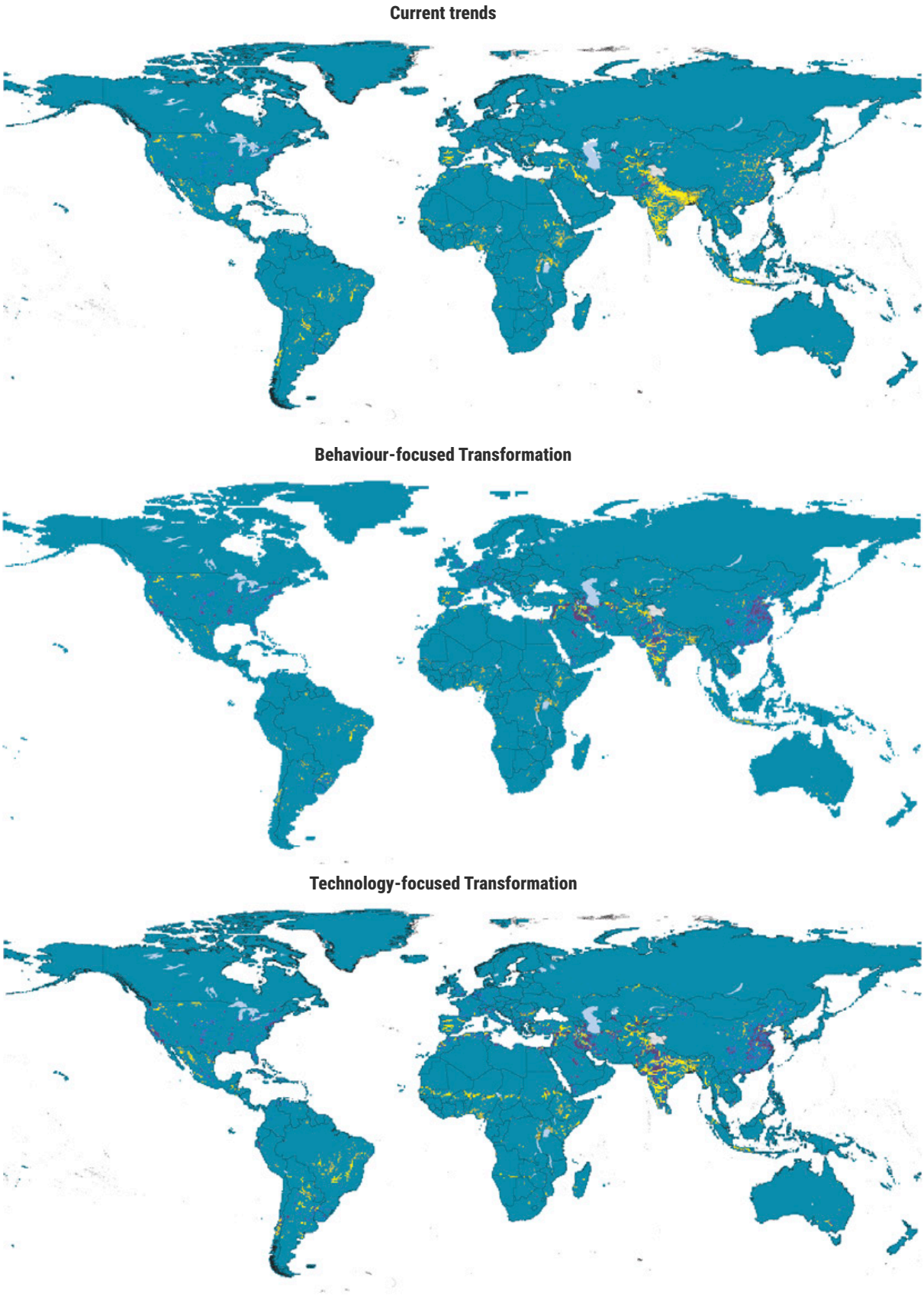
Source: IMAGE-GNM model

Figure 11.20: Area in Mkm² in 2050 which has a concentration above the threshold of nitrogen in groundwater, nitrogen in surface water, and phosphorus in surface water



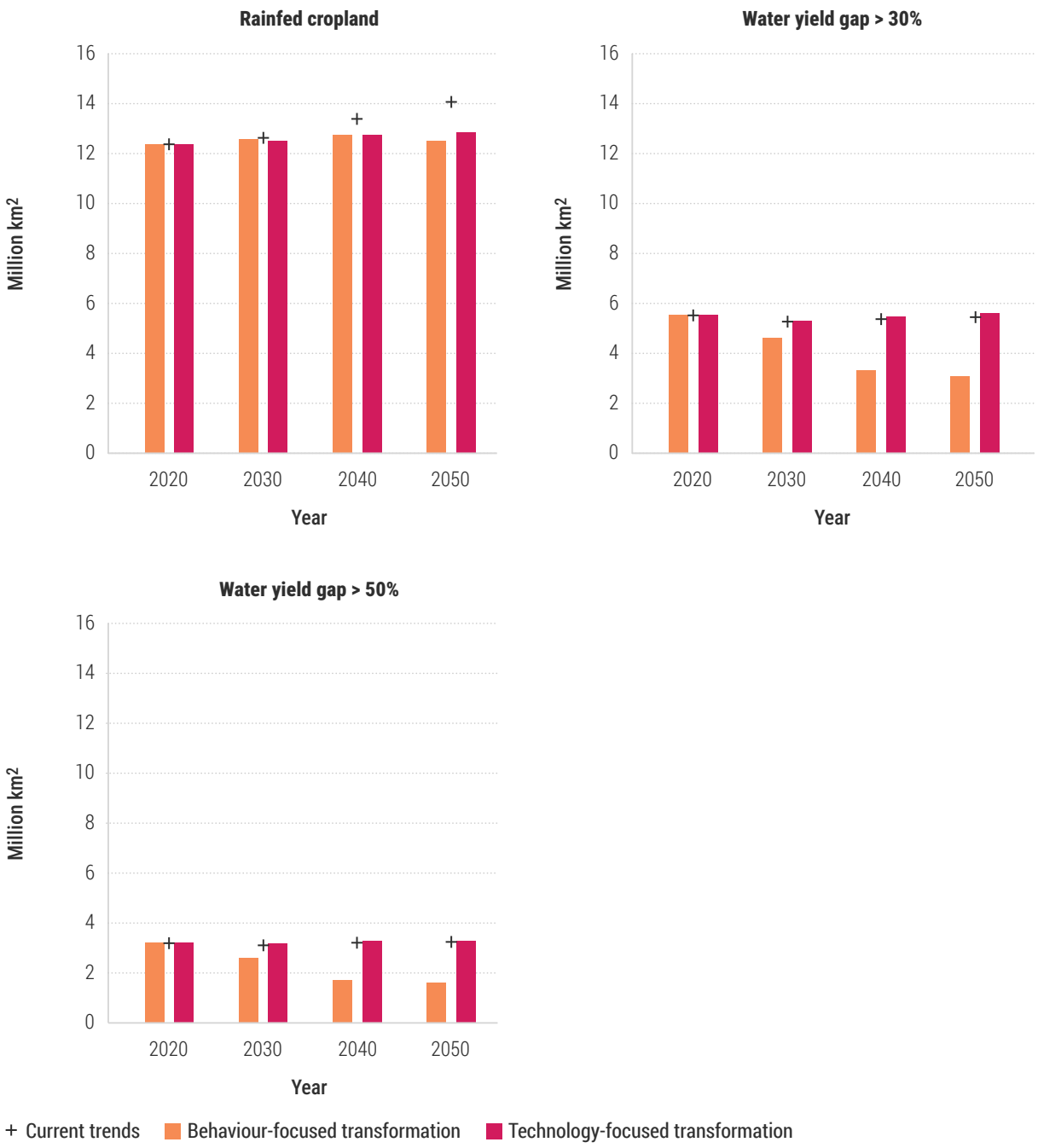
Source: IMAGE-GNM Model

Figure 11.21: Change in total blue water withdrawal (2020 to 2050) for irrigation, energy generation (including cooling water), and industrial and municipal use



Source: IMAGE-LPJml Model

Figure 11.22: Changes in total rainfed cropland extent, and the rainfed cropland that is experiencing a water yield gap of over 30 per cent and 50 per cent



Source: IMAGE-LPJml Model

undernourishment, relative to the Current Trends pathway, by 2050 (**Figure 11.23**). In the Technology-focused pathway this is achieved via technologically assisted yield improvements and boosted incomes from economic growth (11.3.2; 11.5.5). In the Behaviour-focused pathway, improved agricultural management, food distribution and shifting dietary patterns are the main drivers of food security.

The described changes in agricultural production contribute to alleviating hunger, but they cannot solve the problem of food access. Addressing physical and economic barriers and facilitating improved access and affordability, through food prices and nutrition education for example, is critical in both Transformation Pathways (Drewnowski et al. 2020; Kasprzak et al. 2021). To achieve the undernutrition target in the Transformation Pathways, the

Figure 11.23: Trend in selected SDG targets

Source: IFs model

distribution of calories globally needs to match the food distribution equality of countries performing above the 90th percentile (Verhagen et al. 2023). This points towards the requirement of additional calorie distribution measures (Aziz et al. 2021; Fabian, Gomez and Rosete 2023). Furthermore, an inclusive nutrition education needs to recognize Indigenous Knowledge about local diets, acknowledge food preferences and make information about new types of foods universally accessible.

Universal access to electricity results in nearly 120 million electricity connections by 2050, beyond what is projected in the Current Trends scenario. Most of these additional connections would be in rural areas where electricity may be limited and building new connections can be costly (Mitra and Buluswar 2015; Dagnachew et al. 2017; Perez-Arriaga et al. 2019; Sahadevan et al. 2023). However, universal electricity access enables households to move away from traditional cookstoves, a major cause of indoor air pollution and associated respiratory disease and infections (11.4.2), especially for women. However, there is some conflicting evidence of the benefits (Checkley et al. 2021; Rasul et al. 2025) of access to clean cooking that needs to be assessed, especially for Indigenous Peoples. Although traditional cooking methods are typically without monetary cost, it is important to consider the economic implications of subsidizing this new technology for Indigenous Peoples' families and local communities (World Bank 2020), otherwise a new inequity may arise.

In both Transformation Pathways, 300 million more people have access to safely managed water sources by 2050 and nearly 1 billion more people have access to safely managed sanitation than under Current Trends. The cost of this expansion is estimated to be US$ 1.2 trillion.

11.5.2 Good health

As already outlined, the Transformation Pathways improve human health by alleviating hunger and undernourishment, expanding access to water and sanitation services and reducing air pollution. Consequently, the overall burden of disability-adjusted life years is reduced by up to 2 per cent annually, enabling more than 750 million years of healthy living by 2050, increasing to over 3 billion by 2100 in both Transformation Pathways.

By reducing the prevalence of both communicable and noncommunicable diseases (**Figure 11.24**) the Transformation Pathways avert nearly 9 million premature deaths by 2050 and more than 50 million by 2100. Communicable disease deaths disproportionately affect young children (GBD 2019 Child and Adolescent Communicable Disease Collaborators 2023) and the Transformation Pathways can rapidly reduce child mortality rates. Neonatal and under-5 child mortality rates are projected to reach the respective SDG target values three years ahead of the Current Trends. Mortality from noncommunicable diseases is also improved by reducing heart disease, already the top cause of mortality globally, through improved diets and air quality (Reddy and Katan 2004; Jankovic et al. 2015; Naghavi et al. 2021). This reduction is prominent under the Behaviour-focused Transformation Pathway, which results in 1.4 million fewer annual deaths from heart disease by 2050, compared with 0.5 million in the Technology-focused pathway.

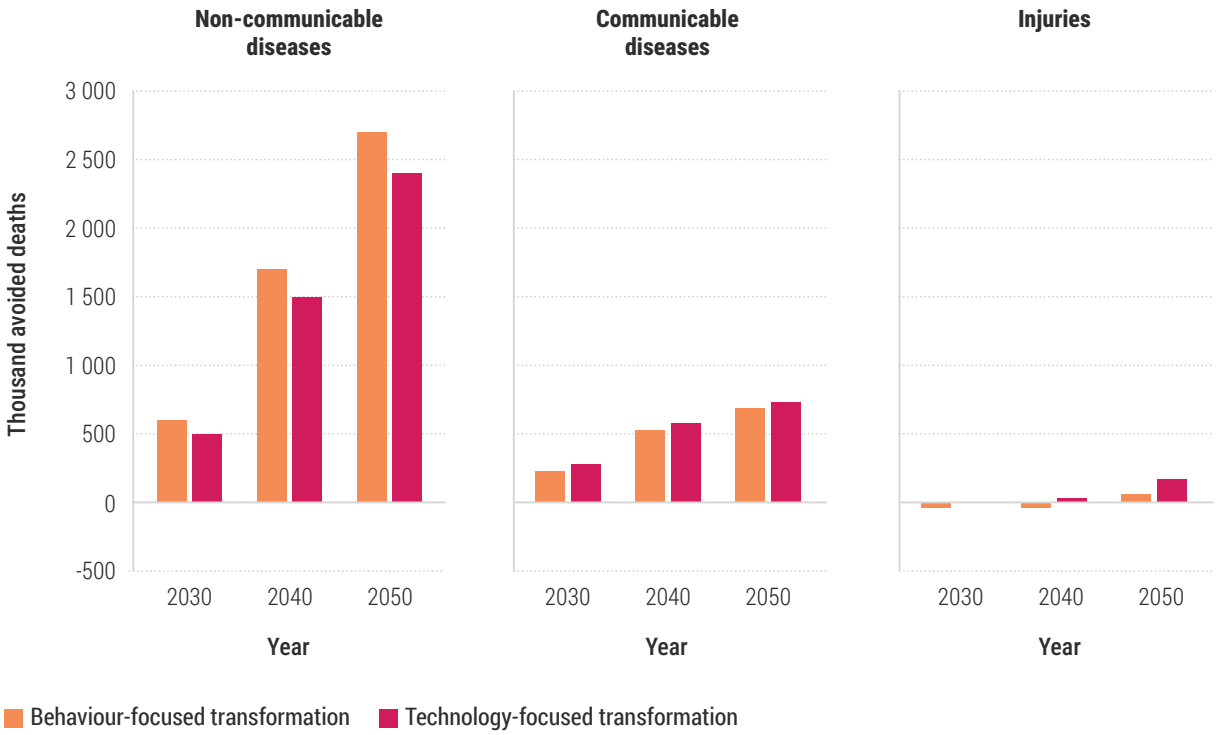
As a result of the Transformation Pathways leading to a healthier and longer-living population, age-related deaths become more prevalent. The Transformation Pathways increase overall life expectancy by 0.1 years in the first few decades and 0.3 years by the end of the century, in addition to improvements seen in the Current Trends pathway. In low-income economies, life expectancy improves by more than one year by the latter half of the century in the transition pathways.

11.5.3 Fair and just societies

Section 10.6.3 shows that poverty is expected to fall gradually in the Current Trends projection, but that progress is not sufficient to meet development targets. While the Transformation Pathways do not include interventions to address poverty directly, by avoiding substantial climate and environmental damages and fostering economic growth, both Transformation Pathways result in more than 150 million people escaping extreme poverty compared to the Current Trends (**Figure 11.23**).

One measure of just societies is their ability to adequately distribute resources to the most vulnerable populations (Hancher et al. 2022). **Figure 11.25** highlights the difference in extreme poverty rates between women and men in different regions. The large imbalances in regions with significant poverty is further mitigated in all projections, but at a faster rate

Figure 11.24: Annual avoided deaths of the transformation pathways relative to the current trends



Source: IFs model

in the Transformation Pathways. However, by 2050, some of this imbalance remains, particularly in Asia and the Pacific, and Africa, highlighting the need for extra effort to ensure gender justice.

11.5.4 Security

Expected economic growth will generally improve global security in the Current Trends scenario (10.6.4). There is evidence that worsening environmental conditions can lead to conflicts over increasingly scarce natural resources (Abel et al. 2019). Environmental crises may also lead to greater migration, which could cause additional strain in destination countries, further increasing conflicts (Hegre and Sambanis 2006; Goldstone et al. 2010; Mach *et al*. 2019). By easing the pressures on natural resources and averting environmental crises, the Transformation Pathways could reduce the risk of conflict and instability in the long run. Additionally, overall improvements in human development and well-being lower the likelihood of violent conflict (Fearon and Laitin 2003; Hegre and Sambanis 2006).

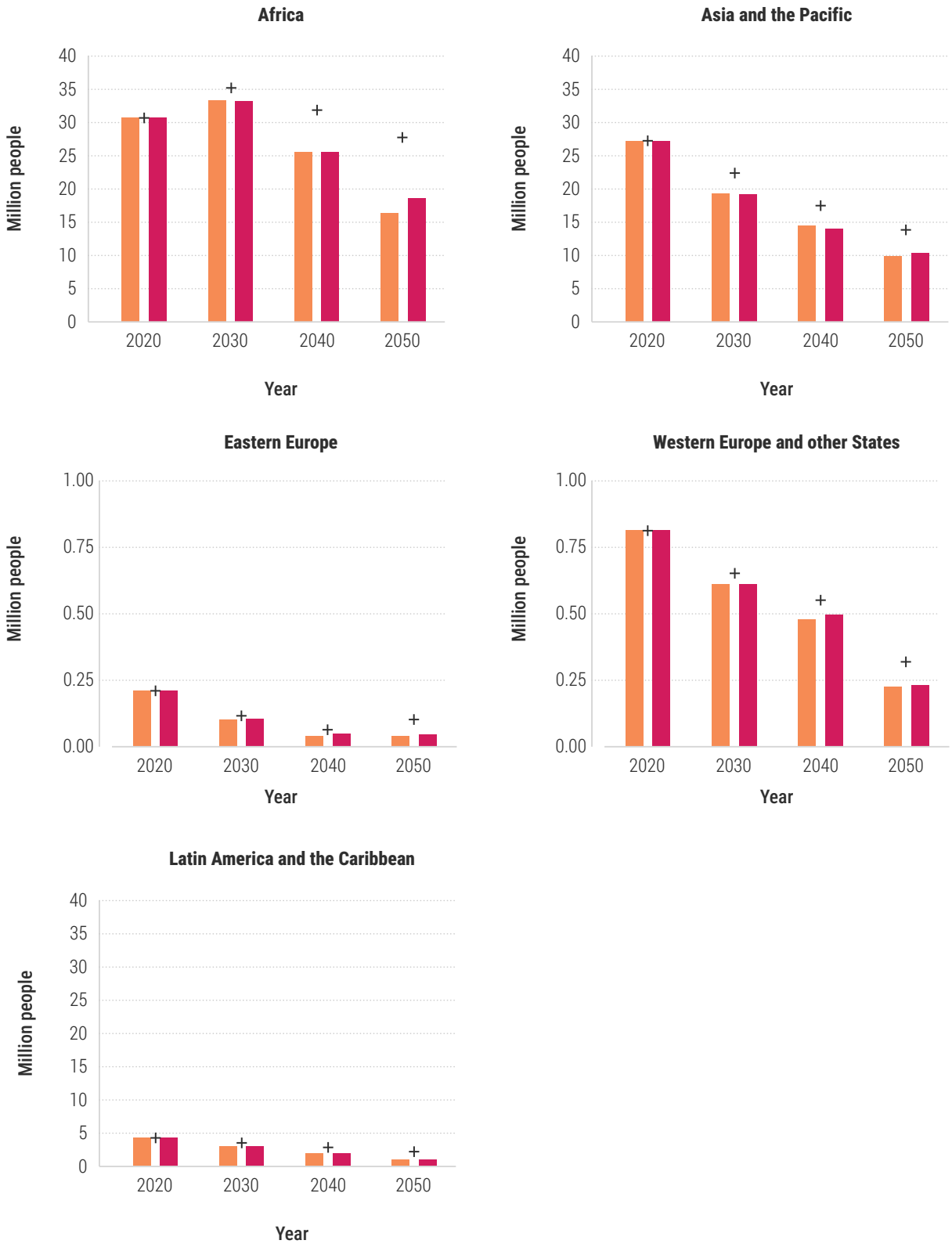
Several other determinants of security are not addressed directly in the Transformation Pathways. For instance, there is evidence that political institutions are an important determinant of the risk of armed conflict (Hillesund et al. 2018). Other drivers include horizontal inequalities, social ties and movements (Forsberg 2014; Nagle 2016). Global cooperation to strengthen migration governance in line with the Global Compact for Safe, Orderly and Regular Migration, as well as inclusive peacebuilding efforts, can mitigate the risks of environmentally induced displacement, migration, and conflict (International Organization for Migration 2024).

Security outcomes of the Transformation Pathways should be understood as highly uncertain, especially at country level. Models that forecast future patterns of conflict rely on structural factors and historical patterns of conflict, and these may change over time, or even not hold for future conflicts (Hegre *et al*. 2016; Bowlsby et al. 2020; Moyer et al. 2023). Unintended consequences of sustainable development that are not factored into these models may also exacerbate insecurity (Moyer 2024).

11.5.5 Economic impacts and employment

The Transformation Pathways imply major changes in the economic and finance systems, with important implications for local economies. The outcomes depend on a combination of factors: the capacity of different

Figure 11.25: The number of women in excess of men living in extreme poverty (less than US$ 2.15 per day at PPP in 2017 US$) for the ages 24-55, by UN regions and pathway across time



Note: Figure does not show absolute number of women in poverty, but rather the imbalance of female poverty with respect to men.
For legibility, the graphs of Eastern Europe and Western Europe and other States are displayed using on a different scale of the vertical axis.

Source: IFs 8.26.2 model

countries to supply essential materials and services, their consumption and production patterns' capacity to change, their financial profiles and the composition of population and labour force, among others.

The costs entailed in the Transformation Pathways – ignoring the benefits of avoided climate change – imply a small but negative impact on GDP, leading to a 1.5 per cent lower cumulative GDP over the 2025–2100 period when compared with the Current Trends. This is in line with empirical findings regarding the economic impacts of decarbonization (IPCC 2023a; Fujimori et al. 2023). The negative consequences are mostly visible in the short to medium term as most of the required investments are generally more expensive than the carbon-intensive incumbents, and the infrastructure is not in place. The benefits of most of the options are only visible in the long term, including energy and operating-cost savings and higher disposable income.

It is important to note that these GDP effects only account for the cost of the transformation and the effects of emissions pricing. They also exclude the damage costs arising from climate change and environmental degradation in the Current Trends. Including these costs of inaction, the Transformation Pathways display

Table 11.2: Required system transformations between 2020 and 2050 to meet the goals set out in Sections 9.3

Climate change	Biodiversity loss	Halt pollution	Land degradation	Food security	Water access	Energy access
Limiting total energy demand via lifestyle changes or increased efficiency, leading to energy intensity (per economic output) reduction of around 60–75 per cent. Rapid decarbonization of the energy system with emission intensity of energy supply reducing by 10–15 per cent per year and increasing the share of renewables to around 50–55 per cent of total energy supply, and 85–95 per cent of electricity supply. Consistent scale-up of renewables by 5–7 per cent per year. Increase the electrification rate of final energy to at least 45 per cent. Land use acting as CO2 sink with up to 5Gt CO2/yr each from land use and bioenergy with CCS. {11.3.1; 11.4.1}	Protect 30–50 per cent of land, across all biomes and ecosystems. Increase forest and other natural land areas by up to 660 Mha. {11.3.2; 11.3.4}	Improve air pollution control technology. {11.4.2}	Protect 30–50 per cent of land across all biomes and ecosystems. Restore former agricultural lands. Increase forest and other natural land areas by up to 660 Mha. Regenerate degraded lands increasing terrestrial carbon stocks by up to 30 Gt of carbon. {11.3.2; 11.3.4; 11.4.3}	Dietary changes reducing animal product consumption by 20–45 per cent in line with healthy diets (share of crops consumed increasing from 82 per cent to 90 per cent). Improving crop yields (0.7–0.9 per cent per year). Reduction of food waste by up to 50 per cent. Improve food distribution equivalent to best-performing countries today. {11.3.5; 11.3.2; 11.5.1}	Increased access to water for an additional 1 billion people. Use advanced irrigation measures (drip irrigation, rainwater harvesting). {11.3.5; 11.4.6; 11.5.1}	Complete phase-out of traditional cookstoves and provide access to modern stoves. Universal access to electricity, particularly in rural areas, with 120 million new connections above baseline. Funnel revenues from emission pricing towards improved energy access for poor households. {11.3.1; 11.3.5; 11.5.1}

Note: the associated synergies and trade-offs between these goals are elaborated in Table 11.3

no GDP loss by 2050, and benefits of 6 per cent by 2070, increasing to over 25 per cent by 2100. Thus, despite the upfront costs, the Transformation Pathways result in an extra US$ 20 trillion per year of value by 2070 and over US$ 100 trillion per year by 2100. These results are in line with other assessments of the costs of transformation and climate damage across a variety of methods (Piontek et al. 2021; Riahi et al. 2022.

The short-term economic costs of both Transformation Pathways lead to small but negative effects on short-term employment, with unemployment rates about 1–2 per cent higher than the Current Trends between 2030 and 2040 and decreasing thereafter. There are key differences concerning the employment characteristics of the pathways, with the Technology-focused pathway having higher employment growth in industry and manufacturing, while the Behaviour-focused transformation increases employment in public transportation, agriculture and energy. Labour intensity increases in the Behaviour-focused pathway due to lower technological progress and a focus on activities that are more labour-intensive.

11.6 Synergies in the transformation

Table 11.2 summarizes the massive system transformations that are required to avert global environmental crises. By taking advantage of synergies across the systems, it is nevertheless possible to achieve all the goals simultaneously, without necessarily having to compromise. The integrated modelling helps explore these cross-system links, with specific transformations either acting as enablers or posing risks across the systems. **Table 11.3** points out the synergies to be harnessed and the possible risks that need to be averted or managed.

Lower demand enabled by lifestyle changes through the Behaviour-focused transformation or efficiency improvements through the Technology-focused transformation – especially when compared to the Current Trends but even compared to 2020 – makes it significantly easier to meet climate goals. This also enables an easier and more rapid uptake of renewables, with a lower demand for natural resources. This is particularly important since, even with the scale-up of renewable electricity in recent years, an overall increase in total energy demand means emissions have not reduced accordingly (IEA 2023a; IEA 2023b). Reducing energy demand also limits the risk of depending on prospective and unproven technologies such as CCS and CDR. Yet the pathways still depend to an extent on CO_2 removal, since the remaining carbon budget to meet the 1.5°C target is very tight, as highlighted in the IPCC's 6th Assessment Report (IPCC 2023b). Decarbonizing the energy system also has associated benefits for water demand and quality, due to the reduced requirement of cooling water for thermal power plants (11.3.1). Furthermore, the energy system projections, together with implications for the demand for infrastructure and changes in material flows, lead to significantly lower demand for materials.

These changes have important implications for the land system. Lower energy needs reduce the demand for biomass and bioenergy, leading to reduced land requirements, which are significant in other climate change mitigation pathways (Daioglou et al. 2019; Fujimori et al. 2022). However, the land system benefits most from a reduction in areas dedicated to agricultural production. Thus, the Behaviour-focused transformation presents fewer risks due to its significant dietary shifts and reduction in land for livestock and does not depend on massive increases in agricultural yields. This alleviates the need for trade-offs concerning biodiversity, fertilizer use, water use and pollution, while also freeing up of huge tracts of land. This makes it easier to align with associated goals and to make the land system a net CO_2 sink, contributing to climate change mitigation. Focusing purely on nature protection and restoration could also contribute to these goals, but without significant changes to the agricultural system, these measures could jeopardize food security by restricting land availability for food production.

Synergies across human well-being goals, beyond those represented in the modelling framework, may also be achieved if certain implementation bottlenecks can be overcome. Universal electrification requires equity solutions that overcome social stratification and income disparities (Dugoua, Liu and Urpelainen 2017) and opens possibilities for universal energy access to promote gender empowerment and more employment opportunities (Pearl-Martinez 2020; Dinkelman 2011; Das et al. 2023). Land-based mitigation through natural vegetation restoration and afforestation affects water availability (Filoso et al.

Table 11.3: Summary of possible synergies (green) and risks or trade-offs (red) that need to be negotiated to meet all the goals described in Section 9.3 and Table 9.1, repeated in the "diagonal"

Solutions across systems/ Implications, synergies or trade-offs	Implications for climate change	Implications for Biodiversity loss	Implications for pollution	Implications for land degradation	Implications for food security	Implications for clean water access	Implications for energy access
Solutions for climate change	**Limit global mean temperature increase to 1.5°C**	Reforestation/revegetation to create carbon stocks can also protect biodiversity Avoiding climate change-driven biodiversity loss, the main driver of biodiversity loss during the 21st century {11.3.2; 11.3.4}	Reduction of fossil fuels improve air quality {11.3.1; 11.4.2}	Land-based mitigation with natural vegetation restoration Land-based mitigation with planted forests (monocultures) or bioenergy production from energy crops could lead to land degradation {11.3.4; 11.4.3}	Avoided negative climate impacts on food systems improve supply of food Redistribution of carbon revenues can help increase food access for poor households Avoided economic damages from climate change, and improved skills workforce increase households' purchasing power Land-based mitigation could create competition for land which may disproportionately affect poor households' food security {11.5.5}	Reduced use of thermal power plants reduces water withdrawal and contamination Reduction in changes in precipitation and evaporation, and hydrology related climate impacts (water scarcity and flooding) Land-based mitigation with natural vegetation restoration (help to protect and restore water bodies) {11.3.1; 11.4.1}	Targeted provision of energy-efficient technologies can help poor households meet energy needs without increasing the overall burden on the energy system Redistribution of carbon revenues can help increase energy access for poor households Avoided economic damages from climate change, and improved skills workforce increase households' purchasing power Increased carbon prices on energy may be regressive and disproportionately affect poor households {11.5.5}
Solutions for biodiversity loss	Protected areas and natural vegetation restoration can act as carbon sinks {11.3.4; 11.4.1}	**No further loss of biodiversity by 2030, and an increase towards 2050**	Protected areas can act as a barrier for fires and deforestation, decreasing emissions and air pollution	Protected areas and natural vegetation can restore land quality {11.3.4; 11.4.3}	The protection of natural land may increase land competition, driving up food prices		

Table 11.3: Summary of possible synergies and risks or trade-offs that need to be negotiated to meet all the goals described in Section 9.3 and Table 9.1, repeated in the "diagonal" (cont.)

Solutions across systems/ Implications, synergies or trade-offs	Implications for climate change	Implications for Biodiversity loss	Implications for pollution	Implications for land degradation	Implications for food security	Implications for clean water access	Implications for energy access
Solutions for pollution	Decrease of some air pollutants and emissions from agriculture reduces climate change and may lead to less fossil fuel use Reduction of aerosols and sulfur emissions could increase warming {11.3.1; 11.4.2}	Decrease in air pollutant and nitrogen emissions reduces pressure on biodiversity Reduction in resource use, and associated land use {11.3.3}	**Limit population exposed to ambient PM2.5 to less than 20 per cent by 2030, and less than 10 per cent by 2050**	Reduced fertilizer use through increased efficiency or non-intensive agricultural practices	Averted crop yield losses from ozone pollution Lower fertilizer use may reduce crop yields and food availability {11.4.2}	Lower water pollution from more efficient or decrease in fertilizer use {11.4.5}	Rapid changes in the energy system could jeopardize equitable access to clean energy Use of modern fuels in line with energy access goals {11.4.2}
Solutions for land degradation	Protection of natural lands and terrestrial carbon stocks {11.3.4; 11.4.1; 11.4.3}	No deforestation, and large-scale restoration Agricultural practices to increase carbon in the soil {11.3.4}		**Halt loss of natural land by 2030, and increase carbon stocks in 30 per cent and 50 per cent of agricultural lands by 2030 and 2050**	The protection of natural land may increase land competition, driving up food prices		Reduced land availability for energy infrastructure

Table 11.3: Summary of possible synergies and risks or trade-offs that need to be negotiated to meet all the goals described in Section 9.3 and Table 9.1, repeated in the "diagonal" (cont.)

Solutions across systems/ Implications, synergies or trade-offs	Implications for climate change	Implications for Biodiversity loss	Implications for pollution	Implications for land degradation	Implications for food security	Implications for clean water access	Implications for energy access
Solutions for food security	Dietary changes leading to reduced animal product consumption reduce non-CO2 greenhouse gases and reduce deforestation/increase afforestation. Use of agricultural residues to provide bioenergy (possibly combined with carbon capture and storage leading to negative emissions) {11.3.2; 11.4.1}	Dietary changes leading to reduced animal product consumption free up a lot of land otherwise used for feed and grazing Improvements in crop yields (closing the yield gap) can free up land for restoration Nature-positive agricultural production methods Intensive use of agrochemicals {11.3.4}	Using regenerative and mixed-system agriculture, and increasing nitrogen-use efficiency Avoided nitrogen pollution from reduced livestock production and increased nitrogen-use efficiency Intensive use of agrochemicals {11.4.2, 11.4.5}	Using regenerative and mixed-system agriculture, and increasing nitrogen-use efficiency Avoided nitrogen pollution from reduced livestock production and increased nitrogen-use efficiency Intensive use of agrochemicals {11.4.2, 11.4.5}	**Achieve universal access to adequate food by 2050**	Using regenerative and mixed-system agriculture, increasing nitrogen-use efficiency, and improving water quality Dietary changes leading to reduced animal product consumption avoid nitrogen pollution Advanced water management techniques (drip irrigation, rainwater harvesting) can increase yields while conserving water Intensive use of agrochemicals and irrigation leads to a decrease in water availability and quality {11.4.5; 11.4.6}	Improved health can increase household purchasing power {11.5.2; 11.5.5}

Table 11.3: Summary of possible synergies and risks or trade-offs that need to be negotiated to meet all the goals described in Section 9.3 and Table 9.1, repeated in the "diagonal" (cont.)

Solutions across systems/ Implications, synergies or trade-offs	Implications for climate change	Implications for Biodiversity loss	Implications for pollution	Implications for land degradation	Implications for food security	Implications for clean water access	Implications for energy access
Solutions for clean water access						Appropriate irrigation methods can close yield gaps and increase agricultural production Wasteful irrigation may lead to water scarcity {11.4.6}	**Achieve universal access to safe water and sanitation by 2050**
Solutions for energy access	Access to modern fuels (particularly through electrification) reduces the use of polluting solid fuels, particularly coal, charcoal, and traditional biomass. Increased energy demand may put stress on energy system and decarbonization efforts {11.3.1; 11.3.3; 11.5.1}	Moving away from traditional biomass reduces interference on land	Access to modern fuels significantly reduces indoor air pollution, avoiding up to 1 million premature deaths {11.4.2}	Moving away from traditional biomass reduces interference on land	Access to clean energy improves health and gender equality and possibilities for increasing household purchasing power Possible competition for land for renewable energy {11.5.1; 11.5.2; 11.5.3}	Access to clean energy improves health and gender equality and possibilities for increasing household purchasing power {11.5.1; 11.5.2; 11.5.3}	**Ensure universal access to electricity and reliance on clean fuels**

Note: the table shows how specific solutions per system (rows) affect other systems (columns). Where available, sections in Chapter 11 that provide further details are also shown.

2017; Hoek van Dijke et al. 2023) and biodiversity (Atkinson et al. 2022). Another synergy relates to air pollution and biodiversity goals. Creating protected areas to halt the loss of biodiversity also decreases deforestation in tropical areas (Andam et al. 2008). Deforestation is directly linked to air pollution through forest fires (Reddington et al. 2021; Burke et al. 2023) and consequently to health issues. Finally, there is the crucial issue of reducing the use of agrochemicals, particularly pesticides, due to their consequences for human health (Tang et al. 2021; Gerken et al. 2024). All these examples reinforce the importance of a holistic understanding of the implications of the solutions adopted.

Reduced pressure across the systems, bringing the demand for natural resources more in line with planetary boundaries, is the key enabling factor allowing multiple goals to be met simultaneously (Rockström et al. 2009). This reduction, presented here in the form of efficiency improvements and lifestyle changes, creates important synergies that make meeting multiple goals possible and complementary. This analysis further highlights that benefits across multiple systems arise from actions that are not siloed or focused solely on a single environmental or social crisis (McElwee et al. 2025). Instead, response options should be streamlined and consistent, with the aim of exploiting synergies and minimizing trade-offs.

11.7 Challenges and opportunities

11.7.1 The necessary governance transformation as an enabler

The two Transformation Pathways present alternative futures that achieve multiple environmental and social goals. The implemented measures and associated synergies evident when comparing transformation of systems could result in win-win situations. However, such positive outcomes are also driven by implicit and explicit assumptions in the narratives and the model framework used. Both Transformation Pathways depend on effective regulation, high levels of technological development, and well-regulated markets, where externalities are appropriately identified and priced. The presence of strong governance, effective policymaking and legitimate and well-functioning institutions that mediate social and political conflicts is implicit in both pathways. Synergies and trade-offs can also play distinct roles in different geographic and socioeconomic contexts. Policy and legal frameworks that recognize Indigenous Knowledge and Local Knowledge, perspectives, and responses can help inform how best to exploit theses potential synergies (Office of the United Nations High Commissioner for Human Rights 2021; Carmona et al. 2024; Rahmah and Sulstyono 2024).

There are also significant infrastructural and distributional challenges to be overcome. For instance, the pricing of externalities, if not deployed correctly, could exacerbate inequality and the associated social problems (Emmerling, Andreoni and Tavoni 2024). Scaling up renewables will increasingly face integration, land-use, infrastructure, skills and critical mineral bottlenecks, especially concerning storage, interconnectivity, and ageing electricity networks (Jagger, Foxon and Gouldson 2012; Wang et al. 2022; IEA 2023a). This is also reflected in the goal of achieving universal electricity access, which requires a massive expansion of electricity networks, particularly in areas that may involve significant costs (11.3.1). Similarly, concerning hunger and malnutrition, while the Transformation Pathways solve the problem of food availability, they are insufficient to solve the problem of access. Eliminating undernourishment requires additional distributional measures (Aziz et al. 2021; Fabian, Gomez and Rosete 2023) to achieve near equality in the distribution of calories – a massive challenge, especially in countries with high undernourishment rates (11.5.1).

Rebound effects may be significant, especially in the Technology-focused pathway, with its very high levels of technological improvements and efficiency gains. These effects need to be controlled through additional regulation and appropriate pricing of potential externalities from increased intensification. For example, increased efficiencies and agricultural yields in the Technology-focused Transformation Pathway reduce agricultural land needs, opening space for natural vegetation restoration. However, using this land for planted forest monocultures may aid carbon sequestration but also affect biodiversity and water. Thus, additional measures would also be needed to prevent the negative effects of intensive agriculture on biodiversity, soil quality, water availability and pollution. In the Behaviour-focused pathway, high levels of rebound are pre-empted through the narrative of sufficiency and a cultural shift in the

relationship between human settlements and the natural environment, leading to lowered pressures.

The modelled pathways assume that transformation takes place rapidly and without economic and social friction. Accordingly, both narratives need to deal with the social implications of reduced consumption, technology, and the adoption of automation, including artificial intelligence. This includes the effects on employment, energy and resource use, culture and identity. Appropriate educational and training systems, as well as safeguards for employment and other impacted activities, are needed. The transitions may face significant opposition from vested interests – across all the systems and social strata – which prefer the status quo. This points to a conclusion that the required transformation is principally a cultural and political one, requiring fundamental changes to the relationship we have with nature.

11.7.2 Implications for Indigenous Peoples and other communities

An often-overlooked challenge is the potential negative impact of the adopted solutions on some populations, particularly Indigenous Peoples and households in rural areas. This is especially true for the *Technology-focused* pathway whose narrative considers the transition to a more urbanized world and the continued dominance of large enterprises, for example, agribusiness. The expansion of large enterprises for renewable energy (wind and solar plants, hydropower), highly efficient agribusiness, and mining (for required rare earth metals for the energy transition, for example) is already leading to displacement and conflicts – directly or indirectly – by reducing local community access to land and water, as well as increasing the risks of contamination and other environmental and social impacts (Chiarelli et al. 2022; Comissão Pastoral da Terra [CPT] 2022; Peixoto, Soares and Ribeiro 2022; Kennedy et al. 2023; Sales and Sales 2023; IPES-Food 2024; Aguiar et al. 2025). As urban centres in low- and middle-income countries are often chaotic and unplanned (Christiaensen and Todo 2013; Nagendra et al. 2018), additional solutions will be needed to guarantee economic alternatives, appropriate services and human well-being, while avoiding urban sprawl, land-grabbing and poor planning.

For Indigenous Peoples to benefit fully from any transformations, it is vital to safeguard the transmission of Indigenous Knowledge and the practice of traditional ways of life, which are closely associated with the care and ownership of their territories. A transition towards socioenvironmental justice and sustainability requires recognizing the knowledge systems, respecting the individual and collective rights of Indigenous Peoples and integrating their worldviews and actions into the search for global solutions (IK & LK Dialogues 2025).

There are also opportunities to learn from and build upon Indigenous Peoples' practices and co-create solutions (Ford et al. 2020; Ogar, Pecl and Mustonen 2020; Food and Agriculture Organization [FAO] 2021; Turner, Cuerrier and Joseph 2022), as they have demonstrated a commitment to caring for the environment in a sustainable manner (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem [IPBES] 2019; FAO 2021). Self-autonomy and the implementation of free, prior and informed consent are key enablers in processes where Indigenous Knowledge is mainstreamed (Mistry, Bilbao and Berardi 2016; IK & LK Dialogues 2025).

11.7.3 Opportunities to be harnessed

Despite the challenges, the Transformation Pathways also present multiple opportunities. An obvious example would be the avoided costs of inaction described in Chapter 10: in the long term, climate damage alone could reduce future GDP by US$ 20 trillion per year in 2070 and over US$ 100 trillion per year by 2100, based on median estimates (10.6.5). The estimated costs of transformation are considerably smaller: US$ 1 trillion per year until 2050, or approximately 1 per cent of global GDP in 2050 (11.5.5), with significant benefits thereafter.

Further socioeconomic benefits can arise from the transformation. The appropriate and effective pricing of environmental and social externalities can help reduce poverty through the redistribution of revenues. Additionally, the Transformation Pathways show a potential positive effect from the requirement of highly skilled labour and the resultant improved household income.

An overarching theme of this chapter is the enabling effect of reducing the demand for primary resources. This encompasses lifestyle changes in energy and food consumption, adoption of better technologies and techniques including Indigenous Knowledge and Local Knowledge, efficiency improvement of different processes, reduction of waste and promotion of circularity, or combinations of these. With safeguards on natural capital and equitable distribution of resources,

Credit: siwabudv/Envato

addressing the global environmental crises while achieving important human development goals is entirely possible. If appropriately implemented, the transformation of economy and finance, energy, land, materials/waste and environmental systems can help improve the state of the environment and the quality of life for millions of people. The foremost challenge and opportunity in achieving the goals is to simultaneously promote inclusive and thriving societies while recognizing the role and contributions of different genders, as well as Indigenous Peoples' and local communities and practices.

Chapters 12–18 build upon the insights presented here to identify specific solution pathways involving necessary conditions, actors and levers that can accelerate the transformation. Chapters 19 and 20 further explore the required transformation from a regional perspective. Finally, Chapter 21 synthesizes all the insights to assess how sustainable transformations can be accelerated. This puts the focus squarely on the question of how to achieve the transformations while optimizing the synergies and minimizing potential trade-offs.

Appendix 11.1: Narratives quantification and mapping to solution pathways

	Behaviour-focused transformation		
	Narrative	**Solution pathways mapping**	**Modelling protocol (quantification assumptions)**
General assumptions	Goals are achieved through lifestyle, behavioural and value changes aligned with the sufficiency worldview. It envisions a future of regionalized economies where increased societal awareness of global environmental crises drives a shift towards sufficiency. The transformation is guided by principles of sharing, reciprocity, responsibility and care, aiming to reconcile human well-being with ecosystem health. Multiple forms of knowledge are combined, including mainstream science and Indigenous Peoples' and local communities' philosophies, practices and values.	**n.a.**	GDP – Current Trends (SSP2) Population – Current Trends (SSP2) Inequality – Decreased GINI coefficient (SSP1) Urbanization – Lower than SSP2 (based on SHAPE Project Resilient Communities Scenario) (SDP-RC) Regionalization – Increasing trade barriers (based on SSP3). Trade and flows of labour/capital are still allowed, but at a lower extent than the Technology-focused pathway Technology: • Technology efficiency improvement – Medium • Availability of prospective technologies – Some • Technology adoption – Medium/High • Reference learning rates Climate policy applied globally, aligned to meeting a 1.5°C target with low overshoot.
Economic systems	Reduction of externalities mainly through a combination of pricing and non-pricing instruments. Investments in technological and social solutions oriented towards enabling human and nature well-being.	S14.4 Making sustainability core in economic governance	A mix of standards, mandates and prices drives changes. Internalization of externalities through carbon prices.
Circularity	Low material footprints due to reduced conspicuous consumption and a digitally supported sharing economy. Repairing, refurbishing and recycling become the norm.	S15.5 Circular society pathway	Material demand follows energy service demand. Increased renovation/refurbishment compared to reference. Recycling rates increased above reference, following best current practices.
Energy systems	Behavioural and lifestyle changes lead to reductions in energy demand in rich regions, while middle- and lower-income regions catch up as basic energy services are satisfied. Emergence of "prosumers" facilitated through small-scale electricity generation. Local renewable resource endowments dictate energy systems, including wind, solar and biomass, leading to high regional variability in energy systems. For high-density urban and industrial environments, deployment of larger-scale technologies also takes place. Microgrids, demand-side management and distributed storage are scaled up to deal with variability.	S16.1 Provide environmentally sustainable, safe, reliable, and affordable energy access and clean cooking, and eliminate energy poverty for all S16.2 Improve energy management S16.3 Decarbonize and transition away from fossil fuels S16.4 Shift to a responsible and sustainable Critical Energy Transition Mineral Value Chain	Electrification levels: Medium – endogenous. Universal access to electricity by 2050. Use of traditional fuels – Complete phase-out by 2050. Electrification of final energy > 40 per cent by 2050. Increased share of communal and small-scale technologies (i.e. rooftop PV, onshore wind). Limits to CCS: • BECCS < 3 GtCO2/yr • Fossil CCS < 6 GtCO2/yr Demand for energy services: Reduced compared to Current Trends. Industry/Commercial: • Lower demand for industrial and commercial products (approx. 25 per cent reduction). Residential: • Higher occupancy rates – approx. 20 per cent higher. • Lower floorspace – Limit to 35m2/cap. • Lower appliance ownership (or communal use of appliances). No ownership of multiple instances of the same appliance. Limit ownership of appliances not necessary for decent living (e.g. clothes dryers). • Lower cooking energy demand by approx. 25 per cent (shared meals, etc.). • Lower demand for heating/cooling by adjusting thermostat settings.

Appendix 11.1: Narratives quantification and mapping to solution pathways (cont.)

	Behaviour-focused transformation		
	Narrative	**Solution pathways mapping**	**Modelling protocol (quantification assumptions)**
Energy systems			Transport: • Lower demand of passenger and freight km. Approx. 75 per cent of reference case Bioenergy demand: • Limited to 20 EJ/yr from energy crops • Lower availability from residues as an increased fraction (>50 per cent) left on the field for ecosystem services • Total availability of primary bioenergy approx. 70 EJ/yr
Food systems	Shift from input-based, to biodiversity-based practices. Increase the use of mixed systems and Indigenous Knowledge and Local Knowledge in production. Focus on rainwater management to increase yields on rain-fed cropland. Community-based food production and distribution reduce waste. Strong shift to plant-based foods and sustainable diets. Lower demand for industrial and processed foods, with an emphasis on the need to recover ancestral foodways as survival strategies in times of food crisis.	S17.1 Shifting to environmentally sustainable and healthy diets S17.2 Improved crop, livestock and aquatic food production and land use systems S17.3 Reducing loss and waste and increasing circularity S17.5 Restructuring the food industry market structure and trade	Agricultural management: • Crop yields – Medium increase, especially in regions/countries with large yield gaps • Livestock efficiency – Same as Current Trends scenario • Irrigated area – Lower increase in irrigated area Food distribution – SSP1 (based on Hasegawa et al. 2015). Dietary Patterns – Reach EAT-Lancet in 2050 (Willett et al. 2019): 50 per cent decrease in meat consumption, 100 per cent increase in nuts, vegetables, fruits and legumes). Food-waste reduction – Reduction in food waste losses by 50 per cent compared to Current Trends Water management • Irrigation efficiency – Same as reference • Increased infiltration – Medium improvement (gradual increase between 2020–2040) • Soil moisture conservation – Medium improvement • Rainwater harvesting – Medium improvement • Erosion prevention – Very high • Wastewater treatment – High Nutrient management • Nitrogen Use Efficiency (NUE) - Best between reference and 50 per cent of maximum NUE • Phosphorus efficiency – High
Environmental systems	Nature and the environment are culturally valued and mutually beneficial with human settlements, aligned to the "Nature as Culture" defined in the IPBES Nature Futures Framework (NFF) (Pereira et al. 2020). Guided by principles of land-sharing, there is an increase in mutually beneficial and sustainable use of protected areas (terrestrial, freshwater and marine) aiming for 50 per cent of the world in 2050. Natural regrowth/restoration on abandoned agricultural lands due to changes in the food system provides a carbon removal service, helping mitigate climate change.	S18.1 Enhancing ecosystem services through regenerative systems and biodiversity conservation S18.2 Nature-based solutions for conservation, restoration and adaptation	Protection of terrestrial ecosystems: Regulatory – protected areas (at least 30 per cent protection of natural ecosystems, aiming towards 50 per cent) and peatland protection Protection of groundwater availability and environmental flows (70 per cent) plus restricted groundwater use. Land-based mitigation limits – Only allow natural regrowth on abandoned lands.

Appendix 11.1: Narratives quantification and mapping to solution pathways (cont.)

	Technology-focused transformation		
	Narrative	**Solution pathways mapping**	**Modelling protocol (quantification assumptions)**
General assumptions	Goals are achieved by gains in efficiency through innovation and technological solutions. It envisions a future characterized by a largely globalized and urbanized economy with significant trade, in which society relies on price-mediated and technological solutions to solve the global environmental crises and transform current systems.	n.a.	GDP/Population/Inequality – Same as Behaviour-focused Urbanization – Current Trends (SSP2) Regionalization – Increased free trade and policy harmonization (SSP1) Technology: • Efficiency improvement – Very high • Availability of prospective technologies – High • Technology adoption – High • Learning rates – High Climate policy applied globally, aligned to meeting a 1.5°C target with low overshoot.
Economic systems	Reduction of externalities through pricing mechanisms and efficiency gains. High investments in technical solutions to environmental and social problems.	S14.1 - Internalizing the externalities (correcting pricing)	Prices in general are the main driver of change in the global economy. Internalization of externalities through carbon prices.
Circularity	Design driven by cradle-to-cradle concerns. Increased efficiency and reduced waste. Efficient modular design in buildings increases their longevity and ability to be refurbished. Monitoring, reviewing and redesigning of products, associated with the implementation of necessary infrastructure, leads to recyclability and high recycling rates.	S15.1 Designing out waste/ Designing circularity into the full life cycle of products	Lower demand via improved design, material substitution. Very high recycling rates near technical potential of recycling by 2050. High levels of renovation/refurbishment of buildings.
Energy systems	Supply-side investments; focus on efficiency, clean energy, interconnectivity and high levels of electrification. Technological solutions, including power-to-liquids, biofuels, hydrogen, and carbon capture and storage (CCS) are also prevalent if the economics are appropriate. Nuclear energy and fossil fuels are used sparingly, and technological innovations help to reduce their negative impacts. Centralized distribution networks, large-scale supply and storage of electricity, and large-scale grid interconnections with reduced transmission losses.	S16.1 Provide environmentally sustainable, safe, reliable, and affordable energy access and clean cooking, and eliminate energy poverty for all S16.2 Improve energy management S16.3 Decarbonize and transition away from fossil fuels	Electrification levels – High Universal access to electricity by 2050. Use of traditional fuels – Complete phase-out by 2050. Electrification of final energy > 45 per cent by 2050. Advanced technology (hydrogen, bioenergy with carbon capture and storage [BECCS], direct air carbon capture and storage etc.) available by 2030, but only used if cost-competitive. Preferential deployment of large-scale renewable projects (hydropower, offshore wind, etc.). Globally best-available technology adoption by 2040. Limits to carbon capture and storage (CCS) • BECCS < 5 GtCO2/yr • Fossil CCS < 8 GtCO2/yr Demand for energy services (all sectors) – Medium (SSP2). Bioenergy demand – Price-based • Limited to 50 EJ/yr from energy crops • Total availability of primary bioenergy approx. 120 EJ/yr

Appendix 11.1: Narratives quantification and mapping to solution pathways (cont.)

	Technology-focused transformation		
	Narrative	**Solution pathways mapping**	**Modelling protocol (quantification assumptions)**
Food systems	Agricultural intensification and technological solutions, aligned to the land-sparing principle in the environmental system, i.e. producing more in less area, freeing land for nature restoration and conservation. High efficiency, adoption of efficient irrigation and automated agricultural production. Substitution of animal products by novel foods such as cultured meat, further decreasing the need for pasture area. Technical means are adopted to tackle food waste and losses.	S17.1 Shifting to environmentally sustainable and healthy diets S17.2 Improved crop, livestock and aquatic food production and land use systems S17.3 Reducing loss and waste and increasing circularity S17.4 Novel foods and production processes S17.5 Restructuring the food industry market structure and trade	Agricultural management: • Crop yields – Increase in productivity (similar to SSP1) • Livestock efficiency – Increase in productivity (similar to SSP1) • Irrigated area – Higher increase in irrigated area (similar to SSP1) • Irrigation efficiency – Increase in irrigation efficiency above Current Trends Food distribution – Medium (SSP2). Dietary patterns – 50 per cent reduction of meat consumption in High-Income Countries (HIC) by substitution with cultured meat. Food-waste reduction – Reduction in food waste losses by 50 per cent compared to Current Trends. Water management: • Reservoirs – more reservoirs • Erosion prevention – high • Wastewater treatment – very high • Increased infiltration – none • Soil moisture conservation – none • Rainwater harvesting – none Nutrient management: • Nitrogen Use Efficiency (NUE) – Best between reference and 70 per cent of maximum NUE • Phosphorus efficiency – very high
Environmental systems	Transformation is guided by the principle of sparing, for the efficient use of non-protected areas allowing the regeneration of large areas of natural vegetation. Protected areas in biodiversity hotspots. Natural vegetation covering more than 30 per cent is pursued, combining at least 30 per cent fully protected natural ecosystems and REDD policies, aligned to the Nature for Society and Nature for Nature IPBES NFF perspectives. Planted forests that can act as carbon sinks are used to help with climate change mitigation.	S18.1 Enhancing ecosystem services through regenerative systems and biodiversity conservation S18.2 Nature-based solutions for conservation, restoration and adaptation	Protection of terrestrial ecosystems: • Focus on carbon sequestration/price-based • Some land-zoning for biodiversity protection (at least 30 per cent protection of natural ecosystems and REDD policies) • Peatland protection Protection of groundwater availability and environmental flows – none Land-based mitigation limits – Maximum 500 Mha – Allow use of planted monoculture forests.

References

Abel, G.J., Brottrager, M., Crespo Cuaresma, J. and Muttarak, R. (2019). Climate, conflict and forced migration. Global Environmental Change 54, 239-249. https://doi.org/10.1016/j.gloenvcha.2018.12.003

Aguiar, A.P.D., Collste, D., Harmáčková, Z.V., Pereira, L., Selomane, O., Galafassi, D. et al. (2020). Co-designing global target-seeking scenarios: A cross-scale participatory process for capturing multiple perspectives on pathways to sustainability. Global Environmental Change 65, 102198. https://doi.org/10.1016/j.gloenvcha.2020.102198

Aguiar, A.P.D., Collste, D., Cortés-Calderón, S., Sonetti-González, T., Alves-Martins, M., Castro, A.J. et al. (2025). Unraveling deep roots in drylands: a systems thinking participatory approach to SDGs. Global Sustainability 8, e13. https://doi.org/10.1017/sus.2025.6

Andam, K.S., Ferraro, P.J., Pfaff, A., Sanchez-Azofeifa, G.A. and Robalino, J.A. (2008). Measuring the effectiveness of protected area networks in reducing deforestation. Proceedings of the National Academy of Sciences 105(42), 16089-16094. https://doi.org/10.1073/pnas.0800437105

Argumedo, A., Song, Y., Khoury, C.K., Hunter, D., Dempewolf, H., Guarino, L. et al. (2021). Biocultural Diversity for Food System Transformation Under Global Environmental Change. Frontiers in Sustainable Food Systems 5. https://doi.org/10.3389/fsufs.2021.685299

Atkinson, J., Brudvig, L.A., Mallen-Cooper, M., Nakagawa, S., Moles, A.T. and Bonser, S.P. (2022). Terrestrial ecosystem restoration increases biodiversity and reduces its variability, but not to reference levels: A global meta-analysis. Ecology Letters 25(7), 1725-1737. https://doi.org/10.1111/ele.14025

Aziz, N., He, J., Raza, A., Sui, H. and Yue, W. (2021). Elucidating the Macroeconomic Determinants of Undernourishment in South Asian Countries: Building the Framework for Action. Frontiers in Public Health 9. https://doi.org/10.3389/fpubh.2021.696789

Babiker, M., G. Berndes, K. Blok, B. Cohen, A. Cowie, O. Geden, V. Ginzburg, A. Leip, P. Smith, M. Sugiyama, F. Yamba, (2022). Cross-sectoral perspectives. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. P.R. Shukla, J.S., R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley (ed.). Cambridge University Press, Cambridge, UK, and New York, USA. https://doi.org/10.1017/9781009157926.005

Baena, P.A., Brunel, A., Fernández-de-Larrinoa, Y., Martinez-Cruz, T.E., Milbank, C. and Way, M. (2023). In Brief: The White/Wiphala Paper on Indigenous Peoples' Food Systems. In Science and Innovations for Food Systems Transformation. von Braun, J., Afsana, K., Fresco, L.O. and Hassan, M.H.A. (eds.). Cham: Springer International Publishing. 229-259. https://doi.org/10.1007/978-3-031-15703-5_13

Baldermann, S., Blagojevic, L., Frede, K., Klopsch, R., Neugart, S., Neumann, A. et al. (2016). Are Neglected Plants the Food for the Future? Critical reviews in plant sciences 35, 106-119. https://doi.org/10.1080/07352689.2016.1201399

Bennett, E.M. (2017). Changing the agriculture and environment conversation. Nature Ecology & Evolution 1(1), 0018. https://doi.org/10.1038/s41559-016-0018

Bessagnet, B., Bossioli, E., Cholakian, A., Vivanco, M.G., Cuvelier, K., Theobald, M.R. et al. (2024). Impact of air quality model settings for the evaluation of emission reduction strategies to curb air pollution. Environmental Research 255, 119112. https://doi.org/10.1016/j.envres.2024.119112

Bowlsby, D., Chenoweth, E., Hendrix, C. and Moyer, J.D. (2020). The Future is a Moving Target: Predicting Political Instability. British Journal of Political Science 50(4), 1405-1417. https://doi.org/10.1017/S0007123418000443

Brattland, C. and Mustonen, T. (2018). How Traditional Knowledge Comes to Matter in Atlantic Salmon Governance in Norway and Finland. ARCTIC. https://www.jstor.org/stable/26567068

Burke, M., Childs, M.L., de la Cuesta, B., Qiu, M., Li, J., Gould, C.F. et al. (2023). The contribution of wildfire to $PM_{2.5}$ trends in the USA. Nature 622(7984), 761-766. https://doi.org/10.1038/s41586-023-06522-6

Burke, M.J. and Stephens, J.C. (2018). Political power and renewable energy futures: A critical review. Energy Research & Social Science 35, 78-93. https://doi.org/10.1016/j.erss.2017.10.018

Burrows, N., Burbidge, A. and Fuller, P. (2004). Integrating Indigenous Knowledge of Wildland Fire and Western Technology to Conserve Biodiversity in an Australian Desert. https://www.millenniumassessment.org/documents/bridging/papers/burrows.neil.pdf

Büscher, B. and Fletcher, R. (2020). The Conservation Revolution: Radical Ideas for Saving Nature Beyond the Anthropocene. New York City, USA: Verso.

Büscher, B., Fletcher, R., Brockington, D., Sandbrook, C., Adams, W.M., Campbell, L. et al. (2016). Half-Earth or Whole Earth? Radical ideas for conservation, and their implications. Oryx 51(3), 407-410. https://doi.org/10.1017/s0030605316001228

Carmona, R., Reed, G., Ford, J., Thorsell, S., Yon, R., Carril, F. et al. (2024). Indigenous Peoples' rights in national climate governance: An analysis of Nationally Determined Contributions (NDCs). Ambio 53(1), 138-155. https://doi.org/10.1007/s13280-023-01922-4

Carvalho, M., Rego, F., Palmeirim, J. M., & Fa, J. E. (2015). Wild meat consumption on São Tomé Island, West Africa: implications for conservation and local livelihoods. Ecology and Society, 20(3). http://dx.doi.org/10.5751/ES-07831-200327

Cassman, K.G. and Grassini, P. (2020). A global perspective on sustainable intensification research. Nature Sustainability 3(4), 262-268. https://doi.org/10.1038/s41893-020-0507-8

Checkley, W., Williams, K.N., Kephart, J.L., Fandiño-Del-Rio, M., Steenland, N.K., Gonzales, G.F. et al. (2021). Effects of a Household Air Pollution Intervention with Liquefied Petroleum Gas on Cardiopulmonary Outcomes in Peru. A Randomized Controlled Trial. Am J Respir Crit Care Med 203(11), 1386-1397. https://doi.org/10.1164/rccm.202006-2319OC

Chen, L., Guttieres, D., Koenigsberg, A., Barone, P.W., Sinskey, A.J. and Springs, S.L. (2022). Large-scale cultured meat production: Trends, challenges and promising biomanufacturing technologies. Biomaterials 280, 121274. https://doi.org/10.1016/j.biomaterials.2021.121274

Chiarelli, D.D., D'Odorico, P., Müller, M.F., Mueller, N.D., Davis, K.F., Dell'Angelo, J. et al. (2022). Competition for water induced by transnational land acquisitions for agriculture. Nature Communications 13(1), 505. https://doi.org/10.1038/s41467-022-28077-2

Christiaensen, L. and Todo, Y. (2013). Poverty Reduction during the Rural-Urban Transformation - The Role of the Missing Middle. https://elibrary.worldbank.org/doi/abs/10.1596/1813-9450-6445

Comissão Pastoral da Terra (CPT) (2022). Conflitos, Massacres e Memórias: Das Lutadoras e Lutadores Do Cerrado. Goiânia, Brazil: Comissão Pastoral da Terra (CPT). https://www.cptnacional.org.br/publicacao/summary/75-publicacoes-cerrado/14272-conflitosmassacresmemorias

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N. and Leip, A. (2021). Food systems are responsible for a third of global

anthropogenic GHG emissions. Nature Food 2(3), 198-209. https://doi.org/10.1038/s43016-021-00225-9

Curtis, S.K. and Lehner, M. (2019). Defining the Sharing Economy for Sustainability. Sustainability 11(3). https://doi.org/10.3390/su11030567

Dagnachew, A.G., Lucas, P.L., Hof, A.F., Gernaat, D.E.H.J., de Boer, H.-S. and van Vuuren, D.P. (2017). The role of decentralized systems in providing universal electricity access in Sub-Saharan Africa – A model-based approach. Energy 139, 184-195. https://doi.org/10.1016/j.energy.2017.07.144

Daioglou, V., Doelman, J.C., Wicke, B., Faaij, A. and van Vuuren, D.P. (2019). Integrated assessment of biomass supply and demand in climate change mitigation scenarios. Global Environmental Change 54, 88-101. https://doi.org/10.1016/j.gloenvcha.2018.11.012

Das, I., Klug, T., Krishnapriya, P.P., Plutshack, V., Saparapa, R., Scott, S. et al. (2023). Frameworks, methods and evidence connecting modern domestic energy services and gender empowerment. Nature Energy 8(5), 435-449. https://doi.org/10.1038/s41560-023-01234-7

Dinkelman, T. (2011). The Effects of Rural Electrification on Employment: New Evidence from South Africa. American Economic Review 101(7), 3078-3108. https://doi.org/10.1257/aer.101.7.3078

Drewnowski, A., Monterrosa, E.C., de Pee, S., Frongillo, E.A. and Vandevijvere, S. (2020). Shaping Physical, Economic, and Policy Components of the Food Environment to Create Sustainable Healthy Diets. Food and Nutrition Bulletin 41(2_suppl), 74S-86S. https://doi.org/10.1177/0379572120945904

Dugoua, E., Liu, R. and Urpelainen, J. (2017). Geographic and socio-economic barriers to rural electrification: New evidence from Indian villages. Energy Policy 106, 278-287. https://doi.org/10.1016/j.enpol.2017.03.048

Duru, M., Therond, O., Martin, G., Martin-Clouaire, R., Magne, M.-A., Justes, E. et al. (2015). How to implement biodiversity-based agriculture to enhance ecosystem services: a review. Agronomy for Sustainable Development 35(4), 1259-1281. https://doi.org/10.1007/s13593-015-0306-1

Edelenbosch, O.Y., Hof, A.F., van den Berg, M., de Boer, H.S., Chen, H.-H., Daioglou, V. et al. (2024). Reducing sectoral hard-to-abate emissions to limit reliance on carbon dioxide removal. Nature Climate Change 14(7), 715-722. https://doi.org/10.1038/s41558-024-02025-y

Ellis, E.C. and Mehrabi, Z. (2019). Half Earth: promises, pitfalls, and prospects of dedicating Half of Earth's land to conservation. Current Opinion in Environmental Sustainability 38, 22-30. https://doi.org/10.1016/j.cosust.2019.04.008

Emmerling, J., Andreoni, P. and Tavoni, M. (2024). Global inequality consequences of climate policies when accounting for avoided climate impacts. Cell Reports Sustainability 1(1), 100008. https://doi.org/10.1016/j.crsus.2023.100008

Fabian, K.C.C., Gomez, E.L.S. and Rosete, M.A.L. (2023). Determining the Impact of Climate Change and Growth Indicators on Undernourishment Prevalence in Selected ASEAN Countries. International Journal of Research in Engineering, Science and Management 6(12), 40-49. https://journal.ijresm.com/index.php/ijresm/article/view/2880

Fearon, J.D. and Laitin, D.D. (2003). Ethnicity, Insurgency, and Civil War. American Political Science Review 97(1), 75-90. https://doi.org/10.1017/S0003055403000534

Filoso, S., Bezerra, M.O., Weiss, K.C.B. and Palmer, M.A. (2017). Impacts of forest restoration on water yield: A systematic review. PLOS ONE 12(8), e0183210. https://doi.org/10.1371/journal.pone.0183210

Food and Agriculture Organization (2021). The White/Wiphala Paper on Indigenous Peoples' food systems. Rome, Italy. https://openknowledge.fao.org/handle/20.500.14283/cb4932en

Food and Agriculture Organization of the United Nations, Alliance of Bioversity International and CIAT (2021). Indigenous Peoples' food systems: Insights on sustainability and resilience from the front line of climate change. https://www.fao.org/in-action/kore/publications/publications-details/en/c/1414665/

Ford, J.D., King, N., Galappaththi, E.K., Pearce, T., McDowell, G. and Harper, S.L. (2020). The Resilience of Indigenous Peoples to Environmental Change. One Earth 2(6), 532-543. https://doi.org/10.1016/j.oneear.2020.05.014

Forsberg, E. (2014). Transnational Transmitters: Ethnic Kinship Ties and Conflict Contagion 1946–2009. International Interactions 40(2), 143-165. https://doi.org/10.1080/03050629.2014.880702

Fujimori, S., Oshiro, K., Hasegawa, T., Takakura, J. and Ueda, K. (2023). Climate change mitigation costs reduction caused by socioeconomic-technological transitions. npj Climate Action 2(1), 9. https://doi.org/10.1038/s44168-023-00041-w

Fujimori, S., Wu, W., Doelman, J., Frank, S., Hristov, J., Kyle, P. et al. (2022). Land-based climate change mitigation measures can affect agricultural markets and food security. Nature Food 3(2), 110-121. https://doi.org/10.1038/s43016-022-00464-4

Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T. et al. (2018). Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters 13(6), 063002. https://doi.org/10.1088/1748-9326/aabf9f

GBD 2019 Child and Adolescent Communicable Disease Collaborators (2023). The unfinished agenda of communicable diseases among children and adolescents before the COVID-19 pandemic, 1990-2019: a systematic analysis of the Global Burden of Disease Study 2019. Lancet 402(10398), 313-335. https://doi.org/10.1016/s0140-6736(23)00860-7

Gerken, J., Vincent, G.T., Zapata, D., Barron, I.G. and Zapata, I. (2024). Comprehensive assessment of pesticide use patterns and increased cancer risk. Frontiers in Cancer Control and Society 2. https://doi.org/10.3389/fcacs.2024.1368086

Goldstone, J.A., Bates, R.H., Epstein, D.L., Gurr, T.R., Lustik, M.B., Marshall, M.G. et al. (2010). A Global Model for Forecasting Political Instability. American Journal of Political Science 54(1), 190-208. https://doi.org/10.1111/j.1540-5907.2009.00426.x

Godfray et al. (2018) Meat consumption, health, and the environment. Science 361. https://doi.org/10.1126/science.aam5324

Guo, J.H., Liu, X.J., Zhang, Y., Shen, J.L., Han, W.X., Zhang, W.F. et al. (2010). Significant acidification in major Chinese croplands. Science 327(5968), 1008-1010. https://doi.org/10.1126/science.1182570

Hancher, L., De Hauteclocque, A., Huhta, K., and Sadowska, M. (2022). Capacity mechanisms in the EU energy markets: law, policy, and economics. Oxford, UK: Oxford University Press. https://doi.org/10.1093/oso/9780192849809.001.0001

He, L. and Rosa, L. (2023). Solutions to agricultural green water scarcity under climate change. PNAS Nexus 2(4). https://doi.org/10.1093/pnasnexus/pgad117

Hegre, H. and Sambanis, N. (2006). Sensitivity Analysis of Empirical Results on Civil War Onset. Journal of Conflict Resolution 50(4), 508-535. https://doi.org/10.1177/0022002706289303

Hegre, H., Buhaug, H., Calvin, K.V., Nordkvelle, J., Waldhoff, S.T. and Gilmore, E. (2016). Forecasting civil conflict along the shared socioeconomic pathways. Environmental Research Letters 11(5), 054002. https://iopscience.iop.org/article/10.1088/1748-9326/11/5/054002

Henry, M., Schraven, D., Bocken, N., Frenken, K., Hekkert, M. and Kirchherr, J. (2021). The battle of the buzzwords: A comparative review of the circular economy and the sharing economy concepts. Environmental Innovation and Societal Transitions 38, 1-21. https://doi.org/10.1016/j.eist.2020.10.008

Hillesund, S., Bahgat, K., Barrett, G., Dupuy, K., Gates, S., Nygård, H.M. et al. (2018). Horizontal inequality and armed conflict: a comprehensive literature review. Canadian Journal of Development Studies / Revue canadienne d'études du développement 39(4), 463-480. https://doi.org/10.1080/02255189.2018.1517641

Hocquette, J.F., Chriki, S., Fournier, D. and Ellies-Oury, M.P. (2025). Review: Will "cultured meat" transform our food system towards more

sustainability? Animal 19 Suppl 1, 101145. https://doi.org/10.1016/j.animal.2024.101145

Hoek van Dijke, A.J., Herold, M., Mallick, K., Benedict, I., Machwitz, M., Schlerf, M. et al. (2022). Shifts in regional water availability due to global tree restoration. Nature Geoscience 15(5), 363-368. https://doi.org/10.1038/s41561-022-00935-0

Hoffman, K.M., Davis, E.L., Wickham, S.B., Schang, K., Johnson, A., Larking, T. et al. (2021). Conservation of Earth's biodiversity is embedded in Indigenous fire stewardship. Proc Natl Acad Sci U S A 118(32). https://doi.org/10.1073/pnas.2105073118

Hoicka, C.E., Savic, K. and Campney, A. (2021). Reconciliation through renewable energy? A survey of Indigenous communities, involvement, and peoples in Canada. Energy Research & Social Science 74. https://doi.org/10.1016/j.erss.2020.101897

IK & LK Dialogues. Indigenous Knowledge and Local Knowledge Dialogues. Global Environment Outlook 7. Mexico City: CopIt-arXives, 2025. https://copitarxives.fisica.unam.mx/SC0011EN/SC0011EN.php Indigenous Knowledge and Local Knowledge Dialogues - Copit Arxives (2025)

International Energy Agency (2023a). Renewables 2023. Analysis and Forecast to 2028. Paris: International Energy Agency (IEA). https://iea.blob.core.windows.net/assets/96d66a8b-d502-476b-ba94-54ffda84cf72/Renewables_2023.pdf

International Energy Agency (2023b). World Energy Statistics and Balances. [International Energy Agency (IEA) https://www.iea.org/data-and-statistics/data-product/world-energy-statistics-and-balances

International Organization for Migration (IOM). (2024). Global Compact for Safe, Orderly and Regular Migration: Report of the Secretary-General. United Nations. https://www.iom.int/global-compact-migration

Intergovernmental Panel on Climate Change (2023a). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC. https://dx.doi.org/10.59327/IPCC/AR6-9789291691647.001

Intergovernmental Panel on Climate Change (2023b). Mitigation Pathways Compatible with Long-term Goals. In Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change (ed.). Cambridge, UK: Cambridge University Press. 295-408. https://www.cambridge.org/core/product/7C750344E39ECA3BD5CB14156FCEEFE9

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Brondizio, E.S., Settele, J., Díaz, S., Ngo, H.T. (ed.). Bonn, Germany: IPBES Secretariat. https://doi.org/10.5281/zenodo.3831673

IPES-Food (2024). Food from somewhere: building food security and resilience through territorial markets. https://ipes-food.org/wp-content/uploads/2024/06/FoodFromSomewhere.pdf

Jägermeyr, J., Pastor, A., Biemans, H. and Gerten, D. (2017). Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation. Nature Communications 8(1), 15900. https://doi.org/10.1038/ncomms15900

Jagger, N., Foxon, T. and and Gouldson, A. (2013). Skills constraints and the low carbon transition. Climate Policy 13(1), 43-57. https://doi.org/10.1080/14693062.2012.709079

Jankovic, N., Geelen, A., Streppel, M.T., de Groot, L.C., Kiefte-de Jong, J.C., Orfanos, P. et al. (2015). WHO guidelines for a healthy diet and mortality from cardiovascular disease in European and American elderly: the CHANCES project. Am J Clin Nutr 102(4), 745-756. https://doi.org/10.3945/ajcn.114.095117

Jansen, A., Wang, R., Behrens, P. and Hoekstra, R. (2024). Beyond GDP: a review and conceptual framework for measuring sustainable and inclusive wellbeing. The Lancet Planetary Health 8(9), e695-e705. https://doi.org/10.1016/S2542-5196(24)00147-5

Kasprzak, C.M., Sauer, H.A., Schoonover, J.J., Lapp, M.M. and Leone, L.A. (2021). Barriers and Facilitators to Fruit and Vegetable Consumption among Lower-Income Families: Matching Preferences with Stakeholder Resources. Journal of Hunger & Environmental Nutrition 16(4), 490-508. https://doi.org/10.1080/19320248.2020.1802383

Kennedy, C.M., Fariss, B., Oakleaf, J.R., Garnett, S.T., Fernández-Llamazares, Á., Fa, J.E. et al. (2023). Indigenous Peoples' lands are threatened by industrial development; conversion risk assessment reveals need to support Indigenous stewardship. One Earth 6(8), 1032-1049. https://doi.org/10.1016/j.oneear.2023.07.006

Kenny, T.-A., Hu, X.F., Kuhnlein, H.V., Wesche, S.D. and Chan, H.M. (2018). Dietary sources of energy and nutrients in the contemporary diet of Inuit adults: results from the 2007–08 Inuit Health Survey. Public Health Nutrition 21(7), 1319-1331. https://doi.org/10.1017/S1368980017003810

Kok, M.T.J., Alkemade, R., Bakkenes, M., van Eerdt, M., Janse, J., Mandryk, M. et al. (2018). Pathways for agriculture and forestry to contribute to terrestrial biodiversity conservation: A global scenario-study. Biological Conservation 221, 137-150. https://doi.org/10.1016/j.biocon.2018.03.003

Kok, M.T.J., Meijer, J.R., van Zeist, W.-J., Hilbers, J.P., Immovilli, M., Janse, J.H. et al. (2023). Assessing ambitious nature conservation strategies in a below 2-degree and food-secure world. Biological Conservation 284, 110068. https://doi.org/10.1016/j.biocon.2023.110068

Kozicka, M., Havlik, P., Valin, H., Wollenberg, E., Deppermann, A., Leclere, D. et al. (2023). Feeding climate and biodiversity goals with novel plant-based meat and milk alternatives. Nat Commun 14(1), 5316. https://doi.org/10.1038/s41467-023-40899-2

Kuhnlein, H., Erasmus, B., Creed-Kanashiro, H., Englberger, L., Okeke, C., Turner, N. et al. (2006). Indigenous peoples' food systems for health: finding interventions that work. Public Health Nutr 9(8), 1013-1019. https://doi.org/10.1017/PHN2006987

Kuhnlein, H.V. and Receveur, O. (1996). Dietary change and traditional food systems of indigenous peoples. Annu Rev Nutr 16, 417-442. https://doi.org/10.1146/annurev.nu.16.070196.002221

Leclère, D., Obersteiner, M., Barrett, M., Butchart, S.H.M., Chaudhary, A., De Palma, A. et al. (2020). Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature 585(7826), 551-556. https://doi.org/10.1038/s41586-020-2705-y

Levis, C., Flores, B.M., Moreira, P.A., Luize, B.G., Alves, R.P., Franco-Moraes, J. et al. (2018). How People Domesticated Amazonian Forests. Frontiers in Ecology and Evolution 5. https://doi.org/10.3389/fevo.2017.00171

Loginova, J., Landauer, M., Joona, J., Datta, R. and Joona, T. (2025). Enabling Indigenous-centred decision-making for a just energy transition? Lessons from community consultation and consent in the circumpolar Arctic. Energy Research & Social Science 120. https://doi.org/10.1016/j.erss.2025.103928

Mach, K.J., Kraan, C.M., Adger, W.N., Buhaug, H., Burke, M., Fearon, J.D. et al. (2019). Climate as a risk factor for armed conflict. Nature 571(7764), 193-197. https://doi.org/10.1038/s41586-019-1300-6

McElwee, P. (2025). A tale of two panels: learning and coordinating across IPCC, IPBES, and other science-policy interfaces. Climatic Change 178(3), 45. https://doi.org/10.1007/s10584-025-03869-9

Melash, A.A., Bogale, A.A., Migbaru, A.T., Chakilu, G.G., Percze, A., Abraham, E.B. et al. (2023). Indigenous agricultural knowledge: A neglected human based resource for sustainable crop protection and production. Heliyon 9(1), e12978. https://doi.org/10.1016/j.heliyon.2023.e12978

Mistry, J., Bilbao, B.A. and Berardi, A. (2016). Community owned solutions for fire management in tropical ecosystems: case studies from Indigenous communities of South America. Philosophical Transactions of the Royal Society B: Biological Sciences 371(1696), 20150174. https://doi.org/10.1098/rstb.2015.0174

Mitra, S. and Buluswar, S. (2015). Universal Access to Electricity: Closing the Affordability Gap. Annual Review of Environment and Resources 40(Volume 40, 2015), 261-283. https://doi.org/10.1146/annurev-environ-102014-021057

Moyer, J. D., Matthews, A. S., Rafa, M., & Xiong, Y. (2023). Identifying Patterns in the Structural Drivers of Intrastate Conflict. British Journal

of Political Science, 53(2), 749–756. https://doi.org/10.1017/S0007123422000229

Moyer, J.D. (2024). A double-edged sword into a plowshare: Analyzing geopolitical implications of alternative socioeconomic development pathways. One Earth. https://doi.org/10.1016/j.oneear.2024.01.002

Mosca, O., Lauriola, M., Manunza, A., Lorenzo Mura, A., Piras, F., Sottile, E. et al. (2024). Promoting a sustainable behavioral shift in commuting choices: the role of previous intention and "personalized travel plan" feedback. Transportation Research Part F: Traffic Psychology and Behaviour 106, 55-71. https://doi.org/10.1016/j.trf.2024.06.027

Nagendra, H., Bai, X., Brondizio, E.S. and Lwasa, S. (2018). The urban south and the predicament of global sustainability. Nature Sustainability 1(7), 341-349. https://doi.org/10.1038/s41893-018-0101-5

Naghavi, M., Ong, K.L., Aali, A., Ababneh, H.S., Abate, Y.H., Abbafati, C. et al. (2024). Global burden of 288 causes of death and life expectancy decomposition in 204 countries and territories and 811 subnational locations, 1990; 2021: a systematic analysis for the Global Burden of Disease Study 2021. The Lancet 403(10440), 2100-2132. https://doi.org/10.1016/S0140-6736(24)00367-2

Nagle, J. (2016). Social Movements in Violently Divided Societies: Constructing Conflict and Peacebuilding. 1st edn. London: Routledge. https://doi.org/10.4324/9781315716770

Newell, P. and and Taylor, O. (2018). Contested landscapes: the global political economy of climate-smart agriculture. The Journal of Peasant Studies 45(1), 108-129. https://doi.org/10.1080/03066150.2017.1324426

Norwegian Meteorological Institute (2024). Transboundary particulate matter, photo-oxidants, acidifying and eutrophying components. EMEP Status Report 2024. Oslo: EMEP Status Report 2024. https://emep.int/publ/reports/2024/EMEP_Status_Report_1_2024.pdf

Ogar, E., Pecl, G. and Mustonen, T. (2020). Science Must Embrace Traditional and Indigenous Knowledge to Solve Our Biodiversity Crisis. One Earth 3(2), 162-165. https://doi.org/10.1016/j.oneear.2020.07.006

Office of the United Nations High Commissioner for Human Rights (2021). Thailand: UN experts warn against heritage status for Kaeng Krachan national park. https://www.ohchr.org/en/press-releases/2021/07/thailand-un-experts-warn-against-heritage-status-kaeng-krachan-national-park

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S. et al. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change 42, 169-180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

Owen, J.R., Kemp, D., Lechner, A.M., Harris, J., Zhang, R. and Lèbre, É. (2022). Energy transition minerals and their intersection with land-connected peoples. Nature Sustainability 6(2), 203-211. https://doi.org/10.1038/s41893-022-00994-6

Pearl-Martinez, R. (2020). Global Trends Impacting Gender Equality in Energy Access. IDS Bulletin 51(1), 7-26. https://doi.org/10.19088/1968-2020.103

Peixoto, F.d.S., Soares, J.A. and Ribeiro, V.S. (2021). Conflicts over water in Brazil. Sociedade & Natureza 34(1). https://doi.org/10.14393/SN-v34-2022-59410

Pereira, L.M., Davies, K.K., den Belder, E., Ferrier, S., Karlsson-Vinkhuyzen, S., Kim, H. et al. (2020). Developing multiscale and integrative nature–people scenarios using the Nature Futures Framework. People and Nature 2(4), 1172-1195. https://doi.org/10.1002/pan3.10146

Perez-Arriaga, I.J., Stoner, R., Rahnama, R., Lee, S.J., Jacquot, G., Protzer, E. et al. (2019). A Utility Approach to Accelerate Universal Electricity Access in Less Developed Countries: A Regulatory Proposal. Economics of Energy & Environmental Policy 8(1). https://doi.org/10.5547/2160-5890.8.1.iper

Petzold, J., Andrews, N., Ford, J.D., Hedemann, C. and Postigo, J.C. (2020). Indigenous Knowledge on climate change adaptation: a global evidence map of academic literature. Environmental Research Letters 15(11), 113007. https://doi.org/10.1088/1748-9326/abb330

Phalan, B., Onial, M., Balmford, A. and Green, R.E. (2011). Reconciling Food Production and Biodiversity Conservation: Land Sharing and Land Sparing Compared. Science 333(6047), 1289-1291. https://doi.org/10.1126/science.1208742

Piontek, F., Drouet, L., Emmerling, J., Kompas, T., Méjean, A., Otto, C. et al. (2021). Integrated perspective on translating biophysical to economic impacts of climate change. Nature Climate Change 11(7), 563-572. https://doi.org/10.1038/s41558-021-01065-y

Pirzadeh, A., Solórzano, J., Xiong, Y., Irfan, M., Kwasi, S., Hanna, T., Moyer, J. D., Azcona, G., Bhatt, A., & Duerto Valero, S. (2023). Gendered analysis of the impact of climate change on poverty, productivity and food insecurity. UN Women. https://www.unwomen.org/sites/default/files/2023-11/gendered_analysis_of_the_impact_of_climate_change_on_poverty_productivity_and_food_insecurity.pdf

Rahmah, M. and Sulistyono, A. (2024). The Integration of Traditional Knowledge and Local Wisdom in Mitigating and Adapting Climate Change: Different Perspectives of Indigenous Peoples from Java and Bali Island. Traditional Knowledge and Climate Change - An Environmental Impact on Landscape and Communities. Penteado, A., ·, S.P.C. and Shaikh, O.H. (eds.). Sydney, Australia, Kolkata, India, and Karachi, Pakistan: University of Notre Dame, University of Engineering and Management and Shaheed Zulfiqar Ali Bhutto University of Law. https://doi.org/10.1007/978-981-99-8830-3

Rasul, R., Sufra, R., Pierre, M.C.J., St Sauveur, R., Rouzier, V., Inddy, J. et al. (2025). Prevalence of Cooking with Polluting Fuels and Association with Elevated Blood Pressure Among Adults in Port au Prince, Haiti: A Cross-Sectional Analysis. Glob Heart 20(1), 22. https://doi.org/10.5334/gh.1405

Reddington, C.L., Conibear, L., Robinson, S., Knote, C., Arnold, S.R. and Spracklen, D.V. (2021). Air Pollution From Forest and Vegetation Fires in Southeast Asia Disproportionately Impacts the Poor. Geohealth 5(9), e2021GH000418. https://doi.org/10.1029/2021gh000418

Reddy, K.S. and Katan, M.B. (2004). Diet, nutrition and the prevention of hypertension and cardiovascular diseases. Public Health Nutrition 7(1a), 167-186. https://doi.org/10.1079/PHN2003587

Riahi, K., R. Schaeffer, J. Arango, K. Calvin, C. Guivarch, T. Hasegawa, K. Jiang, E. Kriegler, R. Matthews, G.P. Peters, A. Rao, S. Robertson, A.M. Sebbit, J. Steinberger, M. Tavoni, D.P. van Vuuren (2022). Mitigation pathways compatible with long-term goals. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.005

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F. et al. (2009). A safe operating space for humanity. Nature 461(7263), 472-475. https://doi.org/10.1038/461472a

Ruscalleda-Alvarez, J., Cliff, H., Catt, G., Holmes, J., Burrows, N., Paltridge, R. et al. (2023). Right-way fire in Australia's spinifex deserts: An approach for measuring management success when fire activity varies substantially through space and time. Journal of Environmental Management 331, 117234. https://doi.org/10.1016/j.jenvman.2023.117234

Sahadevan, P., Kamal, V.K., Sasidharan, A., Bagepally, B.S., Kumari, D. and Pal, A. (2023). Prevalence and risk factors associated with undiagnosed diabetes in India: Insights from NFHS-5 national survey. J Glob Health 13, 04135. https://doi.org/10.7189/jogh.13.04135

Sales, R.M.M. and Sales, L.G.d.L. (2023). Energia Renovável Centralizada e Minerais de Transição Energética - paradoxos entre os negócios de energia e os direitos humanos de povos e comunidades tradicionais do Brasil. https://doi.org/10.5281/zenodo.7970721

Sankaran, S. and McIntyre-Mills, J. (2022). Energy justice in renewable energy projects: How learning about Indigenous Knowledge systems could

inform systemic practice. Systems Research and Behavioral Science 39(5), 962-974. https://doi.org/10.1002/sres.2899

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L. et al. (2018). Options for keeping the food system within environmental limits. Nature 562(7728), 519-525. https://doi.org/10.1038/s41586-018-0594-0

Strefler, J., Merfort, L., Bauer, N., Stevanović, M., Tänzler, D., Humpenöder, F. et al. (2024). Technology availability, sector policies and behavioral change are complementary strategies for achieving net-zero emissions. Nature Communications 15(1), 8440. https://doi.org/10.1038/s41467-024-52424-0

Struik, P.C., Kuyper, T.W., Brussaard, L. and Leeuwis, C. (2014). Deconstructing and unpacking scientific controversies in intensification and sustainability: why the tensions in concepts and values? Current Opinion in Environmental Sustainability 8, 80-88. https://doi.org/10.1016/j.cosust.2014.10.002

Sugiyama, M., Wilson, C., Wiedenhofer, D., Boza-Kiss, B., Cao, T., Chatterjee, J.S. et al. (2024). High with low: Harnessing the power of demand-side solutions for high wellbeing with low energy and material demand. Joule 8(1), 1-6. https://doi.org/10.1016/j.joule.2023.12.014

Tang, F.H.M., Lenzen, M., McBratney, A. and Maggi, F. (2021). Risk of pesticide pollution at the global scale. Nature Geoscience 14(4), 206-210. https://doi.org/10.1038/s41561-021-00712-5

Tittonell, P. (2014). Ecological intensification of agriculture—sustainable by nature. Current Opinion in Environmental Sustainability 8, 53-61. https://doi.org/10.1016/j.cosust.2014.08.006

Turner, N.J., Cuerrier, A. and Joseph, L. (2022). Well grounded: Indigenous Peoples' knowledge, ethnobiology and sustainability. People and Nature 4(3), 627-651. https://doi.org/10.1002/pan3.10321

Turnock, S.T., Allen, R.J., Andrews, M., Bauer, S.E., Deushi, M., Emmons, L. et al. (2020). Historical and future changes in air pollutants from CMIP6 models. Atmos. Chem. Phys. 20(23), 14547-14579. https://doi.org/10.5194/acp-20-14547-2020

United Nations Environment Programme (2024). Global Resources Outlook 2024: Bend the Trend – Pathways to a liveable planet as resource use spikes. Nairobi: United Nations Environment Programme. https://www.resourcepanel.org/sites/default/files/documents/document/media/gro24_full_report_1mar_final_for_web.pdf

van Heerden, R., Edelenbosch, O.Y., Daioglou, V., Le Gallic, T., Baptista, L.B., Di Bella, A. et al. (2025). Demand-side strategies enable rapid and deep cuts in buildings and transport emissions to 2050. Nature Energy 10(3), 380-394. https://doi.org/10.1038/s41560-025-01703-1

van Puijenbroek, P., Beusen, A.H.W., Bouwman, A.F., Ayeri, T., Strokal, M. and Hofstra, N. (2023). Quantifying future sanitation scenarios and progress towards SDG targets in the shared socioeconomic pathways. J Environ Manage 346, 118921. https://doi.org/10.1016/j.jenvman.2023.118921

Vega-Araújo, J. and Heffron, R.J. (2022). Assessing elements of energy justice in Colombia: A case study on transmission infrastructure in La Guajira. Energy Research & Social Science 91. https://doi.org/10.1016/j.erss.2022.102688

Verhagen, W., Bohl, D., Pulido, A., Pirzadeh, A., Meisel, C., Solórzano, J. et al. (2023). Policy strategies to achieve zero hunger by 2040 at the country-level. PREPRINT (Version 1) https://doi.org/10.21203/rs.3.rs-2495038/v1

Waller, L., Rayner, T., Chilvers, J., Gough, C.A., Lorenzoni, I., Jordan, A. et al. (2020). Contested framings of greenhouse gas removal and its feasibility: Social and political dimensions. WIREs Climate Change 11(4), e649. https://doi.org/10.1002/wcc.649

Wang, P., Chen, W.-Q., Cui, X., Li, J., Li, W., Wang, C. et al. (2022). Critical mineral constraints in global renewable scenarios under 1.5 °C target. Environmental Research Letters 17(12), 125004. https://doi.org/10.1088/1748-9326/aca4ea

Way, R., Ives, M.C., Mealy, P. and Farmer, J.D. (2022). Empirically grounded technology forecasts and the energy transition. Joule 6(9), 2057-2082. https://doi.org/10.1016/j.joule.2022.08.009

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S. et al. (2019). Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. Lancet 393(10170), 447-492. https://doi.org/10.1016/s0140-6736(18)31788-4

Wilson, E.O. (2016). Half Earth: Our Planet's Fight for Life. New York, USA: Norton.

World Bank (2020). The State of Access to Modern Energy Cooking Services. Washington, D.C.: World Bank. https://documents1.worldbank.org/curated/en/937141600195758792/pdf/The-State-of-Access-to-Modern-Energy-Cooking-Services.pdf

Yue, H., He, C., Huang, Q., Zhang, D., Shi, P., Moallemi, E.A. et al. (2024). Substantially reducing global $PM_{2.5}$-related deaths under SDG3.9 requires better air pollution control and healthcare. Nature Communications 15(1), 2729. https://doi.org/10.5281/zenodo.797072110.1038/s41467-024-46969-3

Zhu, Q., de Vries, W., Liu, X., Hao, T., Zeng, M., Shen, J. et al. (2018). Enhanced acidification in Chinese croplands as derived from element budgets in the period 1980-2010. Sci Total Environ 618, 1497-1505. https://doi.org/10.1016/j.scitotenv.2017.09.289

Zhu, Q., Liu, X., Hao, T., Zeng, M., Shen, J., Zhang, F. et al. (2020). Cropland acidification increases risk of yield losses and food insecurity in China. Environ Pollut 256, 113145. https://doi.org/10.1016/j.envpol.2019.113145

Greater Cairo, Egypt, at night.
Credit: NASA Visible Earth

PART D

Solution Pathways towards Transformation

Solution Pathways Chapeau

Indigenous Knowledge and Local Knowledge Chapeau D

Chapter 12
Transforming Systems: Principles and Levers in Action

Chapter 13
Methodology for Developing Solution Pathways Towards System Transformations

Chapter 14
Solution Pathways for the Transformation of Economic and Financial Systems

Chapter 15
Solution Pathways for Transformation Towards Circularity

Chapter 16
Energy System Transformation Pathways

Chapter 17
Food Systems Transformation Pathways

Chapter 18
Solution Pathways Enabling a Sustainable and Resilient Environment for Systems Transformation

Credit: Image-Source/Envato

Solution Pathways Chapeau

Internationally agreed environmental, social and economic goals can be realized by taking unprecedented, ambitious and coordinated whole-of-government and whole-of-society approaches. This entails transforming the inter-connected economic/financing, materials/waste, energy and food systems, and improved environmental management. The strong interconnections between the systems (**Figure C.1**) means that systems transformation depends on the parallel co-development and co-implementation of the solutions with diverse actors, breaking policy silos, improved governance, redefined economic and market infrastructures and revised financing and valuation principles. Placing the environment and human well-being first are all critical to improving coordination between the systems (*well established*).

Recognizing and leveraging solutions within one system that create positive synergies and benefits across all systems, while avoiding those that may cause unintended harm to others is vital. This includes embracing the principles of a circular economy, fostering shifts in values and behaviors (**Box 1**), ensuring that solutions are fair and equitable, and integrating diverse perspectives and knowledge systems, with particular emphasis on Indigenous Knowledge. Solution pathways all require transformation of the economic/finance system, which drives the materials/waste, energy, food and environment systems (*well established*).

Figure C.1 Transforming systems: examples of solutions proposed in GEO-7

Each system chapter elaborates on these solution pathways and the actions required to accelerate transformation.

Economics & Finance

- Internalize environmental and social costs
- Reform subsidies to support sustainability
- Reflect long-term goals in economic planning
- Incentivize equitable and green economic activity
- Enhance inclusive and participatory decision-making

Environment

- Protect and restore ecosystems and biodiversity
- Strengthen resilience and governance of socio-ecological systems
- Capitalize on Indigenous and local knowledge systems
- Invest in nature-based solutions for conservation, restoration and adaptation
- Promote sustainable bioeconomy and its infrastructure

Food

- Shift to healthy and sustainable diets
- Reduce food loss and waste
- Promote sustainable and agroecological intensification.
- Secure land tenure and farmers' rights
- Strengthen local food systems and value chains
- Align agricultural subsidies with sustainability goals

Energy

- Ensure universal access to clean energy
- Expand energy efficiency and demand-side measures
- Scale up renewable and low-carbon energy
- Phase out fossil fuel subsidies and investments
- Support just and inclusive energy transitions

Materials & Waste

- Improve resource efficiency across sectors
- Promote circular design and production
- Reduce material use and consumption
- Extend product lifespans through reuse and repair
- Strengthen waste management, recycling, and infrastructure

Box 1: Changing behaviour: why Behavioural, Social, and Cultural (BSC) Insights Matter

Lasting transformation demands more than technological breakthroughs or policy reforms alone — it hinges on human behaviour. From individual consumption patterns to the priorities of groups and institutions, human behaviour is both a root cause of the global environmental crises, and a powerful lever for change (Keck et al. 2025; Merz et al. 2023).

Transforming systems requires transforming behaviours — individually, collectively, and structurally. Whether encouraging new technologies, policies or financial incentives, all solutions are impacted by, and lead to a change in, human behaviour (Shove 2010; Michie, van Stralen and West 2011).

Identifying target behaviours

To change behaviours, they must first be understood. Drawing on Behavioural, Social and Cultural (BSC) sciences can illuminate the complex web of factors that shape behaviours including: personal values, knowledge, emotions, habits, physical infrastructure, incentives, social norms and cultural narratives as well as historical, cultural and economic circumstances. These influences differ across regions, communities, and contexts. Ignoring this complexity risks designing ineffective policies (Slattery 2025).

Identifying 'target behaviours' to change is key to designing effective solutions. Target behaviours will vary depending on the solution goal and context. Selecting the right target behaviours can lead to widespread systemic change (Darnton, 2008; Gollwitzer and Sheeran, 2006; Meadows, 1999; Michie, van Stralen and West, 2011; Shove, 2010).

Designing solutions using BSC

Part D outlines how to design transformative solutions across systems using BSC insights. Frameworks such as the 'Capability, Opportunity, Motivation – Behaviour' (COM-B) system and the 'Easy, Attractive, Social, Timely' (EAST) framework offer structured, behavior-based approaches to intervention design (Michie, van Stralen and West 2011; Service et al. 2014). Embedding BSC approaches ensures that solutions are not only technically viable, but locally relevant, socially accepted, and sustained over time (Atkinson 2025; OECD 2025a). Behavioral change needs focused attention to properly scope interventions and recognize that cultural and lifestyle shifts take time to generate impact.

Rather than relying on a single intervention — like financial incentives or awareness campaigns — effective interventions combine strategies including: nudges, social influence, redesigned infrastructure, participation mechanisms, regulations, and storytelling. These can be tailored for different audiences — from individuals to institutions. However, there is no one-size-fits-all approach: what motivates change in one context may not work in another, especially when taking power dynamics, equity, and/or cultural identity into account (Atkinson, 2025; Rare and The Behavioural Insights Team, 2019).

Successful examples of applying BSC insights to environmental challenges include: reducing microplastic pollution through coordinated tech, policy, and community efforts in Malaysia (Goh et al. 2025), cutting household energy use in the Netherlands and Spain (Niamir et al, 2020), promoting sustainable mobility via social interventions in Lithuania (Vitkauskaite-Ramanauskiene, 2025), reducing food waste in Australia (Boulet and Lauren 2024), and boosting plastic bottle recycling in the US by targeting values and norms, with economic incentives like bottle deposits proving especially effective (Viscusi, Huber and Bell 2011).

References

Atkinson, L. (2025) Net zero: the role of consumer behaviour. POST Horizon Scanning. UK Parliament. https://post.parliament.uk/net-zero-the-role-of-consumer-behaviour/. Accessed 15 April 2025

Atkinson, L. (2025). Net zero: the role of consumer behaviour. POST Horizon Scanning. UK Parliament. https://post.parliament.uk/net-zero-the-role-of-consumer-behaviour/. Accessed 15 April 2025

Boulet, M. and Lauren, N. (2024). Nudging Householders to Reduce Avoidable Food Waste: The OzHarvest Use It Up Tape. Sustainability 16(12), 5132. https://doi.org/10.3390/su16125132.

Darnton, A. (2008). Reference report: An overview of behaviour change models and their uses. London: Government Social Research. https://research.fit.edu/media/site-specific/researchfitedu/coast-climate-adaptation-library/climate-communications/psychology-amp-behavior/Darnton.-2008.-Behaviour-Change-Models-Overview.pdf

Goh, K.C., Kurniawan, T.A., Sarpin, N., Masrom, M.A.N., Othman, M.H.D., Anouzla, A. et al. (2025). Combating microplastic pollution in Malaysia's marine ecosystems using technological solutions, policy instruments, and public participation: A review. Journal of Hazardous Materials Advances 17, 100542. https://doi.org/10.1016/j.hazadv.2024.100542

Gollwitzer, P.M. and Sheeran, P. (2006). Implementation Intentions and Goal Achievement: A Meta-analysis of Effects and Processes. Advances in Experimental Social Psychology 38, 69-119. https://doi.org/10.1016/S0065-2601(06)38002-1

Keck, F., Peller, T., Alther, R., Barouillet, C., Blackman, R., Capo, E. et al. (2025). The global human impact on biodiversity. Nature 641, 395-400. https://doi.org/10.1038/s41586-025-08752-2

Meadows, D.H. (1999). Leverage points: Places to intervene in a system. Hartland, VT: The Sustainability Institute. https://donellameadows.org/wp-content/userfiles/Leverage_Points.pdf

Merz, J.J., Barnard, P., Rees, W.E., Smith, D., Maroni, M., Rhodes, C.J. et al. (2023). World scientists' warning: The behavioural crisis driving ecological overshoot. Science Progress 106(3). https://doi.org/10.1177/00368504231201372

Michie, S., van Stralen, M.M. and West, R. (2011). The behaviour change wheel: A new method for characterising and designing behaviour change interventions. Implementation Science 6(42). https://doi.org/10.1186/1748-5908-6-42%20

Niamir, L., Ivanova, O., Filatova, T., Voinov, A. and Bressers, H. (2020). Demand-side solutions for climate mitigation: Bottom-up drivers of household energy behavior change in the Netherlands and Spain. Energy Research & Social Science 62, 101356. https://doi.org/10.1016/j.erss.2019.101356

Organisation for Economic Cooperation and Development (2025a). Mind shift, green lift: Six behavioural science trends for environmental policy. OECD Public Governance Policy Papers 69. https://doi.org/10.1787/162c5a27-en

Organisation for Economic Cooperation and Development (2025b). Unlocking the potential of demand-side climate mitigation strategies. OECD Net Zero+ policy Papers 9. https://doi.org/10.1787/78b3a9d0-en

Rare and The Behavioural Insights Team (2019). Behavior change for nature: A behavioral science toolkit for practitioners. Arlington, VA: Rare. https://www.bi.team/wp-content/uploads/2019/04/2019-BIT-Rare-Behavior-Change-for-Nature-digital.pdf

Service, O., Hallsworth, M., Halpern, D., Algate, F., Gallagher, R., Nguyen, S. et al. (2014). EAST Framework: four simple ways to apply behavioural insights. London: Behavioural Insights Team. https://www.bi.team/publications/east-four-simple-ways-to-apply-behavioural-insights/

Shove, E. (2010). Beyond the ABC: Climate change policy and theories of social change. Environment and Planning A: Economy and Space 42(6), 1273-1285. https://doi.org/10.1068/a42282

Slattery, P. (2025). Behaviour change 101 series: Five steps to select the right behaviour/s to target. BehaviourWorks Australia Blog, 15 April. https://www.behaviourworksaustralia.org/blog/behaviour-change-101-series-five-steps-to-select-the-right-behaviour-to-target. Accessed 15 April 2025

Viscusi, W.K., Huber, J. and Bell, J. (2011). Promoting Recycling: Private Values, Social Norms, and Economic Incentives. American Economic Review 101(3), 65–70. https://doi.org/10.1257/aer.101.3.65

Vitkauskaite-Ramanauskiene, J. (2025). Application of Action Research Methodology in the Development of Measures to Promote Sustainable Mobility. International Social Science Journal 75(257), 615-624. https://doi.org/10.1111/issj.12575

Credit: Image-Source/Envato

Indigenous Knowledge and Local Knowledge Chapeau D

Recognizing the knowledge systems and sciences of both Indigenous Peoples as well as local communities, which have deep connections to place and nature, is critical in global policy and scientific frameworks for achieving just transitions through self-determination and global goals (Vaziri et al. 2020; Dawson et al. 2021; Just Transitions 2024). A systematic review found that sustainability transformations research often neglects Indigenous Knowledge and local knowledge, arguing that such knowledge contributes to more plural and inclusive solutions for such transformations and how to achieve them (Lam et al., 2020). Techno-scientific approaches to sustainability primarily focus on modelling and technological fixes rather than considering Indigenous Peoples rights and biocultural conservation. Conversely, critical social sciences understand sustainability transformations as inherently political processes. They recognize there are many potential sustainability futures and that achieving positive change requires democratic and pluralist engagement that amplifies marginalized and silenced voices, including those of women (Scoones et al. 2020; Burke et al. 2022).

This engagement incorporates the voices of Indigenous Peoples, acknowledging the human rights requirements for Free, Prior, and Informed Consent (FPIC) as outlined in the United Nations Declaration on the Rights

of Indigenous Peoples and Convention 169 of the International Labour Organization. Relevant political processes must also recognize the validity and potential of Indigenous Peoples knowledge, ontologies (ways of being based on distinct understandings of the nature of reality), and values more broadly beyond Indigenous Peoples' ancestral contexts. Recognition of Indigenous Knowledge and local knowledge in transformation pathways aligns with IPBES assessments that define transformative change as shifts in paradigms, goals, and values (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES] 2019), including the moderation of market values and the amplification of solidarity and care values (IPBES 2022). Such ethics of respect, reciprocity, reverence, gendered equality and care are central to diversified Indigenous Peoples' conceptions of the good life – living well together as part of nature, in balance, with all creation, and lands having agency and value – challenging ethics, relations and structures of domination including patriarchy, governance, and control (Posey and Oxford Centre for the Environment Ethics and Society 1999; Reytar and Veit 2017; Brown and Verschuuren 2018; Sangha et al. 2019; IPBES 2022; Arora and Stirling 2023; IK & LK Dialogues 2025).

Indigenous Peoples can shape entirely new transformational pathways that are completely detached from the idea of sustainable development with its reliance on economic growth (Burke et al. 2022). Holistic understandings of lands, people, gendered knowledge and cultural relations contribute to the design of just transitions that address both environmental sustainability and human well-being (Welden, Chausson and Melanidis 2020; Riechers et al. 2021). They provide effective governance of living lands and create new forms of conservation that allow greater self-determination for Indigenous Peoples (Prosper et al. 2011; Hill et al. 2021; Paul et al. 2021). More broadly, Indigenous Peoples relational ontologies, values, and practices inspire sustainability action around the world (Nelson 2018; Bryer 2023). Indigenous Peoples stewardship of land and nature has often contributed to improving or maintaining biodiversity, land and soil quality and protecting their territories from extraction and misuse (Umeek 2011; Armstrong and Brown 2019; Díaz et al. 2019; ICCA Consortium 2021). There is clear evidence that Indigenous Peoples ontologies, values and practices have benefited and continue to benefit sea and landscapes by enhancing ecosystem function, regeneration, and biodiversity conservation (Balée 2013; Comberti et al. 2015; Ford and Nigh 2015; Reyes-Garcia et al. 2019; Thornton and Bhagwat 2021; Hoffman et al. 2021). Indigenous Peoples also resist unsustainable land management practices driven by capitalist resource extraction and appropriation, as well as cultural transmission pressures resulting from neo-imperialism, education, religion, and environmental pressures (The Atateken Declaration 2019; Makey et al. 2022; Fazito and Vargas 2023; Inman 2024).

As illustrated in Figure 1, Indigenous Knowledges will guide transformations towards sustainability, providing concrete guidance on actions related to the care of territory and life, as well as to energy, food, governance, and economies in socially just and culturally appropriate ways. Fundamental shifts and concrete practices for desired sustainable futures, as identified by participants in the GEO-7 Indigenous Knowledge and Local Knowledge Dialogues (IK & LK Dialogues 2025), include:

a) territorial and life care,

b) sustainable, social and solidarity economy,

c) responsible just energy transition based on self-determination and sovereignty,

d) education that fosters intergenerational transmission of Indigenous Knowledge and local knowledge and the revitalization of Indigenous Knowledge, cultures and languages, and

e) strengthening Indigenous Peoples' customary institutions and other forms of organizations, alliances and networks.

Instead of dismissing Indigenous ontologies, values and practices based on worldviews, and values of care and solidarity (IPBES 2022) or seeking to integrate them into scientific framings and paradigms, sustainability transformations will be better served by reparative actions that give greater space to Indigenous perspectives in decision-making processes and promote the broader uptake of such values (Stein et al. 2023).

Fig 1: Indigenous Peoples' perspectives on desired sustainable and just futures (IK & LK Dialogues 2025).

This figure shows Indigenous Peoples' perspectives on desired futures identified in the GEO-7 Indigenous Knowledge and Local Knowledge Dialogues

Credit: SakuraImageInc/Envato

The Indigenous Knowledge and Local Knowledge Dialogue of GEO -7 identified Indigenous perspectives on desired futures (IK & LK 2025). Figure 1 also illustrates the diversified yet common ways in which Indigenous conceptualizations of life give prominence to the ethics of care, reverence, reciprocity and respect, recognizing that humans are part of a web of life, a web characterized by relations of interdependencies, agency, obligations and sacredness. These ethics underpin self-determination and just transitions. Examples of Indigenous ontologies, values and practices are shown, such as Sumak Kawsay, Kametsa Asaike, Birgejumpi, and Ubuntu, representing aspects of biocultural diversity and conservation (Porsanger and Guttorm 2011; Chibvongodze 2016; Albó 2018; Caruso and Barletti 2019; IPBES 2022).

References

Albó, X. (2018) Suma Qamaña or Living Well Together: A Contribution to Biocultural Conservation. In: Rozzi, R., et al. From Biocultural Homogenization to Biocultural Conservation. Ecology and Ethics 3, 333-342 https://doi.org/10.1007/978-3-319-99513-7_21

Arora, S. and Stirling, A. (2023). Colonial modernity and sustainability transitions: A conceptualisation in six dimensions. Environmental Innovation and Societal Transitions 48(100733). https://doi.org/10.1016/j.eist.2023.100733

Armstrong, C. G. and Brown, C. (2019). Frontiers are frontlines: Ethnobiological science against ongoing colonialism. Journal of Ethnobiology 39, 14–31. https://doi.org/10.2993/0278-0771-39.1.14

Balée, W. (2013). Cultural Forests of the Amazon: A Historical Ecology of People and their Landscapes. Tuscaloosa: University of Alabama https://www.uapress.ua.edu/9780817386559/cultural-forests-of-the-amazon/

Bryer, A. (2023). Critical accounting as an indigenous project. Critical Perspectives on Accounting 93 https://doi.org/10.1016/j.cpa.2023.102579

Brown, S. And Verschuuren, B. (2018). Cultural and spiritual significance of nature in protected and cons'rved areas: The 'd'eply seated bond'. In Cultural and Spiritual Significance of Nature in Protected Areas: Governance, Management and Policy. Verschuuren, B. and Brown, S. (eds.). Abingdon: Routledge. Chapter 1. 1–13. https://doi.org/10.4324/9781315108186-1

Burke, L., Díaz-Reviriego, I., Lam, D. P. M., & Hanspach, J. (2022). Indigenous and local knowledge in biocultural approaches to sustainability: a review of the literature in Spanish. Ecosystems and People 19(1). https://doi.org/10.1080/26395916.2022.2157490

Caruso, E. and Barletti, J.P.S. (2019). Kametsa asaike. In Pluriverse: A post-development dictionary. Kothari, A., Salleh, A., Escobar, A., Demaria, F. and Acosta, A. (eds.). New Delhi: Tulika Books. 220-223 https://radicalecologicaldemocracy.org/wp-content/uploads/2020/09/Pluriverse-full-printable-version-July-2019.pdf

Chibvongodze, D. T. (2016) Ubuntu is Not Only about the Human! An Analysis of the Role of African Philosophy and Ethics in Environment Management. Journal of Human Ecology 53(2),157-166. http://dx.doi.org/10.1080/09709274.2016.11906968

Comberti, C., Thornton, T. F., De Echeverria, V. W. and Patterson, T. (2015). Ecosystem services or services to ecosystems? Valuing cultivation and reciprocal relationships between humans and ecosystems. Global Environmental Change 34, 247-262. https://doi.org/10.1016/j.gloenvcha.2015.07.007

Dawson, N. M., Coolsaet, B., Sterling, E. J., Loveridge, R., Gross-Camp, N. D., Wongbusarakum, S. et al. (2021). The role of Indigenous peoples and local communities in effective and equitable conservation. Ecology and Society 26(3), 19 https://doi.org/10.5751/ES-12625-260319

Díaz., S, Settele, J., Brodizio, E. S., Ngo, H. T., Agard, J., Arneth, A. et al. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. Science 366, eaax3100 https://doi.org/10.1126/science.aax3100

Fazito, M. and Vargas, S. (2023). Free time as a central issue of tourism studies: a genealogy of leisure/idleness based on the indigenous cosmovisions of Latin America. Tourism Recreation Research 48(4), 547–557. https://doi.org/10.1080/02508281.2023.2223472

Ford, A. and Nigh, R. (2016). The Maya forest garden: Eight millennia of sustainable cultivation of the tropical woodlands. London: Routledge. https://www.routledge.com/The-Maya-Forest-Garden-Eight-Millennia-of-Sustainable-Cultivation-of-the-Tropical-Woodlands/Ford-Nigh/p/book/9781611329988?srsltid=AfmBOoo5nCtLlHq8rGVQJTdjEOHY5m-HAiijDpGinrRg_UMq8542uvPGS

Hill, R., Harkness, P., Raisbeck-Brown, N., Lyons, I., Álvarez-Romero, J. G., Kim, M. K. et al. (2021). Learning Together for and with the Martuwarra Fitzroy River. Sustainability Science 17(2), 351-375. https://doi.org/10.1007/s11625-021-00988-x

Hoffman, K.M., Davis, E.L., Wickham, S.B., Schang, K., Johnson, A., Larking, T. et al. (2021).Earth'svation of Earth's biodiversity is embedded in Indigenous fire stewardship. Proceedings of the National Academy of Sciences 118 (32). https://doi.org/10.1073/pnas.2105073118

ICCA Consortium (2021) Territories of Life Report 2021. https://report.territoriesoflife.org/

IK & LK Dialogues (2025). Indigenous Knowledge and Local Knowledge Dialogues. Global Environment Outlook 7. Mexico City: CopIt-arXives. https://copitarxives.fisica.unam.mx/SC0011EN/SC0011EN.php

Indigenous Summit Just Transition (2024). Just TransiPeoples'digenous Peoples' Perspectives, Knowledge, and Lived Experiences. Geneva, Switzerland. https://www.indigenoussummit.org/summit-outcome

Inma", E. N. (2024). "There Are No Tr"e Himbas Anymore": Exploring the Dynamics of the Himba Culture and Land Use in the Face of Change in Kunene Region. Namibia. Sustainability 16 (4), Article 1582 https://doi.org/10.3390/su16041582

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES Secretariat, Bonn, Germany. 1148 pages. https://doi.org/10.5281/zenodo.3831673

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2022). Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Balvanera, P., Pascual, U., Christie, M., Baptiste, B., and González-Jiménez, D. (eds.). IPBES secretariat, Bonn, Germany https://doi.org/10.5281/zenodo.6522522

Lam, D. P., Hinz, E., Lang, D. J., Tengö, M., von Wehrden, H. And Martín-López, B. (2020). Indigenous and local knowledge in sustainability transformations research: a literature review. Ecology & Society 25 (1) http://dx.doi.org/10.5751/ES-11305-250103

Makey, L., Parsons, M., Fisher, K., Te Huna, A., Henare, M., Miru, V. et al. (2022). (Un)Heard Voices of Ecosystem Degradation: Stories from the Nexus of Settler-Colonialism and Slow Violence. Sustainability 14 (22), 14672 https://doi.org/10.3390/su142214672

Nelson, M. K. and Shilling, D. (2018). Traditional ecological knowledge: Learning from Indigenous practices for environmental sustainability. Cambridge University Press. https://doi.org/10.1017/9781108552998

Paul, A., Roth, R., Moo, S.S.B. (2021). Relational ontology and more-than-human agency in Indigenous Karen conservation practice. Pacific Conservation Biology 27 (4), 376-390. https://doi.org/10.1071/PC20016

Porsanger, J. and Guttorm, G. (2011). Working with Traditional Knowledge: Communities, Institutions, Information Systems, Law and Ethics. Dieđut, Guovdageaidnu: Sámi allaskuvla / Sámi University of Applied Sciences. http://hdl.handle.net/11250/177065

Posey, D. and Oxford Centre for the Environment Ethics and Society (1999). Cultural and spiritual values of biodiversity. Intermediate technology publications and UN Environment Programme, London and Nairobi. https://proyectodeautonomia.wordpress.com/wp-content/uploads/2018/04/1999-posey-cultural_spiritual_thebible.pdf

Prosper, K. , McMillan, L. J. , Davis, A. A. (2011). ReturninMi'kmaqtukulimk: Mi'kmaq cultural and spiritual connections with resource stewardship and self-governance. The International Indigenous Policy Journal 2(4) http://ir.lib.uwo.ca/iipj/vol2/iss4/7

Reyes-García, V., Fernández-Llamazares, A., McElwee, P., Molnár, Z., Öllerer, K., Wilson, S.J. et al. (2019). The contributions of Indigenous Peoples and local communities to ecological restoration. Restoration Ecology 27(1) https://doi.org/10.1111/rec.12894

Reytar, K. and Veit, P. (2017). 5 Maps Show How Important Indigenous Peoples and Local Communities Are to the Environment. Washington DC, USA: World Resources Institute. https://www.wri.org/print/57261

Sangha, K. K., Maynard, S., Pearson, J., Dobriyal, P., Badola, R. and Hussain, S. A. (2019). Recognising the role of local and Indigenous communities in managing natural resources for the greater public benefit: Case studies from Asia and Oceania region. Ecosystem Services 39, 100991. https://doi.org/10.1016/j.ecoser.2019.100991

Riechers, M., Balázsi, Á., García-Llorente, M. and Loos, J. (2021). Human-nature connectedness as leverage point. Ecosystems and People 17(1), 215-221 https://doi.org/10.1080/26395916.2021.1912830

Scoones, I., Stirling, A., Abrol, D., Atela, J., Charli-Joseph, L., Eakin, H. et al. (2020). Transformations to sustainability: combining structural, systemic and enabling approaches. Current Opinion in Environmental Sustainability 42, 65-75. https://doi.org/10.1016/j.cosust.2019.12.004

Stein, S., Andreotti, V., Ahenakew, C., Suša, R., Valley, W., Huni Kui, N. et al. (2023). Beyond colonial futurities in climate education. Teaching in Higher Education 28 (5). https://doi.org/10.1080/13562517.2023.2193667

The Atateken Declaration (2019). The North American Regional Declaration on Biocultural Diversity. The Atateken Declaration. Declaration and Recommended Actions. https://www.cbd.int/portals/culturaldiversity/docs/north-american-regional-declaration-on-biocultural-diversity-en.pdf

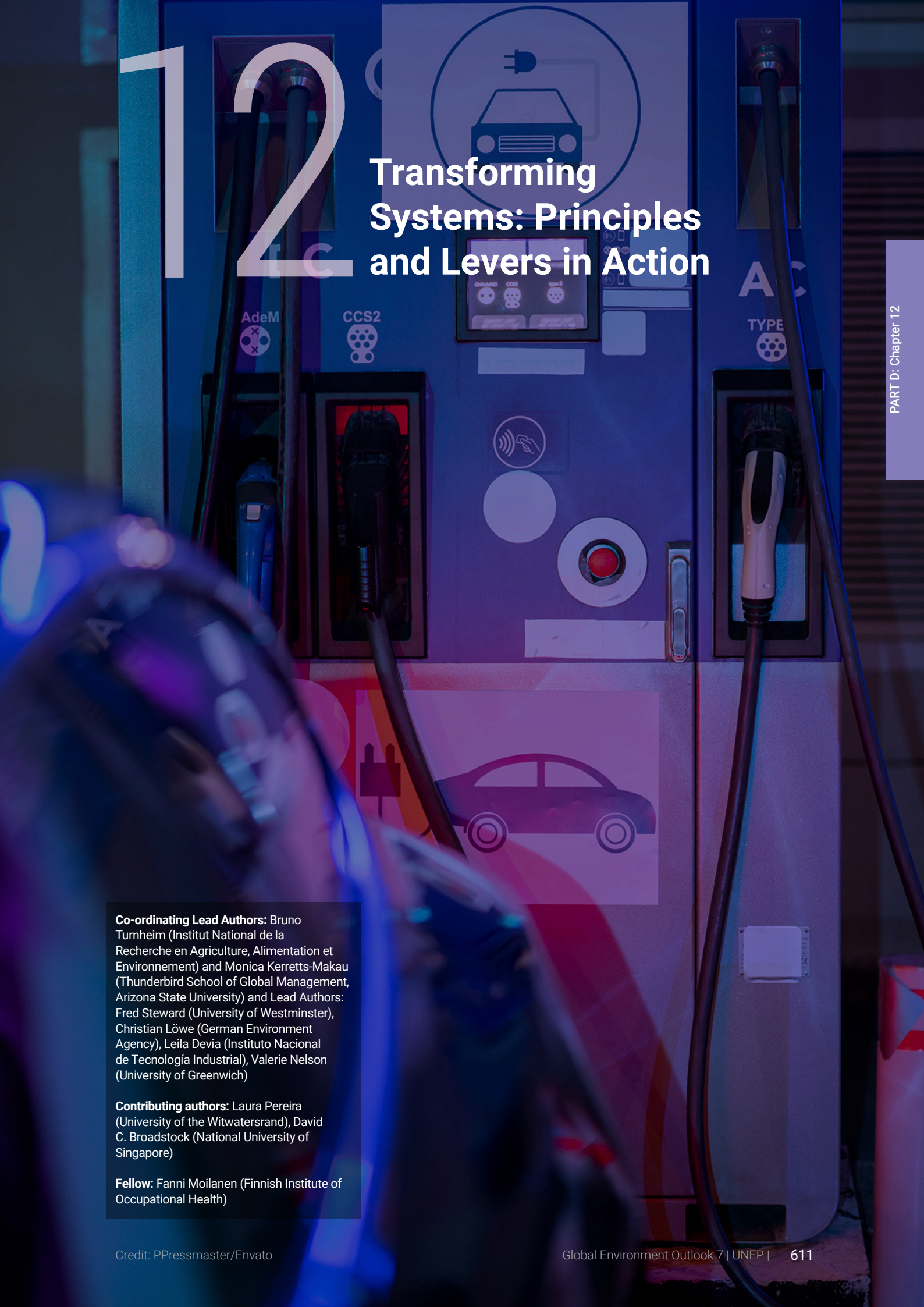
Thornton, T.F. and Bhagwat, S. eds. (2021). The Routledge handbook of indigenous environmental knowledge. London: Routledge. https://doi.org/10.4324/9781315270845

Umeek, E. A. (2011). Principles of Tsawalk. An Indigenous Approach to a Global Crisis. UBC Press. https://doi.org/10.59962/9780774821285

Vaziri, L., Sarrazin, M., Scott, C., Sterling, E. J. and Pascua (2020). Policy Brief 1: Measuring Biocultural Diversity. Centre for Indigenous Conservation and Development Alternatives and American Museum for Natural History Centre for Biodiversity and Conservation https://cicada.world/files/pb/CICADA-CBC_PolicyBrief1_Biocultural-indicators.pdf

Welden, A., Chausson, A. and Melanidis, M. (2020). Leveraging Nature-based Solutions for transformation: Reconnecting people and nature. People and Nature 3, 966-997. https://doi.org/10.1002/pan3.10212

12 Transforming Systems: Principles and Levers in Action



Co-ordinating Lead Authors: Bruno Turnheim (Institut National de la Recherche en Agriculture, Alimentation et Environnement) and Monica Kerretts-Makau (Thunderbird School of Global Management, Arizona State University) and Lead Authors: Fred Steward (University of Westminster), Christian Löwe (German Environment Agency), Leila Devia (Instituto Nacional de Tecnología Industrial), Valerie Nelson (University of Greenwich)

Contributing authors: Laura Pereira (University of the Witwatersrand), David C. Broadstock (National University of Singapore)

Fellow: Fanni Moilanen (Finnish Institute of Occupational Health)

Credit: PPressmaster/Envato

Chapter summary

Credit: liufuyu/Envato

There is widespread international agreement, backed by scientific evidence, that business as usual or continuous incremental improvements will not be enough to deliver global environmental goals. Fundamental transformations of key societal systems, aligned with efforts to deliver more peaceful, just and inclusive societies, are needed *(high confidence)* {12.2}.

The international community, supported by assessments of scientific evidence, has recognized the need for, increased urgency of, and difficulties associated with transformations of key human systems in the face of environmental challenges. Recent global environmental assessment reports have provided various definitions of system transformations and related challenges. Taken together, these reports underline a number of findings including the importance of system-wide changes beyond technological change and the need to align technological, economic, social and political changes. Additionally the reports highlight crucial needs for reconfiguring practices, norms, values and laws and for jointly supporting more sustainable systems while also reconfiguring unsustainable systems. Finally, the reports focus on the need to jointly address structural causes of unsustainability and injustice. However, what "fundamental system transformation" means, what system transformations entail, how to support them or how to track and evaluate progress all remain largely unaddressed.

There is a substantial and growing body of multi- and interdisciplinary scientific knowledge specifically

focused on system transformations, offering complementary perspectives on how societal systems have been or can be transformed, in a variety of sectors and contexts *(high confidence)* {12.3}.

Three social science perspectives engage directly with system transformations and their governance in the context of environmental and societal challenges:

- Socioecological perspectives focus on interactions among environmental components, including local environment, climate and natural factors, and human components such as local communities, cultural practices and institutions. They situate intentional transformative action within nested spheres of the practical, political and personal.

- Sociotechnical perspectives focus on the mutual shaping of technology and society, representing systems as semi-coherent bundles of technology, policy, industry, science, culture, and markets and users. They situate intentional transformative action as interventions targeted at whole systems and lock-ins.

- Socioeconomic perspectives focus on the interaction of economic and social systems, the scope for institutional frameworks and responses to modulate these systems. They situate intentional transformative action as structural interventions targeted at the underlying rules and orientations of economic systems.

These perspectives differ in terms of how system boundaries are drawn, how dynamics of transformations are represented, how future transformations are envisioned, and what are lessons for governance. Taken together, they can inform the evaluation and governance of intentional system transformation with improved resolution.

These three perspectives highlight the need for strategic approaches to the governance of system transformations, their interactions and interlinkages *(high confidence)* {12.3} {12.4}.

The feasibility and effectiveness of strategic efforts to support system transformations can be significantly improved if informed by guiding principles. This chapter proposes the following six guiding principles as requirements for the governance of system transformations:

Principle 1: Be explicitly targeted at whole systems and address underlying sources of lock-in related to current system configurations.

Principle 2: Jointly address opportunities and challenges in new and existing systems, through explicit choices resolving contradictions between what must be developed, phased out, preserved and avoided.

Principle 3: Articulate near and long-term solutions in sequences of action enabling constructive linkages between multiple temporalities and accounting for non-linear dynamics, recognizing justice for future generations and non-humans.

Principle 4: Be supported by new ways of dealing with uncertainties and anticipation.

Principle 5: Involve actors from different societal spheres and a plurality of ways of knowing and being, which implies deliberate forms of coordination, inclusion and participation, including representation of Indigenous Peoples.

Principle 6: Address power relations, vested interests and social inequalities through decisive political choices, guided by explicit notions of justice and respect for Indigenous Peoples' rights.

The implementation of these principles can be worked out through domains of intentional action, referred to as levers. These provide the scope for strategic approaches to system transformation in policy and practice – who and what drives change, how change is influenced, why it is accepted *(moderate confidence)* {12.5}.

The selected levers, namely Economics and Finance, Individual and Collective action, Knowledge and Innovation, Governance, and Capabilities, allow relevant social actors to make sense of difficulties for system transformation and to generate options for transformative action {12.5}. This chapter illustrates how system transformation principles can be implemented through this lever structure {12.6}.

Combining intentional actions in, across and beyond established levers is necessary to create capabilities and coordinated momentum for system transformation.

Credit: wirestock/Envato

Plurality and consideration of marginalized perspectives are essential to the intentional governance of transformative change *(high confidence)* {12.5}.

Plurality – recognizing different perspectives and ontologies – implies centring marginalized ways of being and knowing, as well as those of Indigenous rights holders and local communities with deep connections to the land, and addressing the deep underlying causes of unsustainability. Indigenous Peoples' and other relational worldviews recognize humans as part of nature, with entangled relations of sacredness, spirituality and interdependence. These relational worldviews produce culturally based teachings on obligations and reciprocities and on care for lands, for all beings – human and non-human, animate and inanimate – and for ancestors, as well as present and future generations. Such ontologies and ways of knowing, along with their associated practices, may challenge dominant worldviews, but they are consistent with global goals of peace, equity and justice.

The chapter concludes by focusing on the urgent responsibility of governments to catalyse system transformations. The key areas include orientation, alignment, navigation, and legitimacy of transformative goals and actions {12.7}.

Such coordination efforts are necessary to mitigate the risks of fragmented actions, counterproductive effects and further systemic lock-ins, as well as technocratic solutionism. This calls for a new policy design and a political culture that is inclusive and empowering, which raises the overall feasibility of system transformations by turning it into a widely shared societal project. Noting that governments must consider their attachments to existing structures, actors and interests, they also have particular responsibilities for creating favourable conditions for system transformations and the required governance changes. This responsibility for generating tangible change and hopeful futures can be seen as a way of reaffirming the relevance and legitimacy of democratic institutions for a better world.

12.1 Introduction

The previous chapters have set out the context and the issues ahead in the quest for a desirable world environment. As all Global Environmental Outlook (GEO) reports have shown, addressing systemic environmental challenges extends well beyond the remit of environmental policy and requires a focus on transforming underlying systems, as well as concerted efforts from all societal actors. While previous GEOs have provided policy-response solutions to the issues, as highlighted in Chapter 1, GEO-7 offers a fresh perspective for understanding and supporting system transformations based on the latest scientific evidence.

This perspective calls for establishing new theoretical underpinnings of the dynamics of system transformation, clarifying the means and scope for intentional action, and raising the importance of directionality as a new quality of the political culture for system transformations.

Preceding chapters have assessed the need for transformation based on scientific knowledge of environmental trends and drivers (Chapters 2–8), and provided future-oriented outlooks of the potential solution space from a technoeconomic modelling perspective and supporting archetypal storylines (Chapters 9–11). The purpose of this chapter is to delve further into the dynamics of system transformations, to identify key principles of transformation, and to determine the implications for intentional action. It does so with particular attention to the social, political and process feasibility of system transformations, as well as the necessary capability for intentional governance.

Section 12.2 discusses why system transformations are needed to address global environmental problems. It is based on global science-policy reports.

Section 12.3 summarizes knowledge contributions from three scientific perspectives engaging directly with system transformations within the social sciences, to identify the common evidence base for analysing and governing system transformations in the context of environmental and societal challenges:

- Socioecological transformations to sustainability
- Sociotechnical transitions to sustainability
- Socioeconomic transformations

Credit: tampatra/Envato

These literatures address transformations as a systemic challenge, related to inherent problems with how current systems are configured and locked in. They share some common ground as well as important contrasts.

Section 12.4 formulates six generic principles for system transformations, which are derived from the bodies of knowledge discussed in Section 12.3. They provide a general framework for analysing and evaluating the dynamics of system transformations according to specific criteria and conditions.

Section 12.5 translates the six principles for system transformations into requirements for intentional action. Approaching governance structures as a set of interacting levers (United Nations Environment Programme [UNEP] 2019; United Nations 2023) allows a detailed examination of the scope and locus of transformative interventions within and beyond existing domains of intentional action in policy and practice, referred to as levers.

Section 12.6 provides an exemplification of the approach by mobilizing illustrative cases, clarifying how each principle can become the object of actions within specific levers, across levers, and beyond established lever configurations.

Section 12.7 concludes the chapter by reviewing the governance mechanisms available for system transformation. In particular, it underscores the need for deliberative processes in the formulation of political solutions (United Nations 2023), acknowledging the complex and volatile world and the diversity of societal issues ahead. The section invites all policy actors to reconsider a new political practice of implementing system transformations, focusing on orienting, aligning, navigating and legitimizing key functionalities to safeguard a more stable and long-lasting directionality in governing for system transformations.

12.2 Science-policy rationales for system transformation

There is widespread international agreement, backed by scientific evidence, that business as usual or continuous incremental improvements will not be enough to deliver on global environmental goals and that fundamental transformations are needed (**Box 12.1**). Further, the international environmental community has significantly broadened its remit beyond assessments of the state of the environment towards greater involvement with the dynamics and governance of transformations, following a general trend from problem-based to solutions-focused assessments (Castree et al. 2014; Kowarsch et al. 2017; Beck and Mahony 2018; Jacob and Ekins 2020).

The Sustainable Development Goals (SDGs) point to significant changes in the way social, technical and environmental systems are organized (United Nations 2019; United Nations 2023). The international community, supported by assessments of scientific evidence, has recognized the need for, increased urgency of, and difficulties associated with transformations of most human systems in the face of environmental challenges.

Global environmental assessment reports have provided various definitions of system transformations and related challenges (**Appendix 12.1**). Taken together, these underline important considerations for system transformation that include the importance of system-wide change beyond technologies. These considerations include the need for alignment of technological, economic and social change and for reconfigurations of practices, norms, values and laws. As well, they cover the need to reconfigure unsustainable systems and to jointly support more sustainable systems and address structural causes of unsustainability and injustice (United Nations Development Programme [UNDP], United Nations Office on Drugs and Crime and Office of the United Nations High Commissioner for Human Rights 2024).

Furthermore, there is increased recognition that implementing system transformations also requires transformations of governance and decision-making structures (United Nations 2023; IPBES 2024), such as support for customary Indigenous governance of living territories (IPBES 2024).

Thus, what "fundamental system transformation" means, what system transformations entail, how to support them, or how to track and evaluate progress, remain largely unaddressed. What is needed is a sharper, more resolute and more uncompromising assessment framework for understanding transformations, how they can be supported and how they can be evaluated. This chapter intends to begin addressing this gap.

Box 12.1: Calls for system transformations to address environmental challenges sanctioned by the international community

- "Business-as-usual will not deliver the Sustainable Development Goals by 2030 or even 2050, yet the Goals are the survival kit behind the transformation process that the planet needs. Global scenario projections reveal plausible future pathways where rapid progress can be made towards the Goals. Harnessing these opportunities will require an increased level of ambition, transformative policies, and an integrated approach to organize and coordinate efforts." (United Nations 2023, p. 39)

- "Rapid and far-reaching transitions across all sectors and systems are necessary to achieve deep and sustained emissions reductions and secure a liveable and sustainable future for all. These system transitions involve a significant upscaling of a wide portfolio of mitigation and adaptation options." (IPCC 2023a, p. 28).

- "Goals for conserving and sustainably using nature and achieving sustainability cannot be met by current trajectories, and goals for 2030 and beyond may only be achieved through transformative changes across economic, social, political and technological factors" (IPBES 2019, p. 18).

- "The world has a huge challenge ahead of it to move net zero by 2050 from a narrow possibility to a practical reality. Global carbon dioxide emissions are already rebounding sharply as economies recover from last year's pandemic-induced shock. It is past time for governments to act, and decisively to accelerate the clean energy transformation. As this report shows, we at the IEA are fully committed to leading those efforts." (IEA 2021, p. 4).

Credit: tampatra/Envato

- "Current trajectories are fundamentally unsustainable; these trajectories are interconnected and linked to our main systems of production and consumption; and time is running out to come up with credible responses to bend the trend." (EEA 2019, p. 7).

- "The SDGs set out a vision for transformed societies that are prosperous, peaceful, meet the needs of all people, and protect the planet. There are many goals which the Asia Pacific region is far from achieving, and a transformation in focus and approach will be needed if we are to attain them." (United Nations Economic and Social Commission for Asia and the Pacific [ESCAP], Asian Development Bank [ADB] and the United Nations Development Programme [UNDP] 2018, p. 50)

12.3 Scientific perspectives for system transformations

A variety of scientific perspectives[1] is needed to address sustainability challenges and required system transformations (Turnheim et al. 2015; EEA 2017; Patterson et al. 2017; Loorbach, Frantzekaski and Avelino 2017; Cherp et al. 2018; Clark and Harley 2020). While there are many other perspectives, this chapter focuses on three relevant social science literatures engaging directly with system transformations and their governance in the context of environmental and societal challenges [2]:

- Socioecological transformations to sustainability
- Sociotechnical transitions to sustainability
  Socioeconomic transformations

These perspectives differ in terms of how system boundaries are drawn, how dynamics of transformations are represented, how future transformations are envisioned, and their lessons for governance. Taken together, these different perspectives can inform the challenges and governance of intentional system transformation, leading to improved resolution. The following section presents these perspectives one by one, while Section 12.5 distils them to derive general principles for system transformation and illustrate their applicability within the levers structure.

12.3.1 Socioecological transformations

Socioecological perspectives focus on the dynamic relation between human systems and natural systems. They represent socioecological systems as complex adaptive systems embedded in the biosphere (Folke et al. 2016). They include systems that humans fundamentally depend on for survival, like food systems (Ericksen 2008), but can also be extended to urban systems or cities that involve complex patterns of interaction between human and natural features, for example, ecosystem services, like water, green spaces, and coasts or wetlands (Elmqvist et al. 2018).

Socioecological transformations are rooted in resilience thinking that understands systems as constantly in a dynamic flow of revolting, then reorganizing and exploiting after the crisis, but also remembering, conserving and releasing that happens across scales (Rocha, Lanyon and Peterson 2022; Gunderson and Holling 2002). This perspective provides a meaningful way to think about change as being connected to different subsystems and over space and time. This is useful for helping us to understand the spillover effects of telecoupled systems – those systems that influence each other even if they do not seem to be directly connected (Liu et al. 2018). The key emphasis of this perspective is the fundamental essence of the biosphere, within which all social, economic and technological activities can take place and, related to this, that any deliberate intervention into a complex system can have unintended consequences (**Box 12.2**).

Resilience thinking shows that in the face of pressures, resilient systems are either persistent, adaptive or transformative. Adaptability is referred to as the capacity of people in a socioecological system to build resilience through collective action, whereas transformability is the capacity of people to create a fundamentally new social-ecological system when ecological, political, social, or economic conditions make the existing system untenable (Walker et al. 2004). Over the years, the term transformability has

Box 12.2: Examples of unintended consequences of environmental interventions in complex systems

Examples include conservation efforts in the Amazon, which have led to increased deforestation in surrounding areas, or the regulation of fisheries in one region of the world resulting in increased exploitation in another less stringently regulated region (Pereira et al. 2024).

1 While this section exclusively builds on three scientific perspectives from which to distill established and consensual knowledge on system transformations, this chapter and the entire GEO-7 is receptive to a plurality of relevant forms of knowledge, including Indigenous and Local Knowledge as essential ways of seeing and being that can and must inform system transformations. The principles for system transformations laid out in section 12.4 have been influenced by such a pluralist view.

2 These literatures have been selected because they take 'system transformation' as their primary object of enquiry and because far-ranging consensus exists concerning their core contributions. The European Environment Agency has recognized the policy-relevance of learning from these perspectives to inform transformations towards sustainability (EEA 2017).

been expanded to refer to "transformations towards sustainability" as fundamental changes in structural, functional, relational, and cognitive aspects of socioecological systems that lead to new patterns of interactions and outcomes (de Haan and Rotmans 2011; Hackman and St. Clair 2012; O'Brien 2012; Feola 2015; Patterson et al. 2017), namely for a better inclusion of considerations of power. There is a growing literature on how equity, justice and acknowledging unequal power dynamics are central to navigating transformations (Blythe et al. 2018; Pereira et al. 2019).

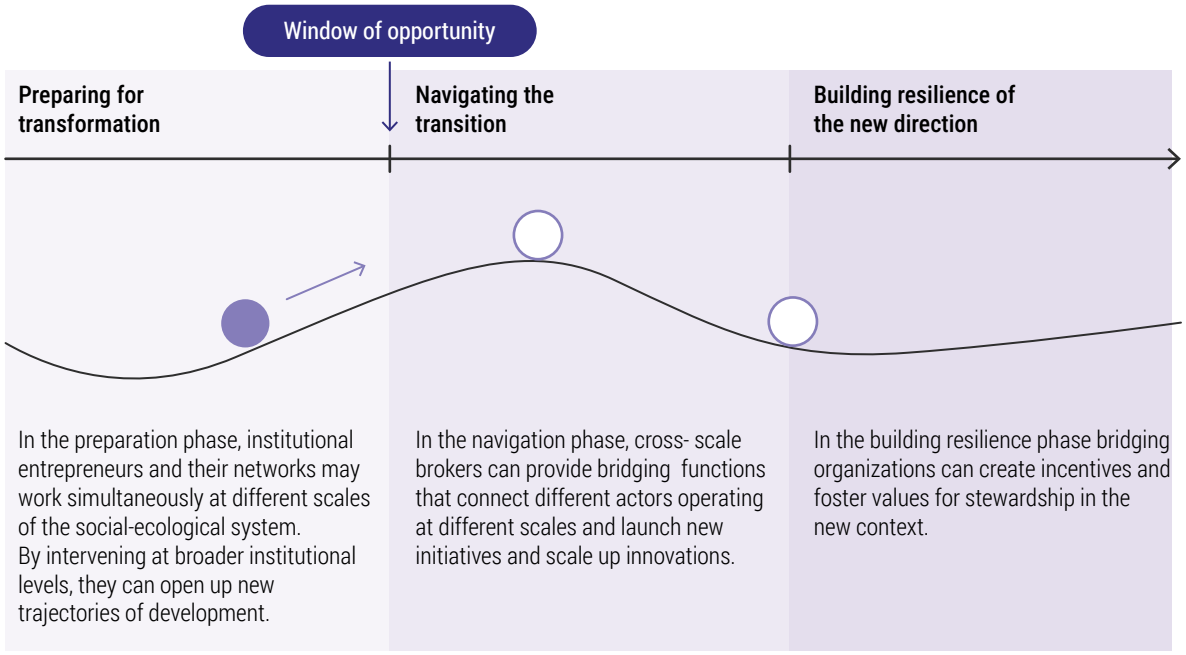
There are three phases to how socioecological transformations are enabled, although these can also be iterative (Olsson, Folke and Hahn 2004; Folke et al. 2010) (**Figure 12.1**):

- **Phase 1:** In the preparation phase, institutional entrepreneurs and their networks may work simultaneously at different scales of the socioecological system. By intervening at broader institutional levels, they can open up new trajectories of development.
- **Phase 2:** In the navigation phase, cross-scale brokers can provide bridging functions that connect different actors operating at different scales to launch new initiatives and scale up innovations.
- **Phase 3:** In the building resilience phase, bridging organizations can create incentives and foster values for stewardship in the new context.

When a system is in limbo between the existing, dominant state and a new alternative state, hybrid approaches to transformative and transitional justice are essential for moving forward. These approaches include addressing backlash dynamics as a relapse back to the former unsustainable system, strengthening the capacities needed to navigate cross-scale dynamics of conflict, and responding to additional shocks, crises and disturbances beyond the primary conflicts (Olsson and Moore 2024).

Given the current planetary ecological pressures, transformation towards new systems has become a necessity as current conditions make the existing system untenable (Rockström et al. 2023). This requires a new trajectory or pathway away from business as usual (Walker et al. 2004; Folke et al. 2010; Westley et al. 2011; Frantzeskaki, Loorbach and Meadowcroft 2012; Pereira et al. 2018). However, the question of where to transform towards remains, given the complex and messy reality of systems and the diverse values that underpin what is deemed preferable, and who makes these decisions (Pereira et al. 2020; Pereira et al. 2023). There is increasing agreement about which options are not preferable because they fall outside a safe and just operating space (Rockström et al. 2023) or do not have

Figure 12.1: Three phases of socio-ecological transformations



Source: Stockholm Resilience Center (2016)

a sustainable human-nature relationship at their core (IPBES 2016; Pereira et al. 2020). This is why co-created visions are critical, as these can inspire transformative futures from which action can be developed (Pereira et al. 2021). Acknowledging the plurality of potentially preferable futures based on diverse value systems has implications for the orientation of transformative interventions (Pereira et al. 2023; Villasante et al. 2022; Chibwe et al. 2024). In addition, the plurality of ontologies and values in sustainability future-making (Harmáčková et al. 2023) implies making space in decision-making for subaltern perspectives, including those of Indigenous Peoples, as a challenge to the dominant formations (Scoones et al. 2020), such as colonial modernities that continue to reproduce and intensify social-ecological damage (Arora and Stirling 2023).

Enabling socioecological transformations requires systemic shifts in mental models and paradigms, and changes in institutions, management routines and resource flows (Meadows 1999; Westley 2013). It is also crucial to recognize the role of human agency and the evolving or expanding roles of the diverse types of actors driving these transformations (Westley et al. 2013). However, there remains a question of how top-down and bottom-up interventions for transformative change interact and whether bottom-up initiatives have sufficient capacity to shift dominant power dynamics (Scoones et al. 2020). A recognition of the need for transformations of structures, systems and individuals is growing, but research gaps remain on how to enable these changes equitably (Pereira et al. 2020). One such pathway is through the strengthening of local initiatives that could lead to more sustainable and equitable futures (Bennett et al. 2016; Pereira et al. 2018). The transformative potential of bottom-up initiatives has been outlined by Tuckey et al. (2023) and how to scale or amplify their impact has been demonstrated by Lam et al. (2020) (**Box 12.3**).

Box 12.3: Examples of scaling in food systems

Specific examples within the food system have tracked niche initiatives that have grown over time in Cape Town, Stockholm and Spain, understanding some of the institutional barriers that they faced and how leveraging networks and building coalitions helped to overcome some of these (Guerrero Lara et al. 2019; Lam et al. 2022; Sellberg et al. 2020).

At the same time, several capacities for transformation have been brought to the fore, including the need for imaginative capacity to envision the transformations required (Moore and Milkoreit 2020). Unpacking agency for enabling transformation across individual to organizational levels is crucial to understand in diverse contexts, as this has implications for the actions that can be undertaken (Charli-Joseph et al. 2018).

12.3.2 Sociotechnical transitions

The sociotechnical transitions literature (Kemp, Schot and Hoogma 1998; Markard, Raven and Truffer 2012; Köhler et al. 2019) focuses on the long-term, fundamental transformation of sociotechnical systems, such as energy, mobility and agrifood, in concrete settings. Rather than focusing on a particular technology or innovation, for example, cell phones, a sociotechnical perspective points to the larger systems that enable the production and consumption of goods and services tied to the provision of societal functions, such as food, heat, power, shelter and health.

Sociotechnical systems are configurations of heterogeneous entities (Geels and Turnheim 2022):

- material elements as artefacts, infrastructures, flows
- relational elements as actors, networks
- institutional elements as regulations, norms, values

The development of sociotechnical configurations is a coevolutionary process in which technologies, infrastructures, supply chains, user preferences, markets, policies and cultural meanings mutually shape each other over extended periods (Geels 2002; Geels 2004). This mutual shaping produces alignment between technical features and institutional features. As a result, once established, sociotechnical configurations are dynamically stable and inherently resistant to change.

The inertia of established sociotechnical systems is structural and enacted (Turnheim 2023) mainly due to:

- structural lock-ins, such as sunk investments, increasing returns to scale, standardization, cognitive routines, asymmetric access to rule-setting, strategic alliances, and normalized

ideologies (Nelson and Winter 1982; Arthur 1989; Pierson 2000; Unruh 2002; Klitkou et al. 2015) that tend to favour existing structures, and actors who make it more difficult for alternative configurations to emerge

- active resistance strategies, notably by incumbent actors – industry, policy, and other actors whose power, resources and vested interests are tied to these systems (Stirling 2019; Turnheim and Sovacool 2020) – who invest in maintenance and improvement activities, reproduce advantageous regime rules, and defend current arrangements when new problems arise.

These mechanisms make sociotechnical transitions rare and difficult. Incremental adjustments and marginal improvements that tend to preserve established configurations are more likely to occur than radical and fundamental transformative change (**Box 12.4**). Even when change happens, it tends to be incremental unless particular conditions are met. Furthermore, sustainability transitions, which are a particular kind of sociotechnical transition guided by new objectives, such as sustainability, present a dual challenge of fundamental changes in sociotechnical configurations, as well as fundamental changes in prevailing performance criteria (Kemp and van Lente 2011).

Given system lock-ins, sociotechnical transitions involve substantially new ways of doing things – radical innovation – and new ways of putting things together – reconfiguration.

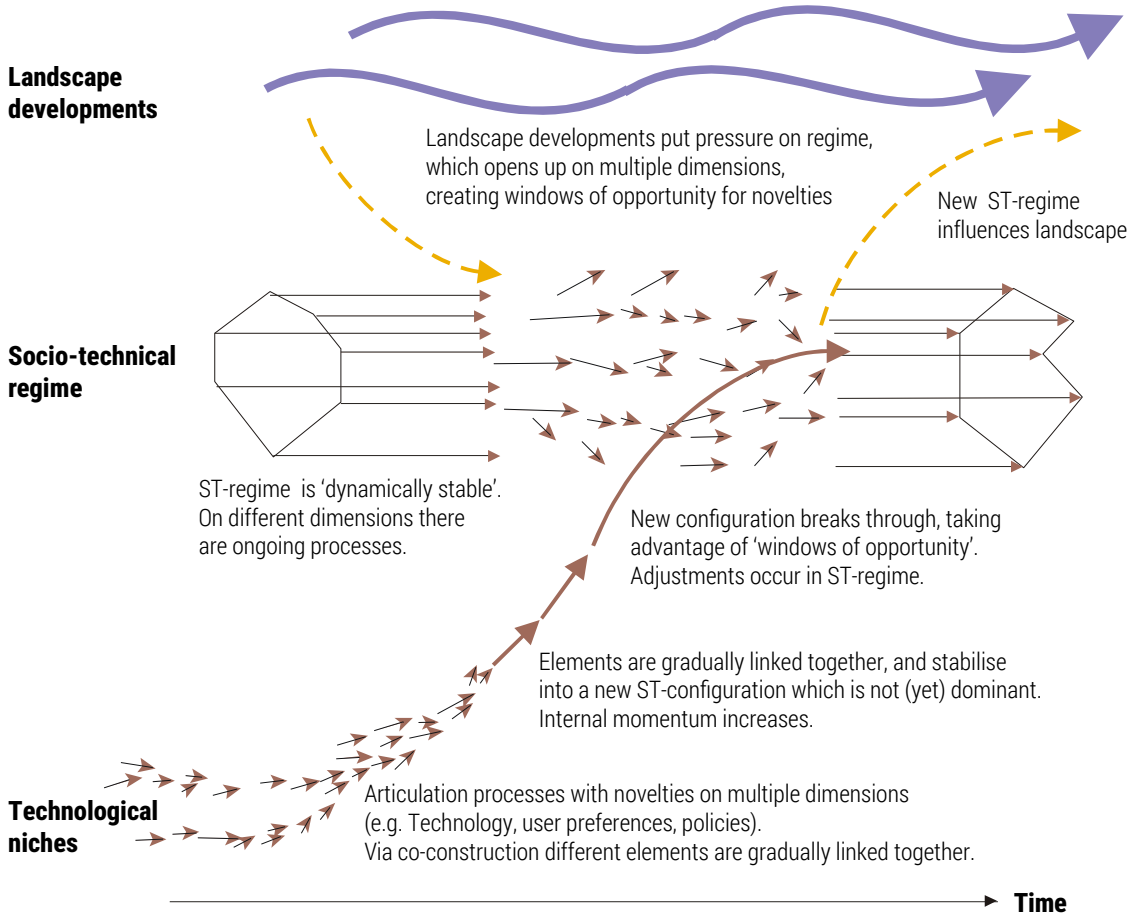
The multidimensional perspective on sociotechnical transitions (Kemp, Schot and Hoogma 1998; Geels 2002; Geels 2004; Geels and Turnheim 2022) further suggests that transitions can be depicted as involving changes within and across three

Box 12.4: Examples of marginal improvement in sociotechnical transitions

Examples of marginal improvement pathways include, for instance, end-of-pipe solutions such as the mandatory installation of catalytic converters in petrol cars to deal with local air pollution problems from the 1970s, or the diffusion of electric vehicles as a means to decarbonize automobility from the 2000s without fundamentally addressing personal mobility patterns. By contrast, a more fundamental system transformation would involve, for instance, a very substantial decline of car-based mobility along with the deployment of slow mobility modes, which would inevitably transform the topology of urbanization (Banister et al. 2011; Wells 2023).

Credit: IciakPhotos/Envato

Figure 12.2: A dynamic multi-level perspective on system innovations



Source: Geels (2002b)

levels of structuring social and technical activities, namely, niches, systems and landscapes. Within this space, characterized by structuration and temporal dimensions, any transition essentially involves the interaction of three processes: radical innovation, generalization and destabilization (**Figure 12.2**).

Radical innovations are developed in niches, that is, relatively protected spaces shielded from prevailing selection pressures (Smith and Raven 2012), by alternative innovation communities and often in response to new problems or new technical promises.

Radical innovations are initially considered hopeful monstrosities that do not fully work; they are initially full of defects, prone to failure and ill-adapted to existing technical capacities or institutional requirements. But they are simultaneously attached to significant expectations (Truffer 2008; van Lente 2012; Konrad and Böhle 2019) concerning their economic or technical development potential, or the promise to address long-standing problems (**Box 12.5**). Most innovations, whether social, technological, organizational or policy, remain stuck at the niche level.

Box 12.5: Examples of radical innovations

Solar photovoltaic technology is an example of a successful radical innovation, which initially was so costly and inefficient that significant hope and imagination were required to envision its mass deployment for civil purposes.

At its beginnings in the late 1800s, the petrol car was far from an inevitable success: it was considered dangerous and costly, had a very limited range and was hindered by the lack of paved roads or repair networks.

Box 12.6: Examples of generalization and diffusion in socio-technical transitions

The generalization of renewable energy technologies as a legitimate, cost-efficient and reliable energy source required scaling and improvements enabled by ambitious incentive programmes, such as Energiewende, the German energy transition plan.

The generalization of conventional or high-input agriculture from the 1950s benefited from major development programmes such as the Green Revolution, supported by the promises of "food for all" legitimized by recurring food shortages and famines in the 1970s, as well as tight-knit networks of technical support prescriptors.

The generalization of innovations involves the development of innovations beyond their initial niche application, through widespread deployment and use. This generalization is not merely the diffusion of standardized products or services through markets (Rogers 1995). It also involves the mutual shaping of innovation and its uses (Leonard-Barton 1988), the establishment of dominant designs, processes of scaling, institutionalization, learning, and network development. It may lead to the displacement of existing systems, their incorporation, or simply coexistence alongside existing systems (Berkhout 2006; Raven et al. 2016; Avelino 2017) (**Box 12.6**).

The destabilization of existing systems is a process by which established sociotechnical configurations "become exposed to challenges significant enough to threaten their continued existence and their 'normal' functioning" (Turnheim 2023, p. 45). This destabilization can lead to full decline, partial decline, reconfiguration, or even system improvement, when challenges are addressed. Destabilization contexts involve combinations of exogenous pressures, for example, landscape changes such as urbanization trends, war and conflict, and environmental problems, and endogenous pressures, such as technical difficulties or accidents, lack of resources, mismanagement, and disbanding of alliances. The intentional destabilization of sociotechnical systems is commonly referred to as phase-out (**Box 12.7**).

Box 12.7: Examples of phase-out

Phase-out has been applied to specific substances such as DDT, asbestos, mercury, class A drugs, or leaded petroleum, to practices such as private animal slaughter, inner-city automobile use, or indoor smoking and, to a lesser extent, to entire systems such as dismantling of tramways, household coal delivery, or whaling.

Credit: rawf8/Envato

12.3.3 Socioeconomic transformations

The literature on socioeconomic transformations relates to the long-term transformation of society and economy. It focuses on the interrelations between economic systems and human development, often in historical perspective. There are different perspectives on socioeconomic transformations, owing to contributions from:

- academic traditions of political economy such as Marx, Polanyi or Keynes, historical sociology such as Tilly or Schor, and institutional theory such as Streeck or Thelen

- advocacy traditions from different organized public sources, including multilateral organizations such as the International Monetary Fund, Organisation for Economic Co-operation and Development, or World Bank and civil society in the form of trade unions, workers' movements, or the post-growth movement, among many others.

Major socioeconomic transformations have influenced the development of national economies and related patterns of lock-in to resources and industries. Structural changes in productive sectors, such as the shift from primarily agricultural to capital-intensive industrialized economies, for instance, are significant socioeconomic transformations that fundamentally alter the nature of economic activities, job and employment prospects, opportunities for capital accumulation, and trade opportunities. In different parts of the world, past socioeconomic trajectories determine current patterns of dependence on resources and industry, for example, oil-rich or mining-dependent countries (Bridge 2008; Adams et al. 2019; Pérez and Claveria 2020), as well as related social and environmental effects, both positive and negative.

Socioeconomic transformations depend on favourable institutional and policy conditions (Chapter 14) that 1) enable and support the reconfiguration of economic systems; 2) modulate the outcomes of the reconfiguration of economic systems, both negative and positive; or 3) may need to be radically transformed themselves. Socioeconomic transformations combine the opportunities offered by new modes of production with the associated technoeconomic paradigms of routines, values and beliefs conditioning economic activity (Freeman and Louça 2001). Perez (2003) identifies five significant surges of technoeconomic development in world history that follow similar overarching patterns, from installation to deployment. Organizational and institutional adjustment to new modes of production lead to new technoeconomic paradigms that become "the shared, established and unquestioned 'common sense' both in the economy and in the socio-institutional framework creating a clearly biased context in favour of the trajectories of the technologies of the revolution and their use across the economy" (Perez 2010 p. 199). Major socioeconomic transformations may require the transformation of institutional and policy conditions themselves.

There are major disparities in socioeconomic transformation patterns. Within the globalization of economic development and trade, socioeconomic transformations are not uniform but follow place-dependent patterns (Boschma et al. 2017), specifically in relation to local natural resource endowments or restrictions, as well as past forms of economic and institutional development (Fritz and Koch 2016).

Different patterns of socioeconomic development have:

- a significant effect on the wealth generated, for example, disparities between economies worldwide

- regional specialization, for example, specialization of productive industries and related flows of goods and services within global supply chains

- the supportive institutional framework, for example, wealth redistribution, welfare systems and safety nets, mitigation of health and environmental impacts

As a general rule, advanced economies have transformed their economic or sectoral structure towards greater variety, more services and less agriculture, while low-income countries remain primarily dependent on the agricultural sector for employment and economic output.

Socioeconomic transformations, while supporting the development of new forms of wealth, value and opportunities, also generate unsettling social and economic outcomes that require active efforts to avoid, reduce or regulate them. The adverse outcomes that can be associated with major socioeconomic changes are a

central theme of scholarship and institutional work on socioeconomic development:

- concentration of structural inequalities – ownership, power, privilege, access – resulting from various forms of private accumulation of means of production – capital, skills – typical of capitalist economies (Marx 1946; Kuznets 1955; Swilling 2020), which runs counter to the possibilities of equal and just societies

- commodification and marketization of everything – nature, skills, things – seen as a historical movement of economic development leading to inherent contradictions (Polanyi 1944), and calling for "re-embedding" markets in the control of democratic institutions and state organization, as these provide the only hopeful prospects for responsibility within liberal economic systems and their primacy of the individual and their freedom

- misplaced indications of value, which tend to condition the performance of social and political interventions to those maximizing monetary economic growth over alternative forms of value and human development, such as well-being, rights, social justice and poverty alleviation (Sen 1983; Sen 2002).

Patterns of change

Socioeconomic transformations involve different kinds of dynamics and patterns:

- structural patterns – for example, capital accumulation, deepening inequalities, structural sectoral shifts – calling for support or correction mechanisms

- cyclical patterns – for example, technological revolutions, business cycles, investment patterns – offer cues for regularities that need to be attended to or anticipated

- counter-movements and social contestation – for example, around particular social or environmental issues – can lead to changes in institutional frame conditions for economic development that may follow more or less abrupt patterns and lead to more or less discontinuous outcomes (Streeck and Thelen 2005)

- socioeconomic transformations are largely influenced by macrotrends such as urbanization patterns or global political economy and macrodisruptions such as wars, conflicts, and other crises.

Relation to social and environmental sustainability

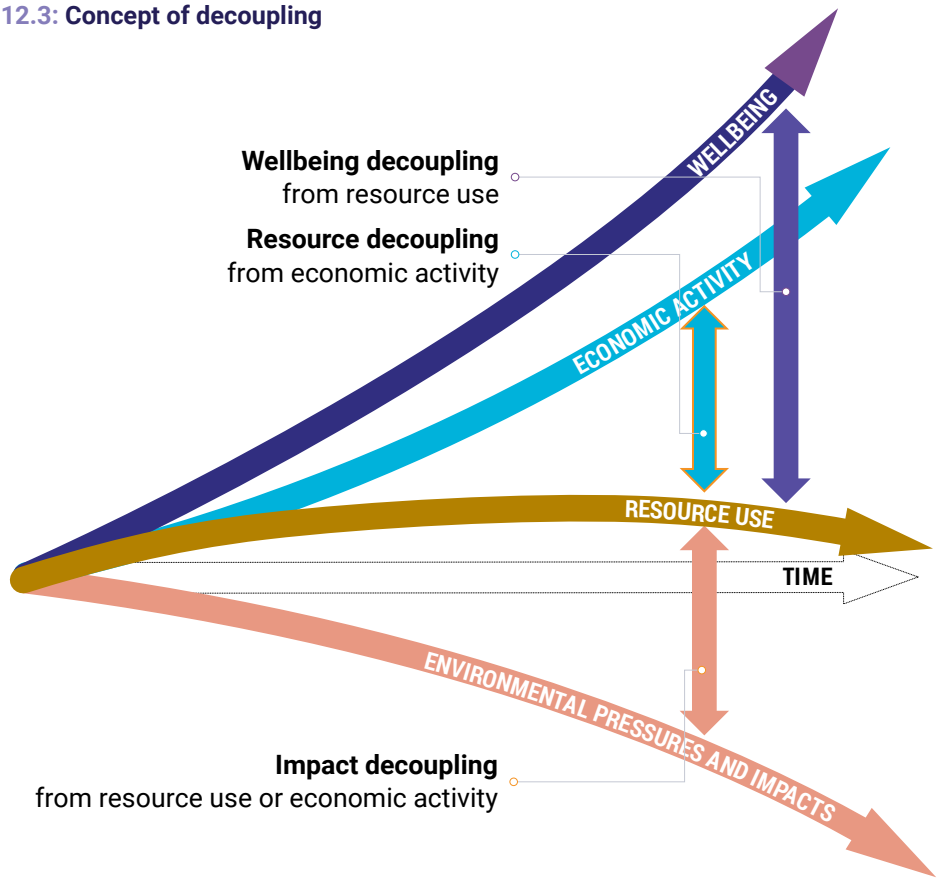
An important starting point is that socioeconomic transformation is not necessarily aligned with environmental or other progressive agendas, and that in some cases, there are deep tensions between economic development and social and environmental goals. For instance, while digitalization has become an important driver of socioeconomic transformation of national economies and sectors, there is no assurance that it will bring about environmental benefits and, in some cases, it may even contribute to greater environmental impacts. Aligning socioeconomic transformations with environmental goals requires dedicated institutions and possibly reorienting prevailing criteria for evaluating economic activity in line with shifts in and related decoupling (**Figure 12.3**).. Several alternative orientations can provide direction for socioeconomic transformations, including the following.

- A greening perspective on socioeconomic transformation suggests that environmental goals can be addressed within current economic systems through reforms and ecological modernization (Tienhaara 2014).

- A just transitions perspective focused on improving social justice, worker rights and access to decent employment conditions (Swilling 2020). Concerning environmental problems, these perspectives emphasize the need for anticipating and planning for training and reskilling needs, notably in areas and sectors with high dependency and vulnerability to activities deemed less desirable in favour of activities that may hold greater promises of development.

- Well-being perspectives suggest that attending to planetary and human limits, and economic policies requires more priority on objectives related to basic human needs (Sen 2002). Economic development should therefore be linked to more concrete provision objectives, for example, "providing high-quality public services,

Figure 12.3: **Concept of decoupling**



Source: Revised from IRP (2019b)

strengthening democracy, establishing greater income equality, ensuring universal access to electricity and clean fuels, improving trade and transport infrastructure, increasing public health coverage, minimizing extractive industries and abandoning economic growth beyond moderate levels of affluence" (Vogel et al. 2021, p. 13). These perspectives point to the relevance of reconfiguring economic systems towards more collective purposes, both social and economic, notably in terms of reducing material and energy waste, stronger public services, a priority for green employment and production, and making more space for care activities (Hickel et al. 2022).

- Post-growth perspectives point to the inherent contradictions of using metrics of economic growth, such as gross domestic product (GDP), as a prime indicator of societal development (Hickel et al. 2025; Kallis et al. 2018; International Panel of Social Progress 2018). Instead, they suggest that decoupling environmental and social effects from economic activity requires fundamentally renewed markers of societal development and social progress (UNEP 2011), which may entail breaking with the expansionary dynamics of capitalism and its inherited power relations in favour of collective, self-limitation and no-harm principles (Brand et al. 2021).

- Applying a pluriversal perspective, "a world where many worlds fit" (Escobar 2021), offers a pathway where environmental and social justice is achieved through transformative processes. A pluriversal approach supports shifts away from domination and control traditions towards lifeways that allow for multiple ways of knowing and being to guide how societies are organized, for example ways based on ethics of care and reciprocity (Escobar 2021). Such an approach provides space for Indigenous Peoples' ways of knowing and being in future decision-making and societal organization. Instead of separate human and nature systems, this envisions interdependent, entangled assemblages of humans and non-humans co-creating life.

More broadly, these socioeconomic perspectives suggest that there is a fundamental tension between equity and efficiency as foundations for economic systems, and that environmental and societal challenges provide a new impetus and various opportunities to address this.

12.3.4 Synthesis of the perspectives on system transformations

The three perspectives discussed in the previous sections offer consistent and complementary insights for the analysis of change dynamics and the scope for governance (**Table 12.1**). By bringing particular sets of relations in their system definition to the fore, each perspective sheds light on essential features and constraints of human systems and related development trajectories. The three perspectives understand system transformation as requiring: 1) a significant departure from powerful stabilizing mechanisms – lock-in, mutual shaping, persistence; and 2) activation of complex change mechanisms. They also highlight structural tensions and adverse outcomes, such as vulnerabilities, negative externalities, power imbalances, structural injustices and contradictions, at the heart of certain transformation paths, hence suggesting that clear orientations of change are necessary to ensure desirable outcomes.

Table 12.1: Juxtaposing three perspectives on system transformation

	System focus	Prevailing dynamics of change	Orientations of change	Lessons for governance and sustainability
Socioecological	Interlinkage between society and ecology	• System vulnerability • System resilience: persistence, adaptation or transformation patterns	• Ecological thresholds and boundaries • Consideration of plural values • Complexity of transformation	• Enhancing transformative capacity • Co-created visions combining practical, political and personal dimensions of change
Sociotechnical	Mutual shaping of technology and society	• Stabilizing mechanisms: lock-ins, actor resistance • Change mechanisms: • innovation, destabilization	• Overcoming lock-ins requires radical innovation: technical or institutional • Normative goals influence the direction of change • Radical change is political	• Phasing in and preserving sustainable entities • Phasing out and avoiding unsustainable entities • Navigating and anticipating inherent uncertainties
Socioeconomic	Mutual shaping of economy and institutions	Dual movement: • Wealth creation • Negative outcomes: injustice, externalities	• Economies can be reformed or reconfigured • Alternative objectives can be legitimate for economies, for example, justice, greening, well-being, post-growth	• Altering institutional conditions for economic development • Avoid, reduce and regulate negative externalities

The governance of system transformations is an inherently political matter involving difficult decisions mediated by societal and value choices, for which technocratic resolution is unlikely to be the most suitable mode of governance.

Combined, these three perspectives offer lessons for the governance of system transformations. Section 12.4 translates these lessons into a set of six principles for system transformations.

12.4 Six fundamental principles for system transformations

As discussed in the previous section, because system transformations are inherently complex and value-laden processes that generate significant challenges for contemporary governance structures, a consistent evidence-based framework for understanding dynamics and governing change in desired directions is necessary for transformation to take place.

This section distils this knowledge into a set of six key principles for system transformations, pointing to essential processes, mechanisms, and normative considerations that all need to be addressed to craft feasible transformation pathways and maximize the likelihood of their implementation. These six key principles also work as a list of criteria and a checklist for system transformations. Chapter 13 presents a methodology for evaluating and monitoring system transformations that builds on the following principles.

12.4.1 System configurations and lock-ins

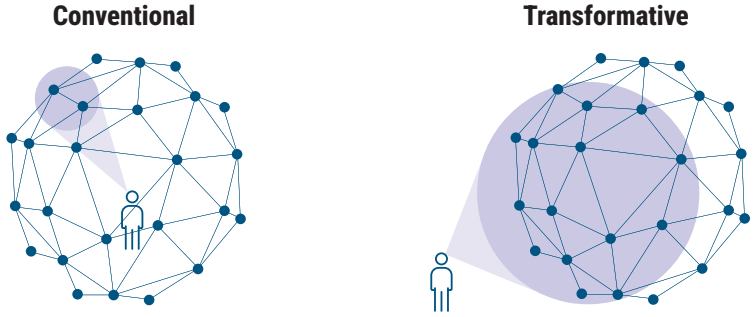
Principle 1: The governance of system transformations needs to be explicitly targeted at whole systems and address underlying sources of lock-in related to current system configurations (**Figure 12.4**).

System transformations to address global environmental crises involve jointly addressing two key challenges (Kemp and van Lente 2011): pervasive adverse effects, and systemic lock-ins. Appropriate representations of these system configurations and related sources of lock-ins (Klitkou et al. 2015; Goldstein et al. 2023) are essential preliminary steps to appreciate the obstacles, possibilities and constraints relating to system transformations.

Actionable system representations show how interlinkages between entities in different dimensions point both to sources of stability and opportunities for transformative change. Ecosystems and societal systems are "wicked" systems that combine high degrees of complexity – they have emergent features of self-organization – and complicatedness, that is, they have high levels of structure resulting from top-down organization (Andersson, Törnberg and Törnberg 2014). For these reasons, representing such systems and their functioning is challenging because they escape formal reduction efforts. Different perspectives emphasize different entities and sets of relations (EEA 2017; Clark and Harley 2020), and hence offer complementary insights for action (**Table 12.1**):

- socioecological perspectives focus on the interactions of environmental components – the local natural environment, climate and nature-related factors – and human components – local human communities, their cultural practices and institutions – and position intentional transformative action within nested spheres of the practical, political and personal (O'Brien 2018)

Figure 12.4: Transformation principle 1: Target policies at whole systems



- sociotechnical perspectives focus on the mutual shaping of technology and society, representing systems as semi-coherent bundles of technology, policy, industry, markets/users, science and culture (Geels 2002; Geels 2004; Marletto et al. 2016; Geels and Turnheim 2022)

- socioeconomic perspectives focus on the interaction of economic and social systems, and the scope for institutional frameworks and responses to structure and modulate these systems

Adequate system representations need to account for the routine functioning of existing systems and underlying configurations-that is, the linkages between heterogeneous elements-to highlight the primary sources of systemic lock-ins and their main challenges. Focusing on whole systems rather than addressing individual elements in isolation is essential; not doing so is likely to lead to incremental or substitution patterns with limited transformative effect. Additionally, scholars suggest that defining systems is a subjective process, hence it is important to consider how a system and its boundaries are framed and by whom (Leventon, Abson and Lang 2021). This further highlights the importance and democratic relevance of jointly mobilizing a plurality of perspectives.

To be effective, system transformations require a combination of actions targeted:

- at entire systems, or linkages between multiple elements of systems

- across social and ecological dimensions, or the underpinning philosophies and values, understanding that a functioning biosphere is needed for all societal transformation

- at different levels, ranging from deep society-wide actions, for example, transforming financial incentive structures, to more targeted actions, for example, sectoral policy and local actions

- at radically altering established configurations, which can be understood as actions seeking to stretch the limits of what is technically possible and actions transforming existing institutional frameworks – the sets of rules at play.

12.4.2 Some things in, some things out

Principle 2: The governance of system transformations needs to jointly address opportunities and challenges in new and existing systems, through explicit choices resolving contradictions between what must be developed, phased out, preserved and avoided.

Desirability, including the diversity of preferences, is a central dimension for orienting choices in system transformations. As new system configurations emerge, value-laden decisions need to be made regarding what novelty is introduced, what is preserved what is avoided, and what is phased out.

Emergence and phase-out

Regardless of their specific pattern, system transformations involve the emergence of new systems and features, as well as the destabilization and possible decline of existing systems and features. Contrary to common representations, for example, in technoeconomic modelling, transformations rarely involve like-to-like or synchronous substitutions of one system for another or purely win-win choices. Instead, they involve reconfiguration patterns determined by the articulation of emergence and destabilization processes (Schot and Geels 2007; Kivimaa and Kern 2016; Geels and Turnheim 2022). Furthermore, substitutional changes are rarely transformative, because they maintain the stability of most systems, without significant potential for empowerment. Too often, transformative action focuses on support for new, desirable things but neglects the importance and difficulties of abandoning and preventing harmful practices and systems. Consequently, it is essential that emergence and destabilization are *jointly* considered as priorities for interventions.

Environmental goals as desirability horizons

The current configuration of societal systems, such as energy, food, mobility and health, is a product of their historical path-dependent development in the achievement of 20th century performance objectives, such as the corresponding access to energy, higher yields, convenient mobility, and access to health. While these objectives remain important, sustainability objectives provide new and commonly accepted goals that can support major reorientations of societal systems. Reorienting system performance towards sustainability requires fundamentally transforming its constitutive

elements towards the achievement of new functions and possibly the abandonment of prior functions. Capacities to envision sustainability futures, including representation of Indigenous and relational philosophies that conceptualize relations of care and reciprocity of care as central to the regeneration of webs of life, are central to sustainability transformations; these focus on relations rather than on components of systems.

Competing norms and objectives

Transformations and transformation goals can be more or less desirable. Transformation concerns not only the deliberate reconfiguration of existing systems towards new performance objectives, which themselves need to be contested as there are plural conceptualizations of sustainability. A number of important transformations, such as digital transformation, deep-sea mining, and the dismantling of the welfare state, are currently ongoing and not necessarily oriented towards sustainability objectives in any way. In such cases, addressing environmental goals may involve avoiding these undesirable dynamics, or reorienting them towards more desirable goals.

Figure 12.5 specifies four broad types of orientations for action that need to be considered jointly in the governance of system transformation:

- Developing new desirable systems
- Preserving existing desirable systems
- Avoiding new undesirable systems
- Phasing out existing undesirable systems

It is essential that any strategy aiming for system transformation considers actions within each of these orientations and addresses potential conflicts or inconsistencies. Each of these orientations implies particular portfolios of action, concerned actors, and types of analysis to anticipate and evaluate the resulting change.

12.4.3 Temporalities and non-linearities

Principle 3: The governance of system transformations needs to articulate near- and long-term solutions in sequences of action enabling constructive linkages between multiple temporalities and accounting for non-linear dynamics (**Figure 12.6**).

System transformations are processes that connect past, present and future. The futures envisioned today – in scenarios, promises or expectations – are conditioned by what is deemed feasible, desirable or supported in the present. Legacies from the past determine present realities and considerably narrow future development options. Knowledge of past crises and transformations, however, also points to the possibility under certain conditions of enacting radical changes beyond imagination or beyond what is currently deemed possible (Schot 2016). Historical precedents of system transformations can be recalled in the present as they provide useful analogues, narratives

Figure 12.5: Transformation principle 2: Combine innovation with phase-out

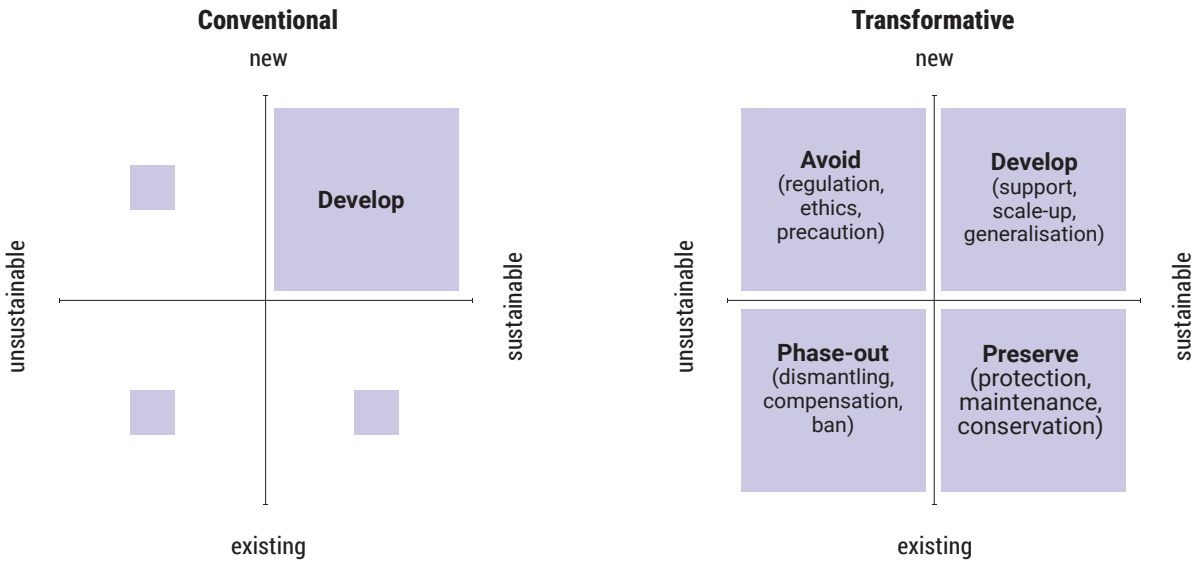
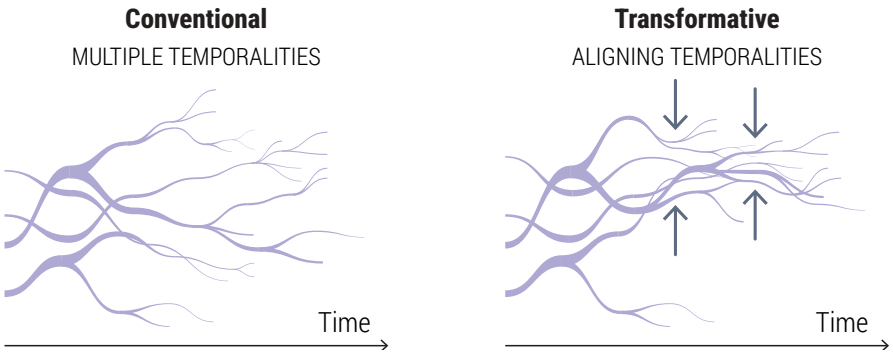


Figure 12.6: Transformation principle 3: Align present prospects with future perspectives



and lessons to inspire change (Samman 2015), reminding us that past transformations were deemed impossible until they became a reality (Dupuy 2002).

System transformations are conditioned by multiple temporalities (**Figure 12.6**). Societal systems and their change horizons are configured by mechanisms at different timescales (Braudel 1970; Sewell Jr 2005), including:

- long-term – infrastructures, scientific and technoeconomic paradigms, macroeconomic cycles, beliefs and values (Braudel 1970; Freeman and Louça 2001; Perez 2010)
- medium-term – strategic business plans, innovation cycles, electoral cycles and issue lifecycles
- short-term – political decisions, policy action, investment decisions, economic transactions, swings of public opinion, events and accidents.

The multiple temporalities of change are rarely aligned and are often dissonant (Haarstad and Rusten 2015). System transformations do not follow a single master process, but sequences of change that articulate multiple causal patterns (Aminzade 1992). Different cultures may have different understandings of time, including circular rather than linear notions, which need to be recognized when envisioning sustainability transformation pathways (Terry et al. 2024).

System transformation becomes more likely when change dynamics are aligned across temporalities. Opportunities for alignment with sociopolitical dynamics include addressing negative feedback, for example, backlashes and resistance by key actors, competing or divergent policy objectives, capture of transformation benefits by vested interests, and anticipation of legitimate losses, and reinforcing positive feedback by generating cumulative patterns of change, for example, planning and control, long-term programmes, lifting sources of divergent interests, and strengthening change coalitions (Lockwood 2015). The articulation of shared visions, promises and expectations is critical to generating greater directional coherence by aligning the interests of the actor constellations involved (Patterson et al. 2017; Roberts et al. 2018). Open deliberation about future options, envisioned transformation pathways and related challenging decisions is essential to generate greater societal involvement and buy-in, and hence to lift latent sources of resistance to change through legitimation processes.

Given that there is no single instrument that can trigger and sustain transformation on its own, governance interventions must combine multiple actions in a temporal sequence. Combinations of action need to target all relevant mechanisms and stages of transformation, including new system configurations such as emergence, acceleration and stabilization and existing, unsustainable system configurations such as destabilization, breakdown and phase-out (Kivimaa and Kern 2016 Fazey and Leicester 2022; Allen and Malekpour 2023). The temporal ordering of near-, mid- and long-term actions needs to not only seek cumulative amplification of change sequences in a given direction (Nilsson and Nykvist 2016), but also to identify critical hurdles and enabling conditions of change. For instance, infrastructure investments – with long lead times and planning constraints – are often critical enablers of further actions and practice changes. Shared transformation pathways and attention to their conditions of feasibility are essential (Turnheim and Nykvist 2019).

System transformations unfold at varying speeds and are exposed to non-linearities. The speed of transformation depends on the scale and scope of transformations (Grubler, Wilson and Nemet 2016), the types of solutions sought (Bento and Wilson 2016), the activation of positive and negative feedback mechanisms, and context-specific events and conditions that may accelerate or slow down change (Fouquet 2016; Sovacool 2016). The vagaries and non-linearity of long-term processes also call for openness and flexibility in the sequencing of transformative actions to provide adaptability to real-world contingencies (Cheng et al. 2015).

Crises and shocks have a strong influence on the possibilities of rapid transformation, both desirable and undesirable, but are inherently unpredictable. Shocks are abrupt, discontinuous and disruptive events with the potential to alter system context and conditions significantly. They can reorient transformation paths by interrupting promising change dynamics, triggering new development paths or accelerating existing ones. Shocks and crises include technical accidents, scandals and failures (Perrow 1997; Newig et al. 2019; Turnheim and Sovacool 2020), institutional events that may lead to regime collapse or revolutions, for example in the context of wars, internal unrest, or state and economic failures (Hay 1999; Streeck and Thelen 2005), as well as irreversible tipping points in social or ecological conditions enabling normal or resilient system functioning (Cumming and Peterson 2017; Lenton et al. 2020; Stammer et al. 2021). Preparedness for possible crises is critical to minimizing their impact and maximizing their transformative potential.

12.4.4 Uncertainty and anticipation

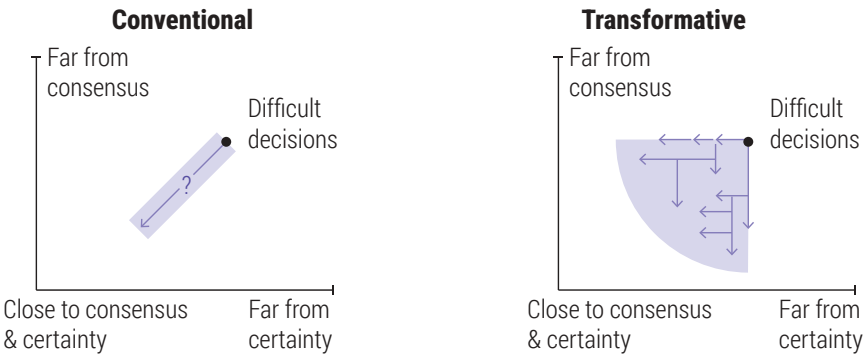
Principle 4: The governance of system transformations needs to be supported by new ways of dealing with uncertainties, anticipation and plural ways of knowing and being (**Figure 12.7**).

System transformations involve radical uncertainty and unpredictability (Andersson, Törnberg and Törnberg 2014) that inherently limit the possibilities of prediction, control and top-down planning (Hajer et al. 2015) of conventional governance styles.

Uncertainty and unpredictability are particularly important with respect to the following.

- Temporalities of change. How fast can new practices or systems be developed and deployed? How fast can harmful practices or systems be abandoned? System transformation processes most often do not follow linear development patterns, but instead are exposed to largely unpredictable detours, setbacks or even backlashes when particular pathways become unviable due to technical, acceptance or political challenges.
- Unforeseen concerns and risks. As new practices or systems are introduced in real-world contexts of use and application, they may reveal unforeseen impacts, societal concerns or risks – for instance, to health or vulnerable social groups – that need to be dealt with by society and its institutions. In some cases, the risks related to novelty are overwhelming and lead to dead ends for particular solutions. In others, these can be addressed through technical or institutional adjustments. In either case, there is an inherent dilemma of control (Collingridge 1980) with the introduction of new solutions and particularly technological solutions, given that in early stages of development, when greater control is possible over technology, little

Figure 12.7: Transformation principle 4: Handle uncertainty – don't avoid it



is known about the potential risks that would warrant control.

- Societal adjustments to change. As new practices or systems are introduced, they need to be integrated into existing structures – technical infrastructures, rules and institutional arrangements, as well as bundles of practices – and may require substantial adjustments or even transformations of these structures. This is a transformative process in itself, which comes with its own uncertainties.

These sources of uncertainty and unpredictability call for more anticipatory, adaptive and precautionary forms of governance, including ways to keep future options open. Foresight, scenario planning, horizon scanning, and participatory processes are crucial ways to generate knowledge and the capacity to plan and anticipate future transformations. Speculative futures studies in the arts, social sciences and humanities provoke imagination and the exploration of plural future possibilities – including radical ones – in order to shape the present. This can include centring of Indigenous ways of knowing and being, as well as other relational ontologies (Nelson et al. 2024). Futures studies can support regional development (Oomen, Hoffman and Hajer 2022), countering the hegemonies that create environmental challenges. Anticipatory forms of governance are primarily concerned with developing the capacity and preparedness for future situations (Guston 2014; Vervoort and Gupta 2018) rather than improving the accuracy of predictions. Adaptive and tentative forms of governance are specifically oriented towards accounting for unforeseeable risks and the unintended effects of policy interventions (Stilgoe, Owen and Macnaghten 2013; Kuhlmann, Stegmaier and Konrad 2019). The approach notably emphasizes the need for learning, re-learning, and real-time evaluation, as well as responsiveness to surprises and to limits for control – what could be regarded as greater humility in our collective ability to predict and plan for the future. Lastly, the governance of system transformations must be guided by a commitment to flexibility (Stirling 2010) so that current choices and decisions maintain openness to unpredictable future changes, given that transformative solutions are rarely certain to achieve intended effects, as well as opening space for participation and inclusivity, given that transformative solutions are rarely consensual (**Figure 12.7**).

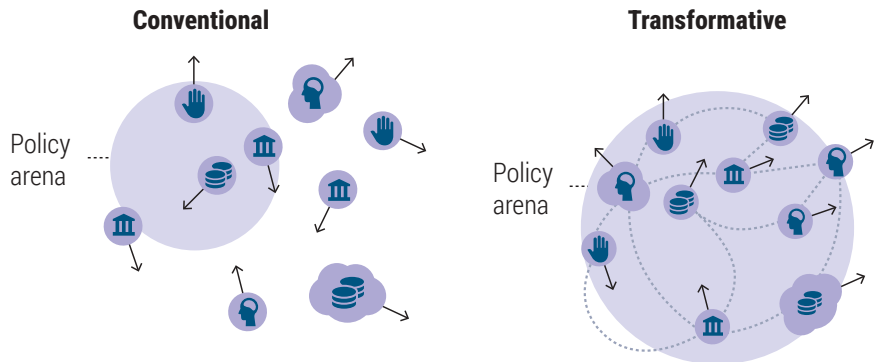
12.4.5 Inclusivity, participation, plurality and coordination

Principle 5: The governance of system transformations needs to involve actors from different societal spheres and a plurality of worldviews, which implies deliberate forms of coordination, inclusion and participation (**Figure 12.8**).

Transformations are multi-actor and multi-action processes, implying that no actor or action can single-handedly trigger a transformation. Nonetheless, actors contribute to transformations through their relative power, authority and competences, as well as by joining forces with other actors, for example in coalitions, social movements and partnerships.

The governance of transformative change involves different constellations of actors across diverse societal spheres or sectors. In each societal sector, individual actors and organizations are endowed with various resources, competences, power, and logics of action (Avelino and Wittmayer 2016). It is possible to envision different styles of transformation governance concerning

Figure 12.8: Transformation principle 5: Mobilise diverse actors



the particular configuration of lead actors of change:

- Market-led transformations involve a dominance of firms and business actors, possibly with state involvement, as with the model of public-private partnerships as a privileged form of addressing challenges in public management

- State-led transformations involve a dominance of State actors – public agencies, governments and municipalities – possibly with a greater emphasis on top-down planning and regulation

- Community-led transformations involve a dominance of local action not driven by profit motives, possibly with the support of civil society – NGOs and associations.

Between these archetypes, real-world transformations will likely involve combinations or hybridization of this logic.

As transformation unfolds, the respective role and power of different actor categories may shift – as has been witnessed with the increasing formalization and commodification of organic food, in a shift away from community-led self-sufficiency towards market-led change with State-level regulation and a continued involvement of NGOs to develop standards and certification. This commodification of organic food has led normative advocates to depart from conventional standards to establish new, more stringent standards for organic food.

Empowerment approaches to transformation suggest that plurality is key because transformation approaches involve contestation over values and ways of being, as they are inherently political processes (Scoones and Stirling 2020). Emancipatory approaches thus actively create space for marginalized ontologies, values and practices (IK & LK Chapeau A). This would include centring Indigenous and other relational ways of knowing and being, and attention to identified causes of unsustainability, such as extractivism and green colonialism (IK & LK Dialogues 2025).

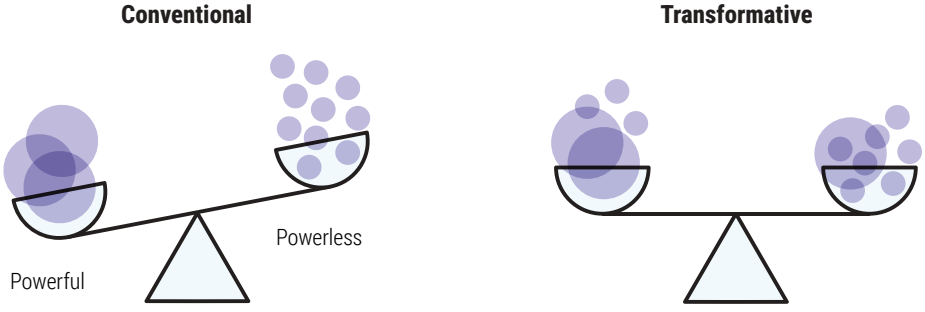
12.4.6 Power and politics

Principle 6: The governance of system transformations needs to address power relations, vested interests and social inequalities through decisive political choices guided by explicit notions of justice (**Figure 12.9**).

Transformations are deeply political because they:

- create winners and losers, in contexts of existing inequalities, unsustainable economies and politics, and uneven accountabilities and effects. Potential losers of transformations include the actors – individuals, social groups, companies and nation states – that are most dependent on existing unsustainable activities such as fossil-fuel extraction, high levels of extraction and consumption of resources, or the use and release of harmful substances into the environment. Transformations can also generate new types of vulnerability, such as environmental and social damages related to the increased demand for lithium extraction to support the projected rise in battery production and use following electrification transformations (Marín 2023). Measures targeted at the underlying causes of unsustainability should target those accountable for damage, such as asset holders, and avoid disproportionate costs for the vulnerable and poor. Loss, vulnerability and related conflicts need to be addressed through adequate anticipation, increased preparedness and compensation measures where appropriate.

Figure 12.9: Transformation principle 6: Don't ignore the political nature of transformations



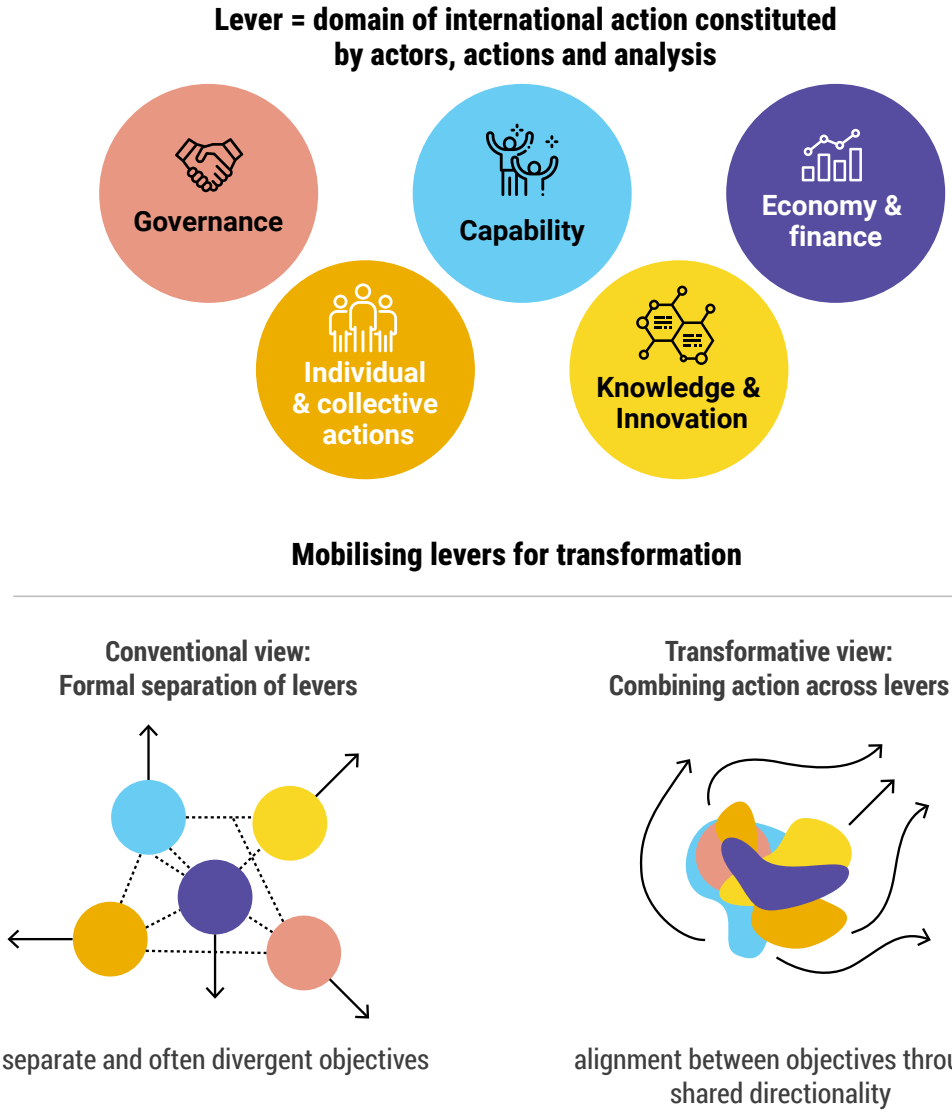
- trigger resistance to change (Brown 2015). Incumbent actors with vested interests in current systems are likely to resist changes, especially when these question the prevailing distribution of assets, business models or investment patterns – potentially generating stranded assets. Such actors, which typically benefit from asymmetric access to and influence over policy, tend to actively mobilize their bargaining and lobbying power, often in ways that do not safeguard the environment or long-term interests of communities. While compensation measures can be appropriate short-term measures if designed with conditionalities, these need to be supplemented with adequate support for the development of less harmful human activities, that is, guided by a transformation that moderates market values and moves to guiding ethics of care and solidarity (IPBES 2022).

- require new political alliances. System transformations, because of their inherent political nature, rest on the enrolment of actors from across society for the co-production of new societal orientations and hopes for change. Civil society actors and proactive business communities can be important drivers of change (Hajer 2011), while governments can shape enabling environments for markets and support solidarity economy alternatives. Intentional, pluralist empowerment processes that give marginalized actors, broadly aligned with sustainability, a greater voice to challenge hegemonic values and ways of being, are part of coalition building and may intertwine with the efforts of social movements (Scoones et al. 2020). Importantly, non-anthropocentric approaches to transformations include the representation of non-human entities in political decision-making, recognizing the agency, sentience and value of non-human life, as well as the interdependencies across human-non-human webs of life and the recognition of rights under law (Haraway 2016; Puig de la Bellacasa 2017). In the context of unprecedented material prosperity for some but rising insecurity for many and a consequential polarization, combined with uncertainty from dangerous environmental planetary change, accelerated system transformation efforts can also contribute to turbulence (UNDP 2022). This is especially true when transition measures affect those who are already vulnerable and insecure.

- generate challenges for representation and accountability. Because system transformations are fundamental societal changes, they also imply changes in future-making, allowing plural ontologies and values, such as Indigenous Peoples' and other relational ways of knowing and being (IK & LK Chapeau A), to have representation in envisioning and enacting sustainability futures. Devising new eco-social contracts, for example about what new and created worlds could look like, what matters in the future, what needs to be safeguarded, what needs to be abandoned, and the very composition, goals and ethics of society should be achieved through pluralist processes. This implies challenging the status quo, giving voice to underrepresented actors and worldviews, for example, citizens, especially marginalized groups, in democratic decision-making (Scoones et al. 2020), and moderating the voice of overrepresented actors, such as powerful incumbent alliances resisting change, to overcome dominant orthodoxies, such as colonial modernities (Arora and Stirling 2023) and relations of domination (IPBES 2024).

- call for new ways to recognize inherent values conflicts and ontological differences and potentialities. Since system transformations are inherently political processes, they cannot be governed in technocratic ways. However, they represent important opportunities for collective, pluralist and democratic decision-making about societal expectations – goals, values, paradigms and ways of being – and supporting eco-social contracts. Achieving transformations in sustainability requires tackling disconnections from and domination of nature, power and wealth inequalities, and short-termism in decision-making. This requires involve a shift in power relations and practices from relations of domination towards relations of care and reciprocity (IPBES 2024; Nelson et al. 2024).

Figure 12.10: Levers and intersections



12.5 From principles to requirements for intentional action within and beyond existing governance structures

Given the discussion in Section 12.4, the question for policymakers and all stakeholders becomes one of how to address system transformation intentionally in policy and practice. The approach in this GEO-7 report consists of the use of levers to apply the six principles for system transformations. As noted in the Introduction, levers can be defined as domains of societal influence which share a configuration of a broad type of actors, actions and analysis (**Figure 12.10**). The solution-oriented focus on societal systems proposed in this GEO-7 fits well with the choice of levers as it avoids a one-sided categorization in terms of social stakeholders, instruments and tools, or mental frameworks.

Instead, it sees these domains as defined by the interaction of actors, institutions, cognition and action. The concept of levers as intentional forms of transformation was introduced in the Global Sustainable Development Report (United Nations 2019) in 2019 to describe four different "powerful agents of change" – governance, economy and finance, individual and collective action, and science and technology. This offered a concise, high-level list of universal, broad types of deliberate, intentional agency. These are quite different to the emergent, unintended drivers of ecological problems; they are rather conceived as arenas where sustainability solutions may be purposefully sought. It is descriptive rather than normative and encompasses various modes of action and analysis, as well as diverse groups of actors.

The fundamental paradox associated with the concept of levers is that the same domains offering the

opportunity for purposive change are also those that serve to perpetuate the current state of affairs. They lend themselves more readily to incremental rather than transformative change. Theories of transformation share the view that they involve challenging the boundaries between well-established levers. A new mix of governance, finance, social action and technology is needed. Similar to a radical innovation in a business organization that crosses departmental boundaries between research and development and marketing, between human resources and strategy, this would be a societal level analogy. In other words, transformation is only possible through "novel combinations of different levers and the novel collaboration of the respective actors in governance, economy and finance, individual and collective action, and science and technology" (United Nations 2019, p. 27). The levers are defined as domains of intentional action and are then applied to the principles of transformation. While authors acknowledge several sets and intersections of levers, five have been selected, based on the comparison, and discussed at the open-ended meeting on October 2022, and at the first author meeting, held in Bangkok in March 2023, with the following structure of transformation-enabling levers that were agreed and applied in the GEO-7 assessment towards the identification and development of solution pathways and trajectories:

- Economics and Finance
- Individual and Collective Action
- Knowledge and Innovation
- Governance
- Capability

While the definitions of each lever are discussed further in Section 12.6, with details and examples of how to apply the principles to the levers, it is important to note that in light of the transformation needed, the term capability is used instead of capacity-building. The idea of capability moves beyond its narrow sense as training towards the capabilities needed to combine different levers effectively, and to address systemic interventions for transformative innovation designed to enable an effective mix of economic, social, knowledge and governance levers. This GEO-7 report also enlarges the lever of science and technology to a broader one of knowledge and innovation, and recognizes the wider plurality of types of knowledge, including Indigenous Knowledge and Local Knowledge (IK & LK). This is to reflect recent research on innovation, which highlights the importance of innovations in business models, organizational forms, lifestyles and consumption, as well as technology. It also recognizes a much wider plurality of types of knowledge in addition to Western science.

12.5.1 Economics and Finance

This lever includes a variety of instruments and tools for enabling transformative change. These range from the need to offset public debt and debt-servicing costs in the poorest countries, to cutting tax avoidance, and investing in piloting and prototyping innovations (United Nations 2023), as well as ensuring certification and transparency in supply chains. It also involves a range of different actors, including international financial institutions and multilateral development banks, governments, private finance – including venture capital and private equity, philanthropists, pension funds, banks and other investors (United Nations 2023).

It is important to note that economic and financial levers are not deployed in isolation. Policy interventions are often needed to activate nonlinear changes to enable transformative shifts within and beyond the financial sector, capitalizing on these transformative dynamics (Lenton et al. 2023). Governments need to adjust the rules of the game, sending clear market signals through new regulations and providing credible long-term policies and targets in order for this lever to reach its full potential (United Nations 2023). It will take political leadership to reallocate resources to better serve people and the planet, ensuring that no one is left behind. This means re-evaluating what counts as national success beyond traditional GDP and measuring the right things, thereby opening up more diverse appreciations of value (IPBES 2023). More generally, public financial institutions need to recognize that nature must be an integral part of fiscal policy, budgets and investments, especially regarding climate risks and adaptation plans (United Nations 2023).

Many Indigenous Peoples' and other relational ways of knowing and being embrace alternative ways of organizing economies, with economic exchange based upon solidarity and care. Commonly based on concepts of humans as part of nature within an assemblage of all life but with humans decentred, the approach embraces interdependencies that carry obligations of reciprocity and care and allows collective good lives, captured in concepts such as Sumak Kawsay (IK & LK Dialogues

2025). Thus, an option for an effective lever in economic and financial terms is making space for ways of knowing, being and valuing that shape practices enabling a transformation in the predominant ways of organizing economies. This would entail shifting from practices such as private ownership of resources and extractivism towards cooperative and commons-based and solidarity economies (Gibson-Graham 1996).

12.5.2 Individual and Collective Action

Reorganizing social practices and cultural processes by mobilizing individual and collective action is fundamental for large-scale societal change towards sustainability (United Nations 2019; United Nations 2023; IPCC 2023b). People's lives all over the globe, and their supporting social and cultural systems, are affected and challenged by global environmental changes, leading to various coping and response strategies (UNEP 2019; UNEP 2021a; United Nations Educational, Scientific and Cultural Organization and International Social Science Council 2013). Large-scale societal change towards sustainability and globally agreed environmental goals requires new forms of sociocultural orientations – social norms, cultural values and ethical practice – social organization, and the mobilization of groups at various levels across society (United Nations 2023). While major paradigm shifts within contemporary societies take time (United Nations 2023), facilitating the envisioning, exploration, experimentation, adoption and mainstreaming of norms, value systems, behaviour, social practices and ways of living by a critical mass of people is essential.

Behavioural change and the emergence of new social practices are part of a broader process of socialization and culturalization. This can be supported by education, information strategies, social movements, activism, campaigns, financial incentives, regulatory processes and legislation (United Nations 2023). Governments at all levels can influence, incentivize and constrain actions and behaviours. This might include providing an enabling environment for micro-level actions, such as community energy projects, or meso-level actions, including social and environmental movements, as well as new forms of political protests or political lobbying, which can spur new behavioural patterns and social practices (United Nations, 2023, p. 75). Promotion of abundant sufficiency in consumption and championing biodiversity in site-based conservation is important for connected conservation that tackles site-based and distant drivers of land-use change (Carmenta et al. 2023, p.6). Governments can seek to support democratic rights to protest and give support to civil society and trade unions to enable advocacy, campaigns and community engagement work to advance sustainability transformations.

Change can also come through the work of artists, including work that engages communities and explores multiple sustainability futures in contexts of high uncertainty, such as futures that challenge or transcend dominant non-sustainability formations. Arts can shift values and create new visions of the future and ways of being by engaging people not only through analytical thought, but also by engaging people's emotions and different senses, for example, through work on soundscapes, to enhance radical attentiveness and connectedness to nature (Bergmann 2016). Individual and collective action can also exert influence on policymaking, through voting, advocacy and collective protest. Importantly, collective action by communities can prefigure alternative ways of organizing society, based on positive sustainability values (Harmáčková 2023). Social learning and co-production can engage diverse groups across various scales in collective learning about values (Slater and Robinson, 2020). Pluralist approaches are important to inherently political transformation processes (Scoones et al. 2020). They are part of empowerment approaches that create space for marginalized groups, perspectives and forms of knowledge to challenge the status quo (Scoones et al. 2020). Indigenous Peoples and other relational philosophies and associated values of ethics of care represent one such perspective that should be centred as part of sustainability transformations; a reparative approach means dominant worldviews and practices cede or give space to these alternatives (Stein et al. 2024).

Social norms, preferences and daily practices are increasingly influenced by new scientific and technological developments in most spheres of daily life, including social media and other forms of information technology, disrupting existing ways of living. When managed sustainably, this might create new potentials and opportunities to reach sustainability gains on a larger scale, that is, smart living (Coalition for Digital Environmental Sustainability 2022; German Advisory Council on Global Change 2019; International Institute for Applied Systems Analysis 2018; International Institute for Applied Systems Analysis 2019).

Overall, the realization of social and behavioural change – and beyond to societal change including values, philosophies and practices – involves contestation

and collaboration processes, preferable based within a culture of public trust and forms of social engagement, inclusiveness and solidarity, including some minimum safeguards of social security and political or institutional stability.

12.5.3 Knowledge and Innovation

Academic analysis and policy practice increasingly see science and technology as part of a broader and more diverse domain – that of knowledge and innovation. This widening scope views innovation as often the result of an interactive diffusion process rather than the direct outcome of a linear push by science and technology. Innovation arises from a system that includes relational capabilities and experiential knowledge, as well as science and technical expertise. Normally used for the pursuit of market economic goals, this systemic approach to knowledge and innovation now needs to address the 21st century global environmental crises, and awareness of plural ways of knowing and being. Rather than simply promoting more knowledge and innovation, this system requires a new directionality towards sustainability, with innovation systems, actors and goals addressing the plurality of values and ways of being. Many of the critical pressures on the environment arise from growth in knowledge and innovation in dominant political economy paradigms and value systems, which have contributed to economic and social development but have ignored these negative consequences, including the suppression of alternatives. Indigenous Peoples' knowledge includes Indigenous scientific long-term observations, and through Two-Eyed Seeing, this knowledge can be brought together with scientific knowledge in support of innovation. Pluralist transdisciplinary processes can also support innovation through co-creation in response to complex sustainability challenges.

Global economic institutions have begun to recognize that innovation systems have to change. The United Nations Conference of Trade and Development report (UNCTAD 2019) calls for new approaches on innovation in support of SDGs' implementation that are mission-oriented to direct innovation to specific environmental goals. This new directionality needs to be combined with a new diversity to embrace a broader range of social actors and types of social and technological innovation. An Organisation for Economic Co-operation and Development report (OECD 2023) seeks to enable transitions in disruptive times through transformative innovation for sustainability transitions. It also recognizes that better directionality must be accompanied with an array of measures to promote new modes of partnership among diverse actors and a plurality of forms of knowledge. Actions targeting both consumption and production are needed for transformative change (IPBES 2024). The World Bank with the United Nations Department of Economic and Social Affairs, UNCTAD and the United Nations Educational, Scientific and Cultural Organization propose Science, Technology and Innovation for SDG Roadmaps to bring together a diversity of stakeholders from different professional communities and societal organizations through a shared framework and common language (European Commission Joint Research Centre and United Nations Inter Agency Task Team on Science, Technology and Innovation for the SDGs 2021). Plurality goes beyond this and is based on the design of processes that give equal value and space to plural forms of knowledge, such as science and Indigenous Peoples' knowledge.

Knowledge and innovation play a fundamental role in transforming societal systems to address environmental sustainability. Science and technology need to be viewed as part of this broader system, but must be driven by clearer commitments to directionality, for example, mission-oriented innovation policy, and diversity, for example, inclusive innovation. Environmental goals must be integrated with a broader, systemic model of the innovation process. Influential actors are beginning to shift their perspectives and actions to address this issue.

A pluralist approach to knowledge and innovation recognizes that these are political processes, and that dominant thinking and approaches contribute to the global environmental crises due to accumulation imperatives enabled by dominant philosophies and values. Knowledge and innovation based on values of individualism and consumerism could shift to approaches that embrace plural values and forms of knowledge, grounded in values of care and solidarity (IPBES 2024).

12.5.4 Governance

The term "governance" has lacked harmonized definitions. Fukuyama (2015) suggests three main views of governance: first, as international cooperation, second as public administration, and third as regulation of social behaviour. Governance Today (2014) posits governance from the idea of the process of decision-making, noting that governance is also concerned with the structure and processes for decision-making, accountability, control and behaviour. Additional authors, such as Rhodes (1997),

Credit: imagesourcecurated/Envato

Kooiman (2003) and Jessop (2002), further discuss the concept of gatekeeping and the idea of limiting what different actors can and cannot do within a sphere of influence. The United Nations (2023), further draws the attention of governance to the ability of actors and governments to build common narratives.

Four things emanate then for the governance lever for transformation:

- it is a tool to analyse social dynamics and institutions at different levels and thus about decision-making processes – including transparency, accountability, effectiveness, equity – involving collective stakes or both conflicting and cooperative interests, thus ensuring that while it may have a political connotation, it is not only about politics resting with an actor

- the governance lever is about coordination and facilitation, the ability to structure interaction/rules of the games of institutions and whether this as one analyses constrains or facilitates actions and in addition that actors can move this lever of actions within the ambit of constraining or facilitating

- there will be myriad actors involved within each domain with different levels of power and different tools – policy, human and financial – that allow them to participate or not participate or make choices on what type of participation they choose to influence the decision-making within a domain

- the governance lever exists in all other levers as one examines the main governance elements present in sustaining or inhibiting transformation and as one identifies what needs to be transformed within the area of influence of that lever and its domain of influence

Environmental governance is frequently assumed to refer to human decision-making and agency, but growing efforts seek to recognize non-human, that is, plant and animal, agency and sentience in political and legal realms.

12.5.5 Capability

This lever seeks to move the ambit of capacity-building in two areas. Firstly, beyond the mere idea of training and development or the acquisition of new skills often found in linear models' education and training, with the notion of developing competences and capacities for future-oriented issues, for example, anticipation and foresight to systematically anticipate, relearn and improve decision-making across multiple sectors (Rohrbeck, Battistella and Huizingh 2015). The different capabilities include:

- innovate and redesign regulatory instruments and manage market failures

- convening divergent views and encouraging political players and all market actors to work through the required policy instruments to transform or dismantle power and political structures

- negotiation and coordination with actors within their different spheres of influence – material, financial or other – that maintain and sustain the status quo.

A recent United Nations report moved the ambit of capacity-building in its definition to include "activities aimed at strengthening and maintaining the capabilities of states and societies to design and implement strategies that minimize the negative impacts of current social, economic and environmental crises and emerging challenges" (United Nations 2023).

Secondly, capabilities in this GEO-7 report are also applied in light of Amartya Sen's work (2002) describing capabilities as substantive freedoms or functional capabilities. In this theoretical framework, capabilities is viewed in a normative framework in which social arrangements are viewed from the perspective of the extent to which they promote functions they value, i.e. what people can do and be and thus for transformation, allowing a pathway for long-term impacts of change and long-term resilience questions applied to the transformation process. This approach also encompasses Māori philosophy, African Ubuntu, Buen Vivir and many more non-Western perspectives (Bockstael and Watene 2016), facilitating policy perspectives that take into consideration the rights of Indigenous communities (Schlosberg and Carruthers 2010; Watene 2016).

For transformation, six areas of influence emerge in this lever:

- the ability to imagine and explore a multiplicity of sustainability futures that embrace plural ways of knowing and being, such as those of Indigenous Peoples, and embrace living well together to reshape the present

- the ability to anticipate and analyse sectoral and social trends, including current and future desirability

- the ability and willingness to analyse, examine and learn from experience and plural forms of knowledge, especially from Indigenous Communities and Local Knowledge, on what sustains or inhibits sustainability transformation

- the ability to innovate and reverse courses of action, be it at philosophies and values, institutional or practice levels, that have sustained and inhibited transformation

- the ability to "coordinate and resolve conflicts and trade-offs as they arise and in identifying and overcoming other common impediments and system lock-ins" (United Nations 2023)

- the ability to analyse and learn or relearn requires an interdisciplinary and transdisciplinary approach that mobilizes levels of knowledge in different sectors and domains, and other levels of practical knowledge (UBA 2020) and unlearning and new learning via plural forms of knowledge, especially those of marginalized groups (Scoones et al. 2020)

- and finally, the extent to which social arrangements provide value to those applying them, including the rights and freedoms of Indigenous Peoples under the Declaration on the Rights of Indigenous Peoples, of women through gender equality, and of marginal social groups.

12.6 Lessons from experiences of intentional transformative action principles acting on levers

Drawing on the definitions of levers already discussed, this section illustrates the implications of transformation principles when applied to the various domains of intentional actions or levers in concrete settings. For each of the six principles presented in Section 12.4, it provides examples of the style of action possible within different systems, alongside evidence from practical experience.

12.6.1 Illustration of Principle 1

Section 12.4.1 presented principle 1 as follows: The governance of system transformations needs to be explicitly targeted at whole systems and address underlying sources of lock-in related to current system configurations.

Example 1a: Carbon financing

A good example of the need for a systemic understanding of transformative change within the economic and financial lever is the sudden growth of carbon financing in the voluntary carbon market, aimed at investing in carbon offset projects (Selomane et al. 2025). Indigenous Peoples identify carbon and biodiversity offsets as examples of false solutions that adversely affect them (IK & LK Dialogues 2025). Carbon offsetting has the potential to create perverse incentives, for example, in the context of tree planting in open grassy ecosystems in Africa (Bond et al. 2019). Evidence suggests that the potential of such carbon offsets are often overestimated, and the assumed ecological co-benefits of increasing carbon stocks are often incorrect and could result in biodiversity losses and degradation, rather than restoration (Bond et al. 2019; Seddon et al. 2020). The emphasis on carbon offsetting has led to proposals that aim to enhance above-ground carbon across numerous biomes in many forms, from natural forest regeneration, reforestation, tree planting, afforestation, fire abatement and a switch to early burning in tropical grassy ecosystems (Zomer et al. 2008; Veldman et al. 2019; Russell-Smith et al. 2021).

However, these options consider only one metric, carbon-as-stored-in-trees, to the detriment of other metrics, such as biodiversity, livelihoods, health and culture, and biophysical processes, such as fire regimes. This framing further perpetuates a simple model of allowing people to continue their lifestyles in one place as long as they can pay people somewhere else to remove the problem, while not recognizing the full costs to the communities of committing extensive land resources to maximizing above-ground carbon at the expense of other forms of use that also provide ecological benefits (Dooley, Nicholls and Meinshausen 2022). A more systemic understanding of carbon markets and their potentially detrimental influence on local people and ecosystems would allow for a more nuanced implementation of finance to achieve local co-benefits from investment. A socioeconomic perspective highlights that market-based measures in conservation, including climate responses, are inherently reformist, rather than transformative, because they do not address accumulation imperatives or rigid dichotomies between humans and an external "nature" (Büscher and Fletcher 2020). For example, in the Amazon, Indigenous Peoples and local communities are being forced to participate in carbon markets in order to protect their forests and way of life, which often comes with rules and regulations for investment returns that are not aligned with their philosophies, values or practices.

Example 1b: Mobility systems

The transformation of mobility systems illustrates the importance of Principle 1. Fossil-fuelled automobility, and motorized transportation more generally, is a significant source of greenhouse gas (GHG) emissions and air pollution worldwide (Jaramillo 2022). It is particularly intense in and around large urban centres. While these problems have been known for decades, difficulties in addressing the environmental effects of automobility point to the systemic nature of the problem and the importance of deep lock-ins related to mobility patterns and paradigms (Sheller and Urry 2000; Sheller and Urry 2016). Prevailing strategies for the "greening of automobility" are insufficient to enable the structural shifts in mobility (Banister 2008) that could lead to far-ranging and lasting environmental improvements.

Such strategies, while relevant, are limited in their overall potential because they focus on end-of-pipe solutions, for example, catalytic converters reducing particular pollutants, or substitutions, for example, biofuels or electric mobility, that tend to displace problems or generate new issues, such as competition for land and induced deforestation for biofuels, pressure on critical minerals and induced emissions from power generation for electrification, without addressing underlying barriers to more sustainable forms of mobility and rampant growth in mobility needs (Wells 2023). The electrification of cars is an iconic illustration of non-transformative policy: it sets all expectations on a technological substitute, while contributing to reinforce the systemic lock-ins related to automobility patterns and increased car dependence.

A systemic perspective on mobility instead points to the need to combine interventions on multiple fronts, including the greening of mobility, reducing the need to travel, enabling modal shifts to alternative modes of travel – such as walking, cycling, public transport and ride-sharing – and land-use changes (Banister 2008). Other interventions could explicitly target the phase-out of automobile dependence, including car use and parking restrictions. Such combined approaches are increasingly the object of urban mobility experimentation programmes (Haarstad et al. 2022). However, it is essential that such programmes are not focused solely on individual innovations, but also take a more systemic approach to provide tangible, working alternatives to individual motorized transport.

Credit: IndustryAndTravel/Envato

12.6.2 Illustration of Principle 2

Section 12.4.2 presented principle 2 as follows: The governance of system transformations needs to jointly address opportunities and challenges in new and existing systems, through explicit choices resolving contradictions between what must be developed, phased out, preserved and avoided, as well as ensuing contradictions

Example 2a: Phasing out nuclear power within the framework of the Energiewende in Germany presents some lessons to be learned:

Large-scale system transformation, like the energy system, requires the organization and mobilization of a political and broader societal consensus on desirable, feasible, and affordable energy future options (Reusswig et al. 2016; Arifi and Winkel 2021; Krüger 2022). Experiences from the Energiewende energy transition plan in Germany shows that social movements and local initiatives play an important role in articulating various future options, creating the societal seedbed to mobilize active support towards the restructuring of the entire energy system from a dominant centralized system of nuclear power towards a more decentralized system of energy production, including various forms of community-based renewable energy-production systems (Sciullo et al. 2020).

Here, individual and collective actions create enabling environments, complemented by legislative, economic and technological developments, to facilitate multiple forms of public ownership of the energy system transformation within the spectrum between globalized energy markets and local energy sovereignty (Rommel et al. 2018). Social movements and local initiatives play a vital role in mediating between competing options, and by mobilizing and accumulating the needed social, economic and political capital to phase out existing forms of energy-production systems, while investing in the creation of a more sustainable, secure option in the long run (Sciullo et al. 2020; Krüger 2022).

Example 2b: Agroecology – developing alternatives to conventional agriculture and maintaining traditional local agricultural practices

Contemporary agrifood systems and related practices are responsible for many persistent environmental problems, such as water pollution, soil degradation, pressures on land use and GHG emissions, and significant pressures on life, including biodiversity loss, health effects of transformed food and persistent chemicals, and water scarcity (Camanzi and Troiani 2021). These impedances are directly attributable to the global diffusion of conventional agricultural practices since the second half of the 20th century. This has been driven

by the primary objective of increasing productivity and year-round availability of a large variety of foods, enabled by the deployment of input-dependent and resource-intensive modes of production, such as synthetic fertilizers and pesticides, seeds, and mechanization, and the intensification of productive units, that is, the concentration and amalgamation of farmland. In some parts of the world, such techniques have spread to the majority of farmland and food production, while in other contexts, traditional farming techniques or extensive farming still prevail (Rathod 2023; Hamadani et al. 2021). Accordingly, strategies for reducing the ecological impact of agrifood systems require practices that are more considerate of human-nature relations, but their orientation and priorities depend on the dominant system configuration. Agroecology promises the transformation of agrifood systems according to more sustainable practices, which is at the heart of the Food and Agriculture Organization's Common Vision for Sustainable Food and Agriculture (Food and Agriculture Organization [FAO] 2014), a concept that has garnered widespread support across United Nations institutions and the international community.

Rather than prescribing specific solutions, the agroecology movement and institutionalized discourse are constructed around 10 core elements that can act as guides for holistic food-system development and transformation. The means for implementing agroecology in practice are diverse and strategies should rest on a combination of interventions. Further, the implementation of agroecology largely depends on local food configurations and related transformation contexts. In the case of intensive farming, such as the monocrop cereal plains in Europe or North America, adopting agroecology requires radical change of conventional farming systems towards environmentally less harmful practices. This largely hinges on support for the development and deployment of alternative practices, for example, organic farming, multifunctional agriculture, conservation agriculture, and short food chains. Contexts where conventional farming has not made such significant inroads and where traditional, less intensive and environmentally harmful practices persist on a wide scale include multifunctional agriculture practised around river deltas or mountain agricultural landscapes. In such cases, the main priority for implementing agroecology is about preserving established practices and ensuring their resilience against the pressures of conventionalization (Hamadani et al. 2021; Somashekar et al. 2024).

12.6.3 Illustration of Principle 3

Section 12.4.3 presented principle 3 as follows: The governance of system transformations needs to articulate near- and long-term solutions in sequences of action enabling constructive linkages between multiple temporalities and accounting for non-linear dynamics

Example 3a: Solidarity economy innovations for transforming food and agriculture

One proposal to reshape food systems is to establish science-based standards for minimum sustainability, to be called Codex Planetarius (Loconto 2024). However, solidarity-economy approaches focus on more locally, self-determined regional or subregional food systems and governance innovations, many examples of which were seen during the COVID-19 pandemic, such as urban bartering and exchange (Nadal and Nazar-Beutelspacher 2023). In Italy, innovations range from microscale community and place-based initiatives, mesoscale territorial assemblages and convergences of initiatives and interactions with local and national public institutions and international movements (Rossi et al. 2021). Specific Italian examples include consumer-producer pacts on the provision of specific products, community-support agriculture for the participation of citizens and sharing of economic risks, and participatory guarantee systems. Italian circular solidarity-economy approaches include emergency support funds, community exchange schemes, and resistance to land-use planning decisions that remove land from agroecological production and community-based controls (Rossi et al. 2021). Linking such place-based microscale initiatives can scale them up (Escobar 2021).

One of the main characteristics of this dynamic is the ability to configure opportunities to become socially engaged as part of the movement in various social roles, increasing the level of involvement of people and institutions with various different backgrounds and interests. Additionally, the mobilization potential of a social movement creates opportunities to become a relevant player in the game, influencing the course of political agenda-setting, or to become a kind of standard-setter, or an institution of public trust (Harris 2021).

Example 3b: The role of shocks on near and remote landscapes

Large-scale industrial accidents provide a valuable illustration of the role that shocks can play in established systems. Major shocks can significantly alter the trajectories of sociotechnical systems and their governance, by accelerating change dynamics, reorienting established pathways, or leading to entirely new pathways. However, the potential effects of shocks is mainly dependent on the conditions in which they occur, the extent of preparedness for such shocks, and the political ability to seize related windows of opportunity (Johnstone and Schot 2023). Accordingly, shocks will not have the same effect in different contexts.

The Fukushima nuclear accident in Japan in 2011 is a notable example. This major nuclear disaster had a profound effect on the discourse, status and long-term future of nuclear energy worldwide, but the effect was different in each country. In Germany, for instance, a country in which anti-nuclear movements had succeeded in stimulating a society-wide debate about the possible end of nuclear power, it bolstered and accelerated an existing programme of nuclear phase-out, which recently completed its final phase (Appunn 2021). In France, the Fukushima accident triggered public and parliamentary debate, but this was short-lived and translated into a reinforcement of a regulatory approach to risk management that kept the politics at bay (Arnhold 2020) and ultimately allowed a nuclear renaissance.

12.6.4 Illustration of Principle 4

Section 12.4.4 presented principle 4 as follows: The governance of system transformations needs to be supported by new ways of dealing with uncertainties, anticipation and plural ways of knowing and being

Example 4a: Transforming ways of thinking and doing

Dealing with uncertainties and anticipating new challenges call for a rethinking of ways of knowing and requires a transformation of the entire societal system. The type of innovation needed to achieve such aspirations is likely to involve a transformation in customary ways of thinking and doing. Such challenge-led directionality requires an innovation policy to promote a much higher degree of diversity than is traditionally the case. Knowledge and innovation need to shift from an individual project focus to facilitating a system-wide portfolio of social and technological innovation activities. Systemic barriers such as constraints by corporate organizations that control much of the ecosystem may often have a higher incentive to stifle multiple pathways of thinking and doing. Thus, it is important to access the various lock-ins of various stakeholders that in turn lock in multiple pathways of solutions. Innovation opportunities should not be confined to the preferences of currently dominant technical advocates or incumbent businesses.

An over-selective focus on emerging new technologies that offer transformative promise can be a trap of making an early speculative bet on a solution-in-search-of-a-problem. An alternative focus on challenges, rather than technologies, avoids this trap. However, if the challenge is very broad in scope, it can face the opposite pitfall: the risk of an over-general problem-in-search-of-a-solution. The participation of a wide variety of actors and the exploration and experimentation with a rich assortment of different innovation pathways are not ends in themselves and may lead to dissipative and directionless diversity. Some sort of balance is needed.

Directionality and diversity present a classic innovation dilemma (Steward 2009) of which many are well known in the business world of innovation management. A portfolio approach can recognize the multiple time frames of different innovation pathways and also the inherent uncertainties in the innovation process itself. The targeting of a challenge is strongly directional, but a variety of innovative solutions need to be nurtured, both in terms of sociotechnical type and maturity or readiness. Near- and long-term perspectives need to be maintained, and strategy should not be dominated by a particular solution advocate. There should be new spaces for user-led social innovation in addition to producer-driven technological innovation.

System innovation portfolio guidance can be pursued in two different ways. It can be used as an ex-ante approach to shape the design and implementation of projects and programmes by funders at the regional or national level. The best example is the Swedish Innovation Agency VINNOVA – a pioneer of challenge-led system innovation policy. Alternatively, portfolios can be constructed as an ex-post approach to map and orient a variety of existing ongoing projects, irrespective of origin or funding source, towards a system-framed mission in a more explicit fashion. These are then treated as a portfolio through coordinative or interactive measures. The European Institute of Innovation & Technology's Climate-Knowledge and Innovation Communities implemented an innovative approach

to constructing project portfolios from existing city-level projects within their Transition Cities initiative.

Optimally, the capabilities required for transformation need a new orientation of how problems and solutions are framed and models of change are represented to understand transformation. For example, reductionist representations of change – as in numeric model representations – are insufficient. They need to be complemented by other forms of anticipatory and future-oriented knowledge. Instead, capabilities that require models and scenarios criticism are required that then build-in imagination and diversity, that challenge prevailing logics such as optimization and efficiency, and manage performativity. These are not easy to do in reality, but recognition that existing logic frameworks often used in scenario modelling may not be adequate will be a start to re-orienting our learning and need to relearn.

Example 4b: Environmental contributions of digital transformations

The uncertainties around the positive and negative environmental effects of digitalization provide a useful illustration of the need for anticipatory approaches to system transformations and regular re-evaluation and adaptation in the face of unforeseen concerns and risks. Digitalization has long been perceived as enabling a significant reduction in the environmental influence of human activities connected to the transportation of people and products, for example, a reduced need to travel and accumulate material goods (Mondejar et al. 2021). However, without denying the significant benefits of digital transformations notably in terms of access to information for all, it has become clear that their ecological effect is at best ambiguous. There is evidence of a growing footprint of digitalization (UNEP 2021b). This concerns significant GHG emissions from energy use, notably in server farms related to cloud computing and storage, material waste accumulation due to planned obsolescence and low levels of e-waste recycling, and significant pressure on mining for rare resources and related environmental and social impacts (Creutzig et al. 2022; Sareen et al. 2023), which tend to be unevenly distributed globally (Sovacool et al. 2020).

The considerable uncertainties clouding the environmental implications of digitalization may make any attempt at accurate prediction futile. This unknowable character of the digital carbon footprint and the associated risks of it spinning out of control suggest that the main priorities should be set on avoiding risks, mitigating adverse effects, and enabling adaptive governance frameworks for rapidly changing circumstances (Gritsenko et al. 2024).

12.6.5 Illustration of Principle 5

Section 12.4.5 presented principle 5 as follows: The governance of system transformations needs to involve actors from different societal spheres and a plurality of worldviews, which implies deliberate forms of coordination, inclusion and participation

Example 5a: Legal instruments to enforce coordination, plurality of voices and gender inclusion and stakeholder participation in Kenya

In Kenya, the inclusion and consultation of all stakeholders were enshrined in the country's Constitution in 2010. This was further enacted in the counties to ensure that rural communities and Indigenous Knowledge among the over 47 tribes in Kenya can share and debate the previous top-down forms of policies. Examples include changes in environmental social impact assessments that now demand that those affected or potentially affected have a voice in shaping policy decisions. Gender considerations are also now taken into account with development programmes now enforcing gender inclusion as a key part of the programme's success across the country. For example, the National Gender and Climate Action Plan in Kenya aims to ensure that investments, policies and programmes are inclusive, equitable and effective.

Programmatic examples include Voices for a Just Climate Action, which aims to ensure that local civil society and underrepresented groups take on central roles as creators, facilitators and advocates of innovative and inclusive climate solutions to address climate change issues. Various approaches have been initiated to address the effects created by climate change, and ultimately, steps to reduce carbon emissions in a bid to forestall environmental degradation and pollution. The Voices for a Just Climate Action is a lobby and advocacy programme implemented by the World Wide Fund for Nature Netherlands, SouthSouthNorth, Akina Mama wa Afrika, Slum Dwellers International and Hivos, and is an example of the many programmes now in place to ensure the inclusion and multiplicity of voices in the environmental space.

A significant change in the plurality of world views in Kenya and Africa has been accelerated by the large

Credit: ©UNEP

number of youth using social media. The rise of different young voices is now seen within the context of social media where Kenyans active on social media raise concerns that now demand policymakers' attention. In effect, this has increased the self-regulation of government by citizens who can now check on the progress of policies. It also allows the inclusion of various diverse voices and their views to be heard and considered. The rise of information technology has further enhanced the accessibility of decision-making in the country, ensuring that alternative news media from grass-roots individuals is now accessible, thus reorienting modes of knowing and doing.

Example 5b: Plurality in biodiversity conservation for Indigenous communities

Traditional protectionist or fortress-conservation approaches traditionally had adverse effects on Indigenous Peoples when redesignation of Indigenous Peoples' lands would lead to dispossessions and displacements (Adams and Mulligan 2003). Plurality in conservation means recognizing multiple forms of knowledge with varying definitions in different academic disciplines, including divergences between the natural and social sciences, but also among different communities and groups who have lay knowledge, including "situated, emotive and intimate" relations with non-human life, and differing conceptions of how to live well together with nature (Pascual et al. 2021). Mobilizing "scientific knowledge and lay knowledge, conservation science policy and practice would be better equipped to identify and facilitate more legitimate and effective goals and actions" rather than imposing contested frameworks (Pascual et al. 2021, p. 569). More collaborative approaches to site-based biodiversity conservation are collaborative in nature (Carmenta et al. 2023), being context-sensitive and prioritizing questions of ethics and justice for humans and non-humans (Nelson et al. 2024). For example, Indigenous Peoples' ways of knowing and being, including their relationships with themselves, lands and others – including plants and animals – are imbued with notions of interdependency and recognition of the vitality and agency of lands and all life, aligned with values and practices of reciprocity and care. In these relational ways of knowing and being, Indigenous Peoples view nature not as something separate from themselves but as deeply connected, and often as kin, as sacred or as a spiritual entity (Bawaka Country et al. 2015).

Valuing nature beyond utilitarian frameworks and instrumental values creates opportunities for more just and effective approaches to conservation, given the effectiveness of Indigenous Peoples' guardianship and care for lands and life. The approach of Indigenous Peoples and Local Communities Conserved Territories and Areas, known as the ICCA Consortium or "territories of life", is a valuable one. It aims to conserve Indigenous territories and protected areas, cultural land and seascapes, sacred natural sites, migration routes of mobile Indigenous Peoples, biocultural heritage territories, and community-managed areas. These involve close connections between

custodians and Indigenous People or local communities, and they lead governance for the area, with governance and management decisions positively contributing to nature conservation of the area (IPBES 2024; Sajeva, Borrini-Feyerabend, Niederberger 2019). The principles guiding such conservation have the potential to support sustainable futures worldwide (Nelson et al. 2024). Efforts are under way, for example in New Zealand, to assign rights to nature – such as rivers and forests – by the Rights of Nature movement (Banwell et al. 2024). Non-human – that is, plant and animal – representation is being assigned to the boards of cooperatives (Nieuwe Instituut 2021) and in transdisciplinary action research projects that embrace plurality, for example, the Embassy of the North Sea. This is a ten-year Dutch initiative involving ecologists, artists, communication specialists and communities, seeking to "listen to", "speak with" and "negotiate for" the North Sea, which has been recognized as a living entity with agency (Embassy of the North Sea, n.d.). It is important to note, however, that site-based conservation is increasingly challenged by forces beyond the territory, which means that action is required to address the global political economy, to shift cultural narratives, to challenge the most impactful sectors and to transform governance systems (IPBES 2024). This also means addressing issues such as perverse subsidies, and measures to manage telecoupled agricultural commodity trade through a connected conservation approach (Carmenta et al. 2023).

12.6.6 Illustration of Principle 6

Section 12.4.6 presented principle 6 as follows: The governance of system transformations needs to address power relations, vested interests and social inequalities through decisive political choices guided by explicit notions of justice.

Example 6a: Financial subsidies

Money is often related to power; the financial system tends to wield some of the most powerful mechanisms for both maintaining the current system and transforming it. The example of subsidies provides a clear illustration of how politics influences the asymmetric deployment of money to certain sectors and actors, often at the detriment of sustainability and equity goals. Creating a more just system that aims to rectify asymmetries in power and access to capital requires powerful actors to reconfigure how they allocate financial resources. Globally, fossil-fuel subsidies totalled US$7 trillion or 7.1 per cent of GDP in 2022, reflecting a US$2 trillion increase since 2020 due to government support from surging energy prices (WEF 2023a; IEA 2025a). Subsidies are expected to decline in the near term as energy price support policies are unwound and international prices fall, but then to rise to US$8.2 trillion by 2030 as the share of fuel consumption in emerging markets – where price gaps are generally larger – continues to climb (WEF 2023a; IEA 2025a). Subsidies are intended to protect consumers by keeping prices low, but they come at a substantial cost: they lead to higher taxes and borrowing or lower spending; promote inefficient allocation of an economy's resources, hindering growth; encourage pollution, contributing to climate change and premature deaths from local air pollution; and are not well targeted at the poor, mainly benefiting higher income households. This not only applies to subsidies of fossil fuels, but also in the fisheries sector where overfishing and inequitable access to resources are prevalent (Sumaila et al. 2019).

Removing subsidies and using the revenue gain for better-targeted social spending, reductions in inefficient taxes, and productive investments can promote sustainable and equitable outcomes. The removal of fossil-fuel subsidies would also alleviate energy security concerns related to volatile fossil-fuel supplies (WEF 2023a; IEA 2025a). The 2022 the World Trade Organization agreement on fisheries subsidies that established binding global regulations compelling governments to assess the legality and sustainability of the fishing activities they subsidize, showcases the potential for transformative change if the power of the financial sector is leveraged for more sustainable and equitable outcomes (Sumaila et al. 2024). In February 2024, World Trade Organization members were uniquely positioned to institute additional regulations that eliminate harmful subsidies, demonstrating their dedication to safeguarding the ocean and charting a more sustainable and equitable pathway forward with a commitment to more equitable trade. This demonstrates how political choices are necessary to harness a financial lever to achieve transformative change for the world's oceans and resources. Changing economies will also require more than specific policy levers; shifts in values and ontologies are central to

3 The BRICS is a group formed by eleven countries: Brazil, Russia, India, China, South Africa, Saudi Arabia, Egypt, United Arab Emirates, Ethiopia, Indonesia, and Iran.

transformations. Transformations require moderating individualism and materialism and amplifying the values of care and solidarity (IPBES 2022; Harmáčková et al. 2023). Alternative visions of economic exchange beyond accumulation already exist in diverse economies around the world (Gibson-Graham 1996) and they are particularly strong within Indigenous philosophies, which present some of the best examples of living sustainably within planetary boundaries (IK & LK Dialogues 2025).

Example 6b: Realignment of country-level governance systems in Africa to mitigate disparities across multiple sectors and thus realign power dynamics and vested interests to include multiple actors

Many countries in Africa face persistent challenges since attaining independence in the 1960s in ensuring the equitable distribution of resources. The power dynamics and vested control, not only from the colonial powers but also from the minority in those countries who have controlled the various domains of economic control across various sectors, have ensured that a select few control natural resources. While the 1990s saw many African countries incorporate human rights and the rule of law, not many have been able to alter the power dynamics and actors that control various sectors. Global realignments such as the BRICS[3] group are viewed as providing alternative options and realigning the lock-ins and vested interests that dominate Africa's governance structures.

At the country level, Kenya's 2010 constitutional change provides a good example of reorienting and navigating power dynamics and vested interests. While it still has a long way to go in ensuring social participation, the new Constitution initiated the division of the country into 47 counties with a political structure that removes power from the central domain of the Presidency. Like the federal system in the United States of America, the Constitution stipulates that decisions across many sectors must be made at the county level. This has shifted the power dynamics, with those marginalized communities now having a voice in the decisions that affect day-to-day resources in their communities. The changes in power from the top at the central level have also started to alter the vested interests entrenched in various sectors. These include: 1) altering the power dynamics and vested interests on infrastructure in the counties; 2) political representation, gender participation and access to political resources; 3) changing and challenging the social structure of society across terms such as rural and city and thus altering policy design, now that each county has a centralized capital; and 4) changing and challenging the age structure, income and access to development projects (Government of Kenya 2010).

The above examples serve to show how levers – domains of intentional action – when applying the principles, can be mobilized to transform entire systems and in doing so, ensure that transformation takes place.

12.7 New policy design for our times

This chapter has provided a conceptual analysis of the dynamics of transformation. In doing so, it has identified six core requirements for transformation and the ways in which these principles can be applied within the levers. These requirements shed light on pathways for dealing with the inherent challenges in transforming entire systems. The requirements are framed within the need to ensure that transformation is not purely normative or theoretical but also meets the practical challenges of our times. They provide a mental map to be used strategically by all actors in society to achieve whole-system change.

In its attempt to ingrain the conceptual analysis within the day-to-day actions of actors, the chapter highlights the role of levers, which it defines as "domains of intentional action" in providing a means for dealing with system transformation. Unique to this GEO-7 report is the role of policy actors in appraising bundles of actions within and across levers. In particular, the policy actor is presented with the six principles and the levers as heuristic models – a conceptual framework – that can be used to define systems and their lock-ins as explicit and shared frameworks for action. This aims to combine the dynamics of phase-out and phase-in with the anticipation of change over the near and long term, to seek modes of intervention that acknowledge uncertainties, and to engage with diverse constellations of actors affected differently by system transformation and with contrasting power and influence.

This conceptual framework provides the actor with the ability to reshape entire sociotechnical, socioecological and socioeconomic systems that need purposeful action to move beyond the many isolated fragments and target whole-system change. The six principles combined with the levers present a set of new practices of policy design that provide purposive action towards collectively defined solution pathways as a basic

condition to enable system transformation through meaningful and targeted politics, governance, and institutional capabilities (Patterson et al. 2017; German Environment Agency [GEA] 2018; United Nations 2023; Bertelsmann Stiftung 2024). Further, it shows that the conventional separation between levers is ill-suited to transformative processes that inevitably cross the boundaries between, for example, the worlds of business strategy, personal lifestyle, government regulation, finance and technology. Instead, the new policy design envisioned in this chapter reveals new boundary-spanning intersections and institutional work between the multiple arenas of societal influence.

12.7.1 Rethinking the politics and political culture of system transformations towards societal sustainability

A key message is that system transformation is a lightly distributed and coevolutionary process that does not fall neatly under the label of public policy (Hajer et al. 2015; GEA 2018). The chapter challenges current institutional set ups and governance practices to rethink their relationship to and influence over prevailing societal structures, market economies, political spheres of influence, patterns of social interactions and arrangements, the institutional structures that arise from these arrangements, collective identity formation, and the forms of political participation available to citizens.

The chapter also acknowledges that the pursuit of urgent sustainability goals requires formal governance institutions to establish goals and frameworks, particularly at national level, to enable the shared framing of problems and solution spaces, to leverage the allocation of public finance, or to support deliberative processes for the formulation of political solutions (United Nations 2023). This interplay of different layers of governance suggests that system transformation as a political means of developing and supporting solution pathways calls for a new political rationality, that is, a new perspective on handling and influencing societal and political realities within a world of growing complexity, volatility and political ambiguity (Eden et al. 2021; Antonacopoulou 2018).

Such a new perspective on the politics of transformation can underpin a new era of purposeful policy and action – policy-by-design, not policy-by-disaster (Nassehi 2024). It needs to encompass the cultural, political and material aspects of human life and how these aspects are socially organized, normatively codified, and structurally institutionalized towards an envisioned societal reality. The formulated principles for transformation can help facilitate the responsiveness, agency, and actions necessary. Thinking of system transformation as a new political practice may lead to fundamentally reconfiguring existing priorities of established arrangements and social order, challenging institutionalized routines, political paradigms, patterns of responsibility, cultural identities, and role models (GEA 2018), as has been shown through the principles when applied within the levers.

The ensuing new role for government not only presents a historical opportunity and responsibility to address major shortcomings of the present handling of environmental crises, but also a requirement to develop analytical and strategic capabilities within existing governance structures and organizations. Within this new understanding of the politics of system transformation, four areas of governmental responsibility are identified as key to system transformation: orienting, aligning, navigating, and legitimizing.

12.7.2 Orienting: humble and open approaches to directionality

Clearer directionality towards sustainability goals, as shown for example by the pursuit of climate emission targets, needs to diffuse more generally in the policy system. However, given the recognition in this chapter that system transformations are inherently complex and uncertain, the scope for planning and control is limited (Stirling 2010). A purely top-down and technocratic approach is neither effective in practice nor ethically justified from an equity and justice perspective (Stirling 2023). Governing system transformations takes uncertainties seriously, and rather than claiming predictability, it gives status to unknown future developments (Beck et al. 2021). Anticipation, precaution, flexibility and reversibility are the guideposts for such an approach. Because the governance of system transformation is not a "deterministic endeavour" nor a "Fordist project" (Nassehi 2024) that promotes conformism to a "one best system", it is essential to have a plurality of possible orientations and pathways that may enable more sustainable systems and societies. Variety and diversity are requirements for system transformation.

Credit: vunavgallery/Envato

Nevertheless, in addition to these precautionary principles of flexibility and diversity, policy also needs a refreshed sense of directionality to address environmental goals, recognizing that transformation is not just a technical matter but always about political and value choices (Scoones and Stirling 2020). Challenge-led missions and transition policies pursue clearly defined sustainability targets while leaving open the types of system transformation to be followed. These new forms of collective directionality and targeted systems (OECD 2024) reconfigure purposive policies and intentional actions towards a more open, non-deterministic system transformation.

Meta-analysis on theories of change shows a significant shift (Juri, Terry and Pereira 2024) from a linear model of "solutionism" – clear causality and input-output as the modus of problem-solving – towards an interactive model of inter-relational agency, network building and interface management (Kok, Loeber and Grin 2021). These new policy practices for system transformation shift attention from the "grand design gesture" (Nassehi 2024) with its often unrealistic claims of radicality and totality. Instead, they draw attention to a more grounded appraisal of the continuously evolving potential of system transformability, less driven by the advocacy of specific technoscientific promises.

12.7.3 Aligning: promoting favourable and discouraging unfavourable alignments

As already discussed, system transformations involve fundamental changes within material, relational and institutional dimensions. Ongoing changes may be contradictory or even pursue environmentally detrimental outcomes. A significant task within the politics of transformation is to generate and sustain positive alignments while avoiding and reducing negative alignments of intentional actions, thereby shaping the configuration of agency. At actor level, this means empowering specific networks and alliances, while discouraging or disbanding alliances working against collectively agreed goals. The process of transformation is a widely distributed one, involving a multiplicity of actions and actors, as well as a vital plurality of positions and worldviews. Research on the dynamics of transformation shows that top-down, technocratic control models are limited and sometimes counterproductive. It also indicates that uncoordinated bottom-up initiatives, although important as envisioned models of transformations, are usually heavily circumscribed, fragmented and difficult to scale or generalize (Easterly 2008; GEA 2015; GEA 2016).

Coordination can be sought through the exploration and experimentation with novel, more effective multilevel models of transformation. This effort requires the identification of interactions, potential tensions and scope for alignment between actions, agency, power positions, and the actors supporting them. The search also requires clarification of the terms and boundaries of desirability in contrast with existing forms of normativity, and regulatory regimes (Forst and Günther 2021). The policy-mix approach

Credit: alexlucru123/Envato

seeks to align a diverse range of public interventions of different types and various domains in a structured and formal manner. Transformative innovation policy can promote a project portfolio approach that involves a variety of actors around common goals (Gunningham and Sinclair 1999; Boas, Biermann and Kanie 2016; Tomor et al. 2019; Richard et al. 2020; Chenoweth and Al-Masri 2021).

12.7.4 Navigating: mapping transformation potentials and evaluating change

The ability to navigate transformations requires individual actors to position themselves in relation to one another, both spatially and socially, as well as temporally. They need a sense of their role in established or emerging systems, as well as an insight into the trajectory and likely timescale of system change. Government policy can play a critical role in facilitating this by enabling society-wide processes of mapping the types and dynamics of system transformation. Many countries have initiated such policy approaches for the net-zero transition, and this transition-policy approach has much more general applicability (United Nations 2023; GEA 2018).

Actors also need new capabilities for interaction and anticipation to navigate system transformation more strategically, either within the context of multi-actor approaches or as part of organizational routines. Many policy initiatives have developed methods and arenas to build such capabilities, including foresight processes, living laboratories or formative evaluation. Place-based approaches seem to be more effective in building such capacity, because of their grounding in contextual intelligence. Foresight is one type of policy process that may be designed to facilitate participative interaction between actors in envisioning futures and facilitating alignments (Murphy and McDonagh 2016; Svenfelt et al. 2019; EEA 2019; European Commission 2021; GEA 2023; Matti, Bontoux and Jensen 2025).

Within a policy design in governing system transformation, developing new policy competence for navigating change becomes increasingly important. Mapping and evaluation of systems and current trajectories of transformation potentials, and monitoring change processes in the making, requires transformation knowledge and formative principles of evaluation. Knowledge and training to strengthen strategic, procedural, and mediating competencies of

civil servants and public agencies can work along with handling normative orientation and conflicting norms to safeguard long-lasting directionality, ideation and editing of political and societal choices (GEA 2021; Jacob et al. 2021).

12.7.5 Legitimizing: political integrity and justice in a polarized world

The policy changes aimed at facilitating system transformations for sustainability present a range of challenges and opportunities for enabling political consensus-building and legitimacy, while mediating between different interests, modes of responsiveness and responsibility, material and non-material trade-offs, private and public resources, and investments for transformation. They imply a more active engagement of citizens and stakeholders in deliberative procedures, political decision-making processes, and strengthened political-administrative management capacities (Hammond 2020).

The political task of governing the inherent "systemness" of complex systems and the transformability of real-world social, economic and political pluralities requires appropriate policy conditions to facilitate the processes of transformation. Such policy conditions include rules of conflict regulation deriving from the transformation, with voices to mobilize collective agency across and beyond existing power asymmetries (Le 2024; Francis 2004). In addition, investments in strategic political communication that enhance the capacity for societal self-orientation and public trust in times of multiple crises and post-polarization need to accompany opportunities for better accessibility to various forms of social involvement and deliberative processes (Friedrich Naumann Foundation 2024; Kleinfeld 2023; Nassehi 2021).

12.8 Towards an operationalization of system transformations

This chapter suggests enriching the public sphere for system transformation. This chimes with a new reorientation by many governments from the market prioritization of the last 30 years, but it also clashes with expressions of populist backlash. There is little doubt that the policy agenda of transformation will be embroiled in these broader political currents in the coming decades and its proponents will need to engage with them.

In addition, the chapter has acknowledged the different policy perspectives among the proponents of sustainability transformations themselves. A spectrum of reform, revolution or reconfiguration has been presented to capture different views of the prospects for current policy systems to innovate sufficiently to enable transformation. This chapter's modest aspiration is that it has identified at least some spaces within the various governance spheres where opportunities for constructive engagement exist to promote sustainability transformations now and in the near future.

A common methodological approach is therefore needed to harness the richness of theoretical and empirical knowledge for system transformations discussed in this chapter. Chapter 13 provides this approach through an operationalization of the principles in a 7-step methodology. This methodology enables the identification and assessment of political options for solution pathways towards system transformation, using the identified principles and concept of levers discussed in this chapter as a baseline analytical, rational, and systemic approach within the GEO-7 assessment.

Appendix 12.1 Definitions of system transformation and transformative change in global environmental assessment reports

	Definition	Reference
IPBES	Transformative change is] a fundamental, system-wide reorganization across technological, economic and social factors, including paradigms, goals and values.	IPBES 2022, p. 544
IPCC	Transformative change: "A system-wide change that requires more than technological change through consideration of social and economic factors that, with technology, can bring about rapid change at scale."	IPCC 2022a, p. 2925
IPCC	Transformation pathways: "Trajectories describing consistent sets of possible futures of greenhouse gas (GHG) emissions, atmospheric concentrations, or global mean surface temperatures implied from mitigation and adaptation actions associated with a set of broad and irreversible economic, technological, societal, and behavioural changes. This can encompass changes in the way energy and infrastructure are used and produced, natural resources are managed and institutions are set up, and in the pace and direction of technological change."	IPCC 2022b, p. 1811
United Nations	"Transformative change will mean harnessing bottom-up social, technological and institutional innovation, including Indigenous Knowledge and creativity at the grassroots level and in the informal sector, particularly – but not exclusively – in developing and emerging economies. … Transformative change also requires the reconfiguration of social practices, social norms, values and laws that promote unsustainable or discriminatory behaviour and choices …"	United Nations 2019, p. 35
EEA	Transformative change, key features: "Alignment of social and environmental challenges with innovation objectives"	EEA 2019, p. 384
FAO	"Transformational change in land use and climate change is characterized by: (i) processes that moves away from the current regime of unsustainable land use, maladaptation and unmitigated greenhouse gas emissions, opening pathways to reverse these outcomes and work towards a sustainable planet (ii) being achieved through sustained changes that accept complexity and uncertainty (iii) a focus on root causes and nurturing relationships between scales and dimensions of change (e.g. organizations, markets, technologies, power and social relations, and ideas) (iv) being based on participation, equity and transparency (v) being supported by knowledge and data used for understanding, evaluation and course corrections"	FAO 2021, p. 8

References

Adams, D., Adams, K., Ullah, S. and Ullah, F. (2019). Globalisation, governance, accountability and the natural resource 'curse': Implications for socio-economic growth of oil-rich developing countries. Resources Policy 61, 128-140. https://doi.org/10.1016/j.resourpol.2019.02.009

Adams, W.M. and Mulligan, M. (2003). Decolonizing Nature: Strategies for Conservation in a Post-colonial Era. London: Routledge. https://www.routledge.com/Decolonizing-Nature-Strategies-for-Conservation-in-a-Post-colonial-Era/Adams-Mulligan/p/book/9781853837494?srsltid=AfmBOooH0L2FmykPYYXQZIYqwJ5C7opC04pSN_x9x28Ta6-xtUFPFmwu.

Allen, C. and Malekpour, S. (2023). Unlocking and accelerating transformations to the SDGs: a review of existing knowledge. Sustainability Science 18(4), 1939-1960. https://doi.org/10.1007/s11625-023-01342-z

Aminzade, R. 1992. Historical Sociology and Time. Sociological Methods and Research 20(4), 456-480. https://doi.org/10.1177/0049124192020004003.

Andersson, C., Törnberg, A. and Törnberg, P. (2014). Societal systems – Complex or worse? Futures 63, 145-157. https://doi.org/10.1016/j.futures.2014.07.003

Antonacopoulou, E.P. (2018). Organisational Learning for and with VUCA: Learning Leadership Revisited. Teoria e práctica em Administração 8(2), 10-32. https://pdfs.semanticscholar.org/47ac/aa47315cec3539f5b8c441a84e152657c2c6.pdf

Appunn, K. (2021). The history behind Germany's nuclear phase-out. Clean Energy Wire. https://www.cleanenergywire.org/factsheets/history-behind-germanys-nuclear-phase-out#. Accessed: 12 June 2025

Arifi, B. and Winkel, G. (2021). Wind energy counter-conducts in Germany: understanding a new wave of socio-environmental grassroots protest. Environmental Politics 30(5), 811-832. https://doi.org/10.1080/09644016.2020.1792730

Arnhold, V. (2021). Normalisation of nuclear accidents after the Cold War. Cold War History 21(3), 261-281. https://doi.org/10.1080/14682745.2020.1806239

Arora, S. and Stirling, A. (2023). Colonial modernity and sustainability transitions: A conceptualisation in six dimensions. Environmental Innovation and Societal Transitions 48, 100733. https://doi.org/10.1016/j.eist.2023.100733

Arthur, W.B. (1989). Competing Technologies, Increasing Returns, and Lock-In by Historical Events. The Economic Journal 99(394), 116-131. https://doi.org/10.2307/2234208

Avelino, F. (2017). Power in Sustainability Transitions: Analysing power and (dis)empowerment in transformative change towards sustainability. Environmental Policy and Governance 27(6), 505-520. https://doi.org/10.1002/eet.1777

Avelino, F. and Wittmayer, J. (2016). Shifting Power Relations in Sustainability Transitions: A Multi-actor Perspective. Journal of Environmental Policy & Planning 18, 628-649. https://doi.org/10.1080/1523908X.2015.1112259.

Banister, D., Anderton, K., Bonilla, D., Givoni, M. and Schwanen, T. (2011). Transportation and the Environment. Annual Review of Environment and Resources 36, 247-270. https://doi.org/10.1146/annurev-environ-032310-112100

Banister, D. (2008). The sustainable mobility paradigm. Transport Policy 15(2), 73-80. https://doi.org/10.1016/j.tranpol.2007.10.005

Banwell, S., Nelson, V. and Dehbi, F. (2025). Achieving sustainability transformations for multi-species justice: assessing the potential of diverse legal pathways and societal struggles. Sustainability Science 20, 1017-1035. https://doi.org/10.1007/s11625-025-01627-5

Bawaka Country, Wright, S., Suchet-Pearson, S., Lloyd, K., Burarrwanga, L., Ganambarr, R. et al. (2016). Co-becoming Bawaka: Towards a relational understanding of place/space. Progress in Human Geography 40(4), 455-475. https://doi.org/10.1177/0309132515589437

Beck, S., Jasanoff, S., Stirling, A. and Polzin, C. (2021). The governance of sociotechnical transformations to sustainability. Current Opinion in Environmental Sustainability 49, 143-152. https://doi.org/10.1016/j.cosust.2021.04.010

Beck, S. and Mahony, M. (2018). The IPCC and the new map of science and politics. WIREs Climate Change 9(6), e547. https://doi.org/10.1002/wcc.547

Bennett, E.M., Solan, M., Biggs, R., McPhearson, T., Norström, A.V., Olsson, P. et al. (2016). Bright spots: seeds of a good Anthropocene. Frontiers in Ecology and the Environment 14(8), 441-448. https://doi.org/10.1002/fee.1309

Bento, N. and Wilson, C. (2016). Measuring the duration of formative phases for energy technologies. Environmental Innovation and Societal Transitions 21, 95-112. https://doi.org/10.1016/j.eist.2016.04.004

Bergmann, Iris (2016). What is the role of the arts in the face of this?: an exploration in the context of systems thinking and the transition to sustainability. Monash University. Journal contribution. https://doi.org/10.4225/03/58535cd356dbb

Berkhout, F. (2006). Normative expectations in systems innovation. Technology Analysis & Strategic Management 18(3-4), 299-311. https://doi.org/10.1080/09537320600777010

Bertelsmann Stiftung (2024). Less democratic, less successful. Güterlosh: Bertelsmann Stiftung. https://doi.org/10.11586/2024043

Blythe, J., Silver, J., Evans, L., Armitage, D., Bennett, N.J., Moore, M.-L. et al. (2018). The Dark Side of Transformation: Latent Risks in Contemporary Sustainability Discourse. Antipode 50(5), 1206-1223. https://doi.org/10.1111/anti.12405

Boas, I., Biermann, F. and Kanie, N. (2016). Cross-sectoral strategies in global sustainability governance: towards a nexus approach. International Environmental Agreements: Politics, Law and Economics 16(3), 449-464. https://doi.org/10.1007/s10784-016-9321-1

Bockstael, E. and Watene, K. (2016). Indigenous peoples and the capability approach: taking stock. Oxford Development Studies 44(3), 265-270. https://doi.org/10.1080/13600818.2016.1204435

Bond, W.J., Stevens, N., Midgley, G.F. and Lehmann, C.E.R. (2019). The Trouble with Trees: Afforestation Plans for Africa. Trends in Ecology & Evolution 34(11), 963-965. https://doi.org/10.1016/j.tree.2019.08.003

Boschma, R., Coenen, L., Frenken, K. and Truffer, B. (2017). Towards a theory of regional diversification: combining insights from Evolutionary Economic Geography and Transition Studies. Regional Studies 51(1), 31-45. https://doi.org/10.1080/00343404.2016.1258460

Brand, U., Muraca, B., Pineault, É., Sahakian, M., Schaffartzik, A., Novy, A. et al. (2021). From planetary to societal boundaries: an argument for collectively defined self-limitation. Sustainability: Science, Practice and Policy 17(1), 264-291. https://doi.org/10.1080/15487733.2021.1940754

Braudel, F. (1970). History and the social sciences: The long term. Social Science Information 9(1), 144-174. https://doi.org/10.1177/053901847000900107

Bridge, G. (2008). Global production networks and the extractive sector: governing resource-based development. Journal of Economic Geography 8(3), 389-419. https://doi.org/10.1093/jeg/lbn009

Brown, K. (2015). Resilience, Development and Global Change. Routledge. https://doi.org/10.4324/9780203498095

Büscher, B. and Fletcher, R. (2020). The Conservation Revolution: Radical Ideas for Saving Nature Beyond the Anthropocene. Verso books. https://www.versobooks.com/products/856-the-conservation-revolution?srsltid=AfmBOoov00MqOKS2n1lbYHBFwcY-u_dnNnWGarRwrbttNeJaB3jfpNcG

Camanzi, L. and Troiano, S. (2021). The evolutionary transformation of modern agri-food systems: emerging trends in consumption, production, and in the provision of public goods. Agric Econ 9, 24. https://doi.org/10.1186/s40100-021-00196-2

Carmenta, R., Barlow, J., Bastos Lima, M.G., Berenguer, E., Choiruzzad, S., Estrada-Carmona, N. et al. (2023). Connected Conservation: Rethinking conservation for a telecoupled world. Biological Conservation 282, 110047. https://doi.org/10.1016/j.biocon.2023.110047

Castree, N., Adams, W.M., Barry, J., Brockington, D., Büscher, B., Corbera, E. et al. (2014). Changing the intellectual climate. Nature Climate Change 4(9), 763-768. https://doi.org/10.1038/nclimate2339

Charli-Joseph, L., Siqueiros-García, J., Eakin, H., Manuel-Navarrete, D. and Shelton, R. (2018). Promoting agency for social-ecological transformation: A transformation-lab in the Xochimilco social-ecological system. Ecology and Society 23. https://doi.org/10.5751/ES-10214-230246

Cheng, C., Sa-Ngasoongsog, A., Beyca, O. F. and Le, T. (2015). Time Series Forecasting for Nonlinear and Nonstationary Processes: A Review and Comparative Study. IIE Transactions 47(10), 1053-1071. https://doi.org/10.1080/0740817X.2014.999180

Chenoweth, J. and Al-Masri, R.A. (2021). The impact of adopting a water-energy nexus approach in Jordan on transboundary management. Environmental Science & Policy 118, 49-55. https://doi.org/10.1016/j.envsci.2021.01.006

Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E. and Sovacool, B. (2018). Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. Energy Research & Social Science 37, 175-190. https://doi.org/10.1016/j.erss.2017.09.015

Chibwe, B., Terry, N., Noumonvi, K.D., Carpenter-Urquhart, L., Tcheton, S. and Pereira, L.M. (2024). African futures: a review of scenarios for Indigenous and local people and nature in Africa. Ecology and Society 29(3). https://doi.org/10.5751/ES-15322-290332

Clark, W.C. and Harley, A.G. (2020). An Integrative Framework for Sustainability Science. In Sustainability Science: A Guide for Researchers. Clark, W.C. and Harley, A.G. (eds.). https://assets.pubpub.org/imuc6raq/3e111738-7917-46e9-9d47-047e295344a4.pdf

Coalition for Digital Environmental Sustainability (2022). Action Plan for a Sustainable Planet in the Digital Age. https://doi.org/10.5281/zenodo.6573509

Collingridge, D. (1980). The Social Control of Technology. Palgrave Macmillan. https://www.goodreads.com/book/show/21351241-the-social-control-of-technology

Cumming, G. and Peterson, G. (2017). Unifying Research on Social-Ecological Resilience and Collapse. Trends in Ecology & Evolution 32(9), 695-713. https://doi.org/10.1016/j.tree.2017.06.014

Creutzig, F., Acemoglu, D., Bai, X., Edwards, P.N., Hintz, M.J., Kaack, L.H. et al. (2022). Digitalization and the Anthropocene. Annual Review of Environment and Resources 47, 479-509. https://doi.org/10.1146/annurev-environ-120920-100056

de Haan, J. and Rotmans, J. (2011). Patterns in transitions: Understanding complex chains of change. Technological Forecasting and Social Change 78(1), 90-102. https://doi.org/10.1016/j.techfore.2010.10.008

Dieppe, A. and Hideaki, M. (2021). Sectoral Sources of Productivity Growth. In Global Productivity: Trends, Drivers, and Policies. Dieppe, A. (eds.). Washington D.C.: World Bank. https://doi.org/10.1596/978-1-4648-1608-6_ch7

Dooley, K., Nicholls, Z. and Meinshausen, M. (2022). Carbon removals from nature restoration are no substitute for steep emission reductions. One Earth 5(7), 812-824. https://doi.org/10.1016/j.oneear.2022.06.002

Dupuy, J.-P. (2002). Pour un catastrophisme éclairé. Quand l'impossible est certain. Points. https://www.editionspoints.com/ouvrage/pour-un-catastrophisme-eclaire-jean-pierre-dupuy/9782020660464

Easterly, W. (2008). Institutions: Top down or Bottom up? The American Economic Review 98(2), 95-99. https://www.jstor.org/stable/29730002

Eden, L., Hermann, C.F. and Miller, S.R. (2021). Evidence-based policymaking in a VUCA world. Transnational Corporations 28(3), 159-182. https://doi.org/10.18356/2076099x-28-3-8

Elmqvist, T., Siri, J., Andersson, E., Anderson, P., Bai, X., Das, P.K. et al. (2018). Urban tinkering. Sustainability Science 13(6), 1549-1564. https://doi.org/10.1007/s11625-018-0611-0

Embassy of the North Sea. (n.d.). Embassy of the North Sea. [online] Available at: https://www.embassyofthenorthsea.com/

Ericksen, P.J. (2008). Conceptualizing food systems for global environmental change research. Global Environmental Change 18(1), 234-245. https://doi.org/10.1016/j.gloenvcha.2007.09.002

Escobar, A. (2021). Reframing civilization(s): from critique to transition. Globalizations, 1-18. https://doi.org/10.1080/14747731.2021.2002673

European Commission (2021). 2021 Strategic Foresight Report: The EU's capacity and freedom to act. Brussels: Secretariat General, European Commission. https://doi.org/10.2792/55981

European Commission Joint Research Centre and United Nations Inter Agency Task Team on Science, Technology and Innovation for the SDGs (2021). Guidebook for the preparation of Science, Technology and Innovation (STI) for SDGs Roadmaps. Luxembourg: Publications Office of the European Union. https://sdgs.un.org/sites/default/files/2021-06/GUIDEBOOK_COMPLETE_V03.pdf

European Environment Agency (2017). Perspectives on transitions to sustainability. Luxembourg: Publications Office of the European Union. https://www.eea.europa.eu/publications/perspectives-on-transitions-to-sustainability

European Environment Agency (2019). The European Environment - State and Outlook 2020: Knowledge for transition to a sustainable Europe. Luxembourg: Publications Office of the European Union. https://www.eea.europa.eu/soer/publications/soer-2020

Fazey, I. and Leicester, G. (2022). Archetypes of system transition and transformation: Six lessons for stewarding change. Energy Research & Social Science 91, 102646. https://doi.org/10.1016/j.erss.2022.102646

Feola, G. (2015). Societal transformation in response to global environmental change: A review of emerging concepts. Ambio 44(5), 376-390. https://doi.org/10.1007/s13280-014-0582-z

Folke, C., Biggs, R., Norström, A.V., Reyers, B. and Rockström, J. (2016). Social-ecological resilience and biosphere-based sustainability science. Ecology and Society 21(3). http://dx.doi.org/10.5751/ES-08748-210341

Folke, C., Carpenter, S.R., Walker, B., Scheffer, M., Chapin, T. and Rockström, J. (2010). Resilience Thinking: Integrating Resilience, Adaptability and Transformability. Ecology and Society 15(4). https://www.jstor.org/stable/26268226

Food and Agriculture Organization (2014). Transformational change to reduce deforestation and climate change impacts: A review of definitions, concepts and drivers in scientific and grey literature. https://www.fao.org/3/cb7314en/cb7314en.pdf

Food and Agriculture Organization (2021). Building a common vision for sustainable food and agriculture: Principles and approaches. https://openknowledge.fao.org/server/api/core/bitstreams/cd7ebb4f-da7c-474d-83df-b5cc224d2ff8/content

Forst, R. and Günther, K. (2021). Normative Ordungen. Suhrkamp Verlag. https://www.suhrkamp.de/buch/normative-ordnungen-t-9783518299425

Fouquet, R. (2016). Historical energy transitions: Speed, prices and system transformation. Energy Research & Social Science 22, 7-12. https://doi.org/10.1016/j.erss.2016.08.014

Francis, D. (2004). Culture, Power Asymmetries and Gender in Conflict Transformation. In Transforming Ethnopolitical Conflict: The Berghof Handbook. Austin, A., Fischer, M. and Ropers, N. (eds.). Wiesbaden: VS Verlag für Sozialwissenschaften. 91-107. https://doi.org/10.1007/978-3-663-05642-3_5

Frantzeskaki, N., Loorbach, D. and Meadowcroft, J. (2012). Governing societal transitions to sustainability. International Journal of Sustainable Development 15(1-2), 1-18. https://www.researchgate.net/publication/262904053_Governing_societal_transitions_to_sustainability

Freeman, C. and Louçã, F. (2001). As Time Goes By: From the Industrial Revolutions to the Information Revolution. Oxford University Press. https://EconPapers.repec.org/RePEc:oxp:obooks:9780199241071

Friedrich Naumann Foundation (2024). Democracies: Challenges and Opportunities in a Changing World [Conference]. https://www.freiheit.org/democracies

Fritz, M. and Koch, M. (2016). Economic development and prosperity patterns around the world: Structural challenges for a global steady-state economy. Global Environmental Change 38, 41-48. https://doi.org/10.1016/j.gloenvcha.2016.02.007

Fukuyama, F. (2015). Why is democracy performing so poorly? Journal of Democracy 26(1), 11-20. https://doi.org/10.1353/jod.2015.0017

Government of Kenya (2010), The Constitution of Kenya, Nairobi: Government Printer. Rev. 2010]

Geels, F.W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Research Policy 31(8), 1257-1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Geels, F.W. (2004). From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. Research Policy 33(6), 897-920. https://doi.org/10.1016/j.respol.2004.01.015

Geels, F.W. and Turnheim, B. (2022). The Great Reconfiguration: A Socio-Technical Analysis of Low-Carbon Transitions in UK Electricity, Heat, and Mobility Systems. Cambridge: Cambridge University Press. https://www.cambridge.org/core/books/great-reconfiguration/982D5F81C3D062D611217320A5E63E11

German Advisory Council on Global Change (2019). Towards our Common Digital Future. Berlin: WBGU. https://www.wbgu.de/en/publications/publication/towards-our-common-digital-future

German Environment Agency (2015). Experimentierraum Stadt: Good Governance für soziale Innovationen auf dem Weg zur Nachhaltigkeitstransformation. Dessau-Roßlau: Umweltbundesamt. https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_04_2015_experimentierraum_stadt_good_governance.pdf

German Environment Agency (2016). Nachhaltiger Konsum durch soziale Innovationen – Konzepte und Praxis. Dessau-Roßlau: Umweltbundesamt. https://www.umweltbundesamt.de/publikationen/nachhaltiger-konsum-durch-soziale-innovationen

German Environment Agency (2018). Transformative environmental policy: Consistently promote and shape sustainable development. A guide for the BMU's area of responsibility. Dessau-Rosslau: Umweltbundesamt. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/transformative_environmental_policy_web.pdf

German Environment Agency (2021). Die Transformationswerkstatt: Fragen und Antworten zum Weiterbildungsformat. Dessau-Rosslau: Umweltbundesamt. https://www.umweltbundesamt.de/publikationen/die-transformationswerkstatt

German Environment Agency (2023). From quantum computing to the future of inner cities and a new world order: Results of the second Horizon Scanning cycle for the Environment Department published. Dessau-Rosslau: Umweltbundesamt. https://www.umweltbundesamt.de/publikationen/from-quantum-computing-to-the-future-of-inner

Gibson-Graham, J.K. (1996). The End of Capitalism (As We Knew It): A Feminist Critique of Political Economy. University of Minnesota Press.

Goldstein, J.E., Neimark, B., Garvey, B. and Phelps, J. (2023). Unlocking "lock-in" and path dependency: A review across disciplines and socio-environmental contexts. World Development 161, 106116. https://doi.org/10.1016/j.worlddev.2022.106116

Gritsenko, D., Aaen, J. and Flyvbjerg, B. (2024). Rethinking digitalization and climate: don't predict, mitigate. npj Climate Action 3(1), 43. https://doi.org/10.1038/s44168-024-00127-z

Grubler, A., Wilson, C. and Nemet, G. (2016). Apples, oranges, and consistent comparisons of the temporal dynamics of energy transitions. Energy Research & Social Science 22, 18-25. https://doi.org/10.1016/j.erss.2016.08.015

Guerrero Lara, L., Pereira, L., Ravera, F. and Jiménez-Aceituno, A. (2019). Flipping the Tortilla: Social-Ecological Innovations and Traditional Ecological Knowledge for More Sustainable Agri-Food Systems in Spain. Sustainability 11(5). https://doi.org/10.3390/su11051222

Gunderson, L.H. and Holling, C.S. (2002). Panarchy: Understanding transformations in systems of humans and nature. Island Press.

Gunningham, N. and Sinclair, D. (1999). Regulatory Pluralism: Designing Policy Mixes for Environmental Protection. Law & Policy 21(1), 49-76. https://doi.org/10.1111/1467-9930.00065

Guston, D.H. (2014). Understanding 'anticipatory governance'. Social Studies of Science 44(2), 218-242. https://doi.org/10.1177/0306312713508669.

Haarstad, H. and Rusten, G. (2015). The challenges of greening energy: policy/industry dissonance at the Mongstad refinery, Norway. Environment and Planning C: Government and Policy 34(2), 340-355. https://doi.org/10.1177/0263774x15614660

Haarstad, H., Sareen, S., Kandt, J., Coenen, L. and Cook, M. (2022). Beyond automobility? Lock-in of past failures in low-carbon urban mobility innovations. Energy Policy 166, 113002. https://doi.org/10.1016/j.enpol.2022.113002

Hackman, H. and St Clair, A.L. (2012). Transformative cornerstones of social science research for global change. Mundo Amazonico

Hajer, M. (2011). The Energetic Society: In search of a governance philosophy for a clean economy. The Hague: PBL Netherlands Environmental Assessment Agency. https://www.pbl.nl/sites/default/files/downloads/Energetic_society_WEB.pdf

Hajer, M., Nilsson, M., Raworth, K., Bakker, P., Berkhout, F., Do Boer, Y. et al. (2015). Beyond Cockpit-ism: Four Insights to Enhance the Transformative Potential of the Sustainable Development Goals. Sustainability 7(2), 1651-1660. https://doi.org/10.3390/su7021651

Hamadani, H. et al. (2021). Traditional Framing Practices and Its Consequences. In: Microbiota and Biofertilizers. Dar, G.H., Bhat, R.A., Mehmood, M.A., Hakeem, K.R. (eds). Cham: Springer. https://doi.org/10.1007/978-3-030-61010-4_6

Hammond, M. (2020). Democratic deliberation for sustainability transformations: between constructiveness and disruption. Sustainability: Science, Practice and Policy 16(1), 220-230. https://doi.org/10.1080/15487733.2020.1814588

Haraway, D. (2016). Staying with the Trouble: Making Kin in the Chthulucene. Durham: Duke University Press

Harmáčková, Z.V., Yoshida, Y., Sitas, N., Mannetti, L., Martin, A., Kumar, R. et al. (2023). The role of values in future scenarios: what types of values underpin (un)sustainable and (un)just futures? Current Opinion in Environmental Sustainability 64, 101343. https://doi.org/10.1016/j.cosust.2023.101343.

Harris, J. (2021). Social Movement Lessons from the Fair Trade Movement. Sentience Institute. https://www.sentienceinstitute.org/fair-trade

Hay, C. (1999). Crisis and the structural transformation of the state: interrogating the process of change. The British Journal of Politics & International Relations 1(3), 317-344. https://doi.org/10.1111/1467-856X.00018

Hickel, J., Dorninger, C., Wieland, H. and Suwandi, I. (2022). Imperialist appropriation in the world economy: Drain from the global South through unequal exchange, 1990–2015. Global Environmental Change 73, 102467. https://doi.org/10.1016/j.gloenvcha.2022.102467

Hickel, J., Kallis, G., Jackson, T., O'Neill, D., Schor, J., Steinberger, J., Victor, P. and Ürge-Vorsatz, D. (2022). Degrowth can work — here's how science can help. Nature 612, 400-403. https://doi.org/10.1038/d41586-022-04412-x.

Hickel, J., Kallis, G., O'Neill, D., Jackson, T., Victor, P., Raworth, K., Schor, J., Steinberger, J. and Ürge-Vorsatz, D. (2025). Post-growth: the science of wellbeing within planetary boundaries. The Lancet Planetary Health 9(1) E62-E78. https://doi.org/10.1016/S2542-5196(24)00310-3

IK & LK Dialogues (2025). Indigenous Knowledge and Local Knowledge Dialogues. Global Environment Outlook 7. Mexico City: CopIt-arXives, 2025. https://copitarxives.fisica.unam.mx/SC0011EN/SC0011EN.php

International Panel of Social Progress (2018). Rethinking Society for the 21st Century: Report of the International Panel on Social Progress: Volume 3: Transformations in Values, Norms, Cultures. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781108399661

International Energy Agency (2025a). Modern Renewables. https://www.iea.org/reports/sdg7-data-and-projections/modern-renewables

International Energy Agency (2025b). Energy End-uses and Efficiency Indicators Highlights. https://www.iea.org/data-and-statistics/data-product/energy-efficiency-indicators-highlights

Intergovernmental Panel on Climate Change (2022a). Climate Change 2022: Impacts, Adaptation and Vulnerability. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FullReport.pdf

Intergovernmental Panel on Climate Change (2022b). Climate Change 2022: Mitigation of Climate Change: Annex I: Glossary. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Annex-I.pdf

Intergovernmental Panel on Climate Change (2023a). Climate change - Synthesis report. A Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf

Intergovernmental Panel on Climate Change (2023b). Summary for Policymakers. Climate change - Synthesis report. A Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/sixth-assessment-report-cycle/

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2016). The methodological assessment report on SCENARIOS AND MODELS OF BIODIVERSITY AND ECOSYSTEM SERVICES. https://files.ipbes.net/ipbes-web-prod-public-files/downloads/pdf/2016.methodological_assessment_report_scenarios_models.pdf

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES Secretariat. https://doi.org/10.5281/zenodo.3553579

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2022). Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Balvanera, P., Pascual, U., Christie, M., Baptiste, B. and González-Jiménez, D. (eds.). Bonn. https://zenodo.org/records/7687931

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2023). Second Indigenous and local knowledge dialogue workshop on the IPBES assessment of transformative change and scenarios of the future. https://files.ipbes.net/ipbes-web-prod-public-files/2023-08/IPBES_TfC_2ndILKDialogue_Report_Final_ForWeb.pdf

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2024). Summary for Policymakers of the Thematic Assessment Report on the Underlying Causes of Biodiversity Loss and the Determinants of Transformative Change and Options for Achieving the 2050 Vision for Biodiversity of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. O'Brien, K., Garibaldi, L., Agrawal, A., Bennett, E., Biggs, O., Calderón Contreras, R., Carr, E. et al. (eds.). Bonn: IPBES Secretariat. https://www.ipbes.net/transformative-change-assessment

International Institute for Applied Systems Analysis (2018). Transformations to Achieve the Sustainable Development Goals. Report prepared by The World in 2050 initiative. Laxenburg, Austria. http://pure.iiasa.ac.at/15347

International Institute for Applied Systems Analysis (2019). The Digital Revolution and Sustainable Development: Opportunities and Challenges. Report prepared by the World in 2050 initiative. Laxenburg, Austria.: International Institute for Applied Systems Analysis (IIASA). https://pure.iiasa.ac.at/id/eprint/15913/

International Energy Agency (2021). Net Zero by 2050: A Roadmap for the Global Energy Sector. https://www.iea.org/reports/net-zero-by-2050

Jacob, K. and Ekins, P. (2020). Environmental policy, innovation and transformation: affirmative or disruptive? Journal of Environmental Policy & Planning 22(5), 709-723. https://doi.org/10.1080/1523908X.2020.1793745

Jacob, K., Paulick-Thiel, C., Teebken, J., Veit, S. and Singer-Brodowski, M. (2021). Change from Within: Exploring Transformative Literacy in Public Administrations to Foster Sustainability Transitions. Sustainability 13(9), 4698. https://doi.org/10.3390/su13094698

Jaramillo, P., Ribeiro, S. K., Newman, P., Dhar, S., Diemuodeke, O.E., Kajino, T., et al. (2022). Transport. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009157926.012

Jessop, B. (2002). Liberalism, Neoliberalism, and Urban Governance: A State–Theoretical Perspective. Antipode 34(3), 452-472. https://doi.org/10.1111/1467-8330.00250

Johnstone, P. and Schot, J. (2023). Shocks, institutional change, and sustainability transitions. Proceedings of the National Academy of Sciences 120(47), e2206226120. https://doi.org/10.1073/pnas.2206226120

Juri, S., Terry, N. and Pereira, L.M. (2024). Demystifying food systems transformation: a review of the state of the field. Ecology and Society 29(2). https://doi.org/10.5751/ES-14525-290205

Kallis, G., Kostakis, V., Lange, S., Muraca, B., Paulson, S. and Schmelzer, M. (2018). Research on Degrowth. Annual Review of Environment and Resources 42, 291-316. https://doi.org/10.1146/annurev-environ-102017-025941

Kemp, R., Schot, J. and Hoogma, R. (1998). Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. Technology Analysis & Strategic Management 10(2), 175-198. https://doi.org/10.1080/09537329808524310

Kemp, R. and van Lente, H. (2011). The dual challenge of sustainability transitions. Environmental Innovation and Societal Transitions 1(1), 121-124. https://doi.org/10.1016/j.eist.2011.04.001

Kivimaa, P. and Kern, F. (2016). Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. Research Policy 45(1), 205-217. https://doi.org/10.1016/j.respol.2015.09.008

Kleinfeld, R. (2023). Polarization, Democracy, and Political Violence in the United States: What the Research Says. https://carnegieendowment.org/research/2023/09/polarization-democracy-and-political-violence-in-the-united-states-what-the-research-says?lang=en

Klitkou, A., Bolwig, S., Hansen, T. and Wessberg, N. (2015). The role of lock-in mechanisms in transition processes: The case of energy for road transport. Environmental Innovation and Societal Transitions 16, 22-37. https://doi.org/10.1016/j.eist.2015.07.005

Kok, K.P.W., Loeber, A.M.C. and Grin, J. (2021). Politics of complexity: Conceptualizing agency, power and powering in the transitional dynamics of complex adaptive systems. Research Policy 50(3), 104183. https://doi.org/10.1016/j.respol.2020.104183

Konrad, K. and Böhle, K. (2019). Socio-technical futures and the governance of innovation processes—An introduction to the special issue. Futures 109, 101-107. https://doi.org/10.1016/j.futures.2019.03.003

Kooiman, J. (2003). Governing as governance. SAGE

Kowarsch, M., Flachsland, C., Garard, J., Jabbour, J. and Riousset, P. (2017). The treatment of divergent viewpoints in global environmental assessments. Environmental Science & Policy 77, 225-234. https://doi.org/10.1016/j.envsci.2017.04.001

Krüger, T. (2022). The German energy transition and the eroding consensus on ecological modernization: A radical democratic perspective on conflicts over competing justice claims and energy visions. Futures 136, 102899. https://doi.org/10.1016/j.futures.2021.102899

Kuhlmann, S., Stegmaier, P. and Konrad, K. (2019). The tentative governance of emerging science and technology—A conceptual introduction. Research Policy 48(5), 1091-1097. https://doi.org/10.1016/j.respol.2019.01.006

Kuznets, S. (1955). Economic Growth and Income Inequality. The American Economic Review 45, 1-28

Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A. et al. (2019). An agenda for sustainability transitions research: State of the art and future directions. Environmental Innovation and Societal Transitions 31, 1-32. https://doi.org/10.1016/j.eist.2019.01.004

Lam, D.P.M., Martín-López, B., Wiek, A., Bennett, E.M., Frantzeskaki, N., Horcea-Milcu, A.I. et al. (2020). Scaling the impact of sustainability initiatives: a typology of amplification processes. Urban Transformations 2(1), 3. https://doi.org/10.1186/s42854-020-00007-9

Lam, D.P.M., Jiménez-Aceituno, A., Guerrero Lara, L., Sellberg, M., Norström, A., Moore, M. et al. (2022). Amplifying actions for food system transformation: insights from the Stockholm region. Sustainability Science 17(6), 2379-2395 https://doi.org/10.1007/s11625-022-01154-7

Le, V.T.H. (2024). Asymmetrical power relations and their influences on climate change adaptation and transformation in Vietnam. Asian Anthropology 23(2), 145-148. https://doi.org/10.1080/1683478X.2023.2292884

Lenton, T.M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W. and Schellnhuber, H.J. (2020). Climate tipping points – too risky to bet against. Nature 575, 592-595. https://doi.org/10.1038/d41586-019-03595-0.

Lenton, T.M., Xu, C., Abrams, J.F., Ghadiali, A., Loriani, S., Sakschewski, B. et al. (2023). Quantifying the human cost of global warming. Nature Sustainability 6(10), 1237-1247. https://doi.org/10.1038/s41893-023-01132-6.

Leonard-Barton, D. (1988). Implementation as mutual adaptation of technology and organization. Research Policy 17(5), 251-267. https://doi.org/10.1016/0048-7333(88)90006-6

Leventon, J., Abson, D.J. and Lang, D.J. (2021). Leverage points for sustainability transformations: nine guiding questions for sustainability science and practice. Sustainability Science 16(3), 721-726. https://doi.org/10.1007/s11625-021-00961-8

Liu, J., Dou, Y., Batistella, M., Challies, E., Connor, T., Friis, C. et al. (2018). Spillover systems in a telecoupled Anthropocene: typology, methods, and governance for global sustainability. Current Opinion in Environmental Sustainability 33, 58-69. https://doi.org/10.1016/j.cosust.2018.04.009

Lockwood, M. (2015). The political dynamics of green transformations: Feedback effects and institutional context. In The Politics of Green Transformation. Scoones, I. and Leach, M.N., Peter (eds.). Oxon: Routledge. 86-101. https://library.oapen.org/bitstream/id/37acb7c4-443f-4ea7-886b-e2c080d8a1d1/9781317601128.pdf

Loconto, A. (2024). State of the art: The impact of sustainability standards. Journal of Fair Trade 5(2), 127-140. https://doi.org/10.13169/jfairtrade.5.2.0127

Loorbach, D., Frantzeskaki, N. and Avelino, F. (2017). Sustainability Transitions Research: Transforming Science and Practice for Societal Change. Annual Review of Environment and Resources 42(1), 599-626. https://doi.org/10.1146/annurev-environ-102014-021340

Marín, A. (2023). Bringing Democracy to Governance of Mining for a Just Energy Transition Studies, I.o.D. IDS Policy Briefing 213. Brighton. https://www.ids.ac.uk/publications/bringing-democracy-to-governance-of-mining-for-a-just-energy-transition/

Markard, J., Raven, R. and Truffer, B. (2012). Sustainability transitions: An emerging field of research and its prospects. Research Policy 41(6), 955-967. https://doi.org/10.1016/j.respol.2012.02.01

Marletto, G., Franceschini, S., Ortolani, C. and Sillig, C. (2016). Mapping Sustainability Transitions: Networks of Innovators, Techno-economic Competences and Political Discourses. Springer

Marx, K. (1946). Capital: a Critical Analysis of Capitalist Production. London: Allen & Unwin

Matti, C, Bontoux, L. and Jensen, K. (2025). Strategic foresight framework for addressing agency in sustainability transitions: a co-creation approach. Frontiers in Sustainability 6. https://doi.org/10.3389/frsus.2025.1507708

Meadows, D.H. (1999). Leverage points: Places to Intervene in a System. The Sustainability Institute. https://donellameadows.org/wp-content/userfiles/Leverage_Points.pdf

Mondejar, M.E., Avtar, R., Baños Diaz, H.L., Kant Dubey, R., Esteban, J., Gómez-Morales, A. (2021). Digitalization to achieve sustainable development goals: Steps towards a Smart Green Planet. Science of The Total Environment 794, 148539. https://doi.org/10.1016/j.scitotenv.2021.148539

Moore, M.-L. and Milkoreit, M. (2020). Imagination and transformations to sustainable and just futures. Elementa: Science of the Anthropocene 8(1), 081. https://doi.org/10.1525/elementa.2020.081

Murphy, F. and McDonagh, P. (eds.) (2016). Envisioning Sustainabilities: Towards an Anthropology of Sustainability. Cambridge Scholars Publishing. https://www.cambridgescholars.com/product/978-1-4438-9537-8

Nadal, A. and Nazar-Beutelspacher, D.A. (2023). COVID-19: Solidarity initiatives for food security in the Mayan indigenous region of south-southeast Mexico. Global Food Security 37, 100697. https://doi.org/10.1016/j.gfs.2023.100697

Nassehi, A. (2021). Unbehagen: Theorie der überforderten Gesellschaft. C.H. Beck. https://www.chbeck.de/nassehi-unbehagen/product/32390717

Nassehi, A. (2024). Kritik der großen Geste: Anders über gesellschaftliche Transformation nachdenken.: C.H. Beck. https://www.chbeck.de/nassehi-kritik-grossen-geste/product/37000397

Nelson, R.R. and Winter, S.G. (1982). An Evolutionary Theory of Economic Change. Harvard University Press

Nelson, V., Garner, B. and Prado Cordova, J.P. (2024). Exploring decolonial and relational paths to sustainability. Global Social Challenges Journal 3(2). https://doi.org/10.1332/27523349Y2024D000000031

Newig, J., Jager, N.W., Kochskämper, E. and Challies, E. (2019). Learning in participatory environmental governance – its antecedents and effects. Findings from a case survey meta-analysis. Journal of Environmental Policy & Planning 21(3), 213-227. https://doi.org/10.1080/1523908X.2019.1623663

Nieuwe Instituut (2021). Introducing Zooeps. https://nieuweinstituut.nl/en/projects/who-is-we/zoop. Accessed: 12 June 2025

Nilsson, M. and Nykvist, B. (2016). Governing the electric vehicle transition – Near term interventions to support a green energy economy. Applied Energy 179, 1360-1371. https://doi.org/10.1016/j.apenergy.2016.03.056

O'Brien, K. (2012). Global environmental change II: From adaptation to deliberate transformation. Progress in Human Geography 36(5), 667-676. https://doi.org/10.1177/0309132511425767

O'Brien, K. (2018). Is the 1.5°C target possible? Exploring the three spheres of transformation. Current Opinion in Environmental Sustainability 31, 153-160. https://doi.org/10.1016/j.cosust.2018.04.010

Olsson, P., Folke, C. and Hahn, T. (2004). Social-Ecological Transformation for Ecosystem Management: the Development of Adaptive Co-management of a Wetland Landscape in Southern Sweden. Ecology & Society 9(4). http://www.ecologyandsociety.org/vol9/iss4/art2/

Olsson, P. and Moore, M.-L. (2024). A resilience-based transformations approach to peacebuilding and transformative justice. Current Opinion in Environmental Sustainability 66, 101392. https://doi.org/10.1016/j.cosust.2023.101392

Oomen, J., Hoffman, J. and Hajer, M.A. (2022). Techniques of futuring: On how imagined futures become socially performative. European Journal of Social Theory 25(2), 252-270. https://doi.org/10.1177/1368431020988826

Organisation for Economic Co-operation and Development (2023). OECD Science, Technology and Innovation Outlook 2023: Enabling Transitions in Times of Disruption. OECD Publishing, Paris. https://doi.org/10.1787/0b55736e-en

Organisation for Economic Co-operation and Development (2024). OECD Agenda for Transformative Science, Technology and Innovation Policies. https://www.oecd-ilibrary.org/science-and-technology/oecd-agenda-for-transformative-science-technology-and-innovation-policies_ba2aaf7b-en

Pascual, U., Adams, W.M., Díaz, S., Lele, S., Mace, G.M. and Turnhout, E. (2021). Biodiversity and the challenge of pluralism. Nature Sustainability 4(7), 567-572. https://doi.org/10.1038/s41893-021-00694-7

Patterson, J., Schulz, K., Vervoort, J., van der Hel, S., Widerberg, O., Adler, C. et al. (2017). Exploring the governance and politics of transformations towards sustainability. Environmental Innovation and Societal Transitions 24, 1-16. https://doi.org/10.1016/j.eist.2016.09.001

Pereira, L.M., Karpouzoglou, T., Frantzeskaki, N. and Olsson, P. (2018). Designing transformative spaces for sustainability in social-ecological systems. Ecology and Society 23(4). https://www.jstor.org/stable/26796848

Pereira, L., Sitas, N., Ravera, F., Jimenez-Aceituno, A. and Merrie, A. (2019). Building capacities for transformative change towards sustainability: Imagination in Intergovernmental Science-Policy Scenario Processes. Elementa: Science of the Anthropocene 7. https://doi.org/10.1525/elementa.374

Pereira, L.M., Davies, K.K., den Belder, E., Ferrier, S., Karlsson-Vinkhuyzen, S., Kim, H. et al. (2020). Developing multiscale and integrative nature–people scenarios using the Nature Futures Framework. People and Nature 2(4), 1172-1195. https://doi.org/10.1002/pan3.10146

Pereira, L., Asrar, G.R., Bhargava, R., Fisher, L.H., Hsu, A., Jabbour, J. et al. (2021). Grounding global environmental assessments through bottom-up futures based on local practices and perspectives. Sustainability Science 16(6), 1907-1922. https://doi.org/10.1007/s11625-021-01013-x

Pereira, L.M., Ortuño Crespo, G., Amon, D.J., Badhe, R., Bandeira, S., Bengtsson, F. et al. (2023). The living infinite: Envisioning futures for transformed human-nature relationships on the high seas. Marine Policy 153, 105644. https://doi.org/10.1016/j.marpol.2023.105644

Pereira, L.M., Gianelli, I., Achieng, T., Amon, D., Archibald, S., Arif, S. et al. (2024). Equity and justice should underpin the discourse on tipping points. Earth System Dynamics 15(2), 341-366. https://doi.org/10.5194/esd-15-341-2024

Perez, C. (2003). Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages. Cheltenham: Edward Elgar

Perez, C. (2010). Technological revolutions and techno-economic paradigms. Cambridge Journal of Economics 34(1), 185-202. https://doi.org/10.1093/cje/bep051

Pérez, C. and Claveria, O. (2020). Natural resources and human development: Evidence from mineral-dependent African countries using exploratory graphical analysis. Resources Policy 65, 101535. https://doi.org/10.1016/j.resourpol.2019.101535

Perrow, C. (1997). Organizing for Environmental Destruction. Organization & Environment 10(1), 66-72. https://doi.org/10.1177/0921810697101009

Pierson, P. (2000). Increasing Returns, Path Dependence, and the Study of Politics. The American Political Science Review 94(2), 251-267. https://doi.org/10.2307/2586011

Polanyi, K. (1944). The great transformation: The political and economic origins of our time. Boston: Beacon Press

Puig de la Bellacasa, M. (2017). Matters of Care: Speculative Ethics in More than Human Worlds. University of Minnesota Press

Rathod, R. V. (2023). Enhancing Resource Use Efficiency in Agriculture through Sustainable Practices and Technological Innovations. In Advanced Farming Techniques. Publisher: BS Global Publication House. Chapter 1. 1-22.

Raven, R., Kern, F., Verhees, B. and Smith, A. (2016). Niche construction and empowerment through socio-political work. A meta-analysis of six low-carbon technology cases. Environmental Innovation and Societal Transitions 18, 164-180. https://doi.org/10.1016/j.eist.2015.02.002

Reusswig, F., Braun, F., Heger, I., Ludewig, T., Eichenauer, E. and Lass, W. (2016). Against the wind: Local opposition to the German Energiewende. Utilities Policy 41, 214-227. https://doi.org/10.1016/j.jup.2016.02.006

Rhodes, R.A.W. (1997). Understanding Governance: Policy Networks, Governance, Reflexivity and Accountability. Buckingham, Open University Press. https://eprints.soton.ac.uk/336524/

Richard, S., Pellerin, R., Bellemare, J. and Perrier, N. (2020). A business process and portfolio management approach for Industry 4.0 transformation. Business Process Management Journal 27(2), 505-528. https://doi.org/10.1108/BPMJ-05-2020-0216

Roberts, C., Geels, F.W., Lockwood, M., Newell, P., Schmitz, H., Turnheim, B. et al. (2018). The politics of accelerating low-carbon transitions: Towards a new research agenda. Energy Research & Social Science 44, 304-311. https://doi.org/10.1016/j.erss.2018.06.001

Rocha, J., Lanyon, C. and Peterson, G. (2022). Upscaling the resilience assessment through comparative analysis. Global Environmental Change 72, 102419. https://doi.org/10.1016/j.gloenvcha.2021.102419

Rockström, J., Gupta, J., Qin, D., Lade, S.J., Abrams, J.F., Andersen, L.S. et al. (2023). Safe and just Earth system boundaries. Nature 619(7968), 102-111. https://doi.org/10.1038/s41586-023-06083-8

Rogers, E.M. (1995). Diffusion of Innovations: Modifications of a Model for Telecommunications. In Die Diffusion von Innovationen in der Telekommunikation. Stoetzer, M.-W. and Mahler, A. (eds.). Berlin, Heidelberg: Springer Berlin Heidelberg. 25-38. https://doi.org/10.1007/978-3-642-79868-9_2

Rohrbeck, R., Battistella, C. and Huizingh, E. (2015). Corporate foresight: An emerging field with a rich tradition. Technological Forecasting and Social Change 101, 1-9. https://doi.org/10.1016/j.techfore.2015.11.002

Rommel, J., Radtke, J., von Jorck, G., Mey, F. and Yildiz, Ö. (2018). Community renewable energy at a crossroads: A think piece on degrowth, technology, and the democratization of the German energy system. Journal of Cleaner Production 197, 1746-1753. https://doi.org/10.1016/j.jclepro.2016.11.114

Rossi, A., Coscarello, M. and Biolghini, D. (2021). (Re)Commoning Food and Food Systems. The Contribution of Social Innovation from Solidarity Economy. Agriculture 11(6), 548

Russell-Smith, J., Yates, C., Vernooij, R., Eames, T., van der Werf, G., Ribeiro, N. et al. (2021). Opportunities and challenges for savanna burning emissions abatement in southern Africa. Journal of Environmental Management 288, 112414. https://doi.org/10.1016/j.jenvman.2021.112414

Sajeva G., Borrini-Feyerabend, G., Niederberger, T. (2019). Meanings and more... Policy Brief of the ICCA Consortium no. 7. https://www.iccaconsortium.org/wp-content/uploads/2019/11/ICCA-Briefing-Note-7-Final-for-websites.pdf

Samman, A. (2015). Crisis theory and the historical imagination. Review of International Political Economy 22(5), 966-995. https://doi.org/10.1080/09692290.2015.1011682

Sareen, S., Smith, A., Gantioler, S., Balest, J., Brisbois, M.C., Tomasi, S. et al. (2023). Social implications of energy infrastructure digitalisation and decarbonisation. Buildings and Cities. https://doi.org/10.5334/bc.292

Schlosberg, D. and Carruthers, D. (2010). Indigenous Struggles, Environmental Justice, and Community Capabilities. Global Environmental Politics 10(4), 12-35. https://doi.org/10.1162/GLEP_a_00029

Schot, J. (2016). Confronting the Second Deep Transition through the Historical Imagination. Technology and Culture 57(2), 445-456. https://doi.org/10.1353/tech.2016.0044

Schot, J. and Geels, F.W. (2007). Niches in evolutionary theories of technical change. Journal of Evolutionary Economics 17(5), 605-622. https://doi.org/10.1007/s00191-007-0057-5

Sciullo, A.W., August, Arrobbio, O., Delvaux, S., Gilcrease, G., Gregg, J., Henfrey, T. et al. (2020). Collective Action Initiatives in the Energy Transition. Supporters of a strong sustainability paradigm? In Paradigms, Models, Scenarios and Practices for Strong Sustainability. Diemer, A.N., Eduard Schellens, Marie and Morales, M.O., Maartje (eds.). Editions Oeconomia. 257-272. https://findit.dtu.dk/en/catalog/5eb43092d9001d013c76126d

Scoones, I. and Stirling, A. (2020). The Politics of Uncertainty: Challenges of Transformation. London: Routledge

Scoones, I., Stirling, A., Abrol, D., Atela, J., Charli-Joseph, L., Eakin, H. et al. (2020). Transformations to sustainability: combining structural, systemic and enabling approaches. Current Opinion in Environmental Sustainability 42, 65-75. https://doi.org/10.1016/j.cosust.2019.12.004

Seddon, N., Chausson, A., Berry, P., Girardin, C.A.J., Smith, A. and Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philosophical Transactions of the Royal Society B 375(20190120). https://doi.org/10.1098/rstb.2019.0120

Sellberg, M.M., Norström, A.V., Peterson, G.D. and Gordon, L.J. (2020). Using local initiatives to envision sustainable and resilient food systems in the Stockholm city-region. Global Food Security 24, 100334. https://doi.org/10.1016/j.gfs.2019.100334

Selomane, O., Fourie, M., Archibald, S., Pereira, L., Sitas, N. and Zoeller, K. (2025). Public finance allocation does not reflect biodiversity priorities. Current Opinion in Environmental Sustainability 74, 101524. https://doi.org/10.1016/j.cosust.2025.101524

Sen, A. (1983). Choice, Welfare, and Measurement. Oxford: Basil Blackwell.

Sen, A. (2002). Rationality and Freedom. London: The Belknap Press of Harvard University Press

Sewell Jr., W.H. (2005). Logics of History: Social Theory and Social Transformation. Chicago: The University of Chicago Press. https://press.uchicago.edu/ucp/books/book/chicago/L/bo3533904.html

Sheller, M. and Urry, J. (2000). The City and the Car. International Journal of Urban and Regional Research 24(4), 737-757. https://doi.org/10.1111/1468-2427.00276

Sheller, M. and Urry, J. (2016). Mobilizing the new mobilities paradigm. Applied Mobilities 1(1), 10-25. https://doi.org/10.1080/23800127.2016.1151216

Slater, K. and Robinson, J. B. (2020). Social Learning and Transdisciplinary Co-Production: A Social Practice Approach. Sustainability 12(18), 7511. https://doi.org/10.3390/su12187511

Smith, A. and Raven, R. (2012). What is protective space? Reconsidering niches in transitions to sustainability. Research Policy 41(6), 1025-1036. https://doi.org/10.1016/j.respol.2011.12.012.

Somashekar, K.S., Abhishek, G.J., Kumar, V., Tiwari, A., Lakra, T.S., Chauhan, B. et al. (2024). Agroecology Principles, Practices and their Impact on Sustainable Food Systems. European Journal of Nutrition & Food Safety 16(9), 249-260. https://doi.org/10.9734/ejnfs/2024/v16i91544

Sovacool, B.K. (2016). How long will it take? Conceptualizing the temporal dynamics of energy transitions. Energy Research & Social Science 13, 202-215. https://doi.org/10.1016/j.erss.2015.12.020

Sovacool, B.K., Hook, A., Martiskainen, M., Brock, A. and Turnheim, B. (2020). The decarbonisation divide: Contextualizing landscapes of low-carbon exploitation and toxicity in Africa. Global Environmental Change 60, 102028. https://doi.org/10.1016/j.gloenvcha.2019.102028

Stammer, D., Martins, M.S., Köhler, J. and Köhl, A. (2021). How well do we know ocean salinity and its changes? Progress in Oceanography 190, 102478. https://doi.org/10.1016/j.pocean.2020.102478

Stein, S., Ahenakew, C., Valley, W., Sherpa, P., Crowson, E., Robin, T. et al. (2024). Toward more ethical engagements between Western and Indigenous sciences. FACETS 9, 1-14. https://doi.org/10.1139/facets-2023-0071

Steward, F. (2009). Tensions, Paradox, and Contradictions in Managing Innovation. In Managing and Shaping Innovation. Conway, S. and Steward, F. (Eds.). Oxford: Oxford University Press. https://researchportal.bath.ac.uk/en/publications/managing-and-shaping-innovation

Stilgoe, J., Owen, R. and Macnaghten, P. (2013). Developing a framework for responsible innovation. Research Policy 42(9), 1568-1580. https://doi.org/10.1016/j.respol.2013.05.008.

Stirling, A. (2010). Keep it complex. Nature 468(7327), 1029-1031. https://doi.org/10.1038/4681029a

Stirling, A. (2019). How deep is incumbency? A 'configuring fields' approach to redistributing and reorienting power in socio-material change. Energy Research & Social Science 58, 101239. https://doi.org/10.1016/j.erss.2019.101239

Stirling, A. (2023). Against misleading technocratic precision in research evaluation and wider policy – A response to Franzoni and Stephan (2023), 'uncertainty and risk-taking in science'. Research Policy 52(3), 104709. https://doi.org/10.1016/j.respol.2022.104709

Stockholm Resilience Centre (2016). Insight #1 Transformation. Resilience thinking can help us understand how to initiate and navigate large-scale transformations in social-ecological systems. https://www.stockholmresilience.org/download/18.3e9bddec1373daf16fa437/1459560363279/INsights_Transformations_111214-2.pdf

Streeck, W. and Thelen, K. (2005). Beyond Continuity: Institutional Change in Advanced Political Economies. Oxford University Press. https://EconPapers.repec.org/RePEc:oxp:obooks:9780199280469

Sumaila, U.R., Alam, L., Abdallah, P.R., Aheto, D., Akintola, S.L., Alger, J. et al. (2024). WTO must complete an ambitious fisheries subsidies agreement. npj Ocean Sustainability 3(1), 6. https://doi.org/10.1038/s44183-024-00042-0

Sumaila, U.R., Ebrahim, N., Schuhbauer, A., Skerritt, D., Li, Y., Kim, H.S. et al. (2019). Updated estimates and analysis of global fisheries subsidies. Marine Policy 109, 103695. https://doi.org/10.1016/j.marpol.2019.103695

Svenfelt, Å., Alfredsson, E.C., Bradley, K., Fauré, E., Finnveden, G., Fuehrer, P. et al. (2019). Scenarios for sustainable futures beyond GDP growth 2050. Futures 111, 1-14. https://doi.org/10.1016/j.futures.2019.05.001

Swilling, M. (2020). The age of sustainability: Just transitions in a complex world. Routledge. https://www.routledge.com/The-Age-of-Sustainability-Just-Transitions-in-a-Complex-World/Swilling/p/book/9780367178161

Terry, N., Castro, A., Chibwe, B., Karuri-Sebina, G., Savu, C. and Pereira, L. (2024). Inviting a decolonial praxis for future imaginaries of nature: Introducing the Entangled Time Tree. Environmental Science & Policy 151, 103615. https://doi.org/10.1016/j.envsci.2023.103615

Tienhaara, K. (2014). Varieties of green capitalism: economy and environment in the wake of the global financial crisis. Environmental Politics 23(2), 187-204. https://doi.org/10.1080/09644016.2013.821828

Tomor, Z., Meijer, A., Michels, A. and Geertman, S. (2019). Smart Governance For Sustainable Cities: Findings from a Systematic Literature Review. Journal of Urban Technology 26(4), 3-27. https://doi.org/10.1080/10630732.2019.1651178

Truffer, B. (2008). Society, Technology, and Region: Contributions from the Social Study of Technology to Economic Geography. Environment and Planning A: Economy and Space 40(4), 966-985. https://doi.org/10.1068/a39170

Tuckey, A.J., Harmáčková, Z.V., Peterson, G.D., Norström, A.V., Moore, M.-L., Olsson, P. et al. (2023). What factors enable social-ecological transformative potential? The role of learning practices, empowerment, and networking. Ecology and Society 28(2). https://doi.org/10.5751/ES-14163-280227

Turnheim, B. (2023). The historical dismantling of tramways as a case of destabilisation and phase-out of established system. Proceedings of the National Academy of Sciences 120(47), e2206227120. https://doi.org/10.1073/pnas.2206227120

Turnheim, B., Berkhout, F., Geels, F., Hof, A., McMeekin, A., Nykvist, B. et al. (2015). Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. Global Environmental Change 35, 239-253. https://doi.org/10.1016/j.gloenvcha.2015.08.010

Turnheim, B. and Nykvist, B. (2019). Opening up the feasibility of sustainability transitions pathways (STPs): Representations, potentials, and conditions. Research Policy 48(3), 775-788. https://doi.org/10.1016/j.respol.2018.12.002

Turnheim, B. and Sovacool, B.K. (2020). Forever stuck in old ways? Pluralising incumbencies in sustainability transitions. Environmental Innovation and Societal Transitions 35, 180-184. https://doi.org/10.1016/j.eist.2019.10.012

United Nations (2019). Global Sustainable Development Report. https://sdgs.un.org/sites/default/files/2020-07/24797GSDR_report_2019.pdf

United Nations (2023). Global Sustainable Development Report. https://sdgs.un.org/sites/default/files/2023-06/Advance%20unedited%20GSDR%2014June2023.pdf

United Nations Conference of Trade and Development (2019). A Framework for Science, Technology and Innovation Policy Reviews: Harnessing innovation for sustainable development. United Nations, Geneva https://unctad.org/system/files/official-document/dtlstict2019d4_en.pdf

United Nations Development Programme. (2022). Human development report 2021/2022: Uncertain times, unsettled lives—Shaping our future in a transforming world. United Nations Development Programme. https://hdr.undp.org/content/human-development-report-2021-22

United Nations Development Programme, United Nations Office on Drugs and Crime and Office of the United Nations High Commissioner for Human Rights (2024). Global Progress Report of Sustainable Development Goal 16 Indicators. At the Crossroads: Breakdowns or Breakthroughs for Peace, Justice and Strong Institutions. https://www.undp.org/publications/2nd-global-progress-report-sdg-16-indicators

United Nations for Economic and Social Commission for Asia and the Pacific, The Asian Development Bank and The United Nations Development Programme (2018). Transformation towards Sustainable and Resilient Societies in Asia and the Pacific. Bangkok, Thailand: United Nations. https://www.adb.org/publications/sustainable-resilient-societies-asia-pacific

United Nations Educational, Scientific and Cultural Organization and International Social Science Council (2013). World Social Science Report: Changing Global Environments. https://en.unesco.org/wssr2013

United Nations Environment Programme (2011). Decoupling: natural resource use and environmental impacts from economic growth. https://www.unep.org/resources/report/decoupling-natural-resource-use-and-environmental-impacts-economic-growth

United Nations Environment Programme (2019). Global Environment Outlook GEO-6: Healthy Planet, Healthy People. https://www.unep.org/resources/global-environment-outlook-6

United Nations Environment Programme (2021a). Making Peace with Nature: A scientific blueprint to tackle the climate, biodiversity and pollution emergencies. Nairobi. https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/34948/MPN.pdf

United Nations Environment Programme (2021b). The growing footprint of digitalisation. https://wedocs.unep.org/bitstream/handle/20.500.11822/37439/FB027.pdf

United Nations Environment Programme (2024). Global Resources Outlook. Global Resources Outlook 2024 | UNEP - UN Environment Programme

Unruh, G.C. (2002). Escaping carbon lock-in. Energy Policy 30(4), 317-325. https://doi.org/10.1016/S0301-4215(01)00098-2

van Lente, H. (2012). Navigating foresight in a sea of expectations: lessons from the sociology of expectations. Technology Analysis & Strategic Management 24(8), 769-782. https://doi.org/10.1080/09537325.2012.715478

Veldman, J.W., Aleman, J.C., Alvarado, S.T., Anderson, T.M., Archibald, S., Bond, W.J. et al. (2019). Comment on "The global tree restoration potential". Science 366(6463), eaay7976. https://doi.org/10.1126/science.aay7976

Vervoort, J. and Gupta, A. (2018). Anticipating climate futures in a 1.5°C era: the link between foresight and governance. Current Opinion in Environmental Sustainability 31, 104-111. https://doi.org/10.1016/j.cosust.2018.01.004

Villasante, S., Macho, G., Silva, M.R.O., Lopes, P.F.M., Pita, P., Simón, A. et al. (2022). Resilience and Social Adaptation to Climate Change Impacts in Small-Scale Fisheries. Frontiers in Marine Science 9. https://doi.org/10.3389/fmars.2022.802762.

Vogel, J., Steinberger, J.K., O'Neill, D.W., Lamb, W.F. and Krishnakumar, J. (2021). Socio-economic conditions for satisfying human needs at low energy use: An international analysis of social provisioning. Global Environmental Change 69, 102287. https://doi.org/10.1016/j.gloenvcha.2021.102287

Vögele, S., Kunz, P., Rübbelke, D. and Stahlke, T. (2018). Transformation pathways of phasing out coal-fired power plants in Germany. Energy, Sustainability and Society 8(1), 25. https://doi.org/10.1186/s13705-018-0166-z

Walker, B., Holling, C.s., Carpenter, S. and Kinzig, A. (2004). Resilience, Adaptability and Transformability in Social-Ecological Systems. Ecology and Society 9(2). https://doi.org/10.5751/ES-00650-090205.

World Economic Forum (2023a). Fostering Effective Energy Transition. https://www3.weforum.org/docs/WEF_Fostering_Effective_Energy_Transition_2023.pdf

World Economic Forum (2023b). Annual Report 2022-2023. https://www.weforum.org/publications/annual-report-2022-2023/

Watene, K. (2016). Valuing nature: Māori philosophy and the capability approach. Oxford Development Studies 44(3), 287-296. https://doi.org/10.1080/13600818.2015.1124077

Wells, P.E. (2023). System confluence and the reinvention of automobility. Proceedings of the National Academy of Sciences 120(47), e2206233119. https://doi.org/10.1073/pnas.2206233119

Westley, F. (2013). Social innovation and resilience: how one enhances the other. Stanford Social Innovation Review 11(3), A6-A8. https://doi.org/10.48558/X1BZ-AK47

Westley, F., Olsson, P., Folke, C., Homer-Dixon, T., Vredenburg, H., Loorbach, D. et al. (2011). Tipping Toward Sustainability: Emerging Pathways of Transformation. Ambio 40(7), 762-780. https://doi.org/10.1007/s13280-011-0186-9

Westley, F., Tjornbo, O., Schultz, L., Olsson, P., Folke, C., Crona, B. et al. (2013). A Theory of Transformative Agency in Linked Social-Ecological Systems. Ecology and Society 18. https://doi.org/10.5751/ES-05072-180327.

Zomer, R.J., Trabucco, A., Bossio, D.A. and Verchot, L.V. (2008). Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. Agriculture, Ecosystems & Environment 126(1), 67-80. https://doi.org/10.1016/j.agee.2008.01.014

13 Methodology for Developing Solution Pathways Towards System Transformations

Coordinating Lead Authors: Parfait M. Eloundou-Enyegue (Cornell University), Henri Rueff (Centre for Development and Environment, University of Bern)

Lead Authors: Joanna Kámiche Zegarra (Universidad del Pacífico), Annamaria Lammel (Université Paris 8 Vincennes-Saint Denis), Aynur Mammadova (University of Padova), Sarah-Lan Mathez-Stiefel (Centre for Development and Environment, University of Bern/Wyss Academy for Nature at the University of Bern), Thang Nguyen Trung (Institute of Strategy and Policy on Agriculture and Environment), Karachepone N. Ninan (Centre for Economics, Environment and Society - CEES)

Contributing Author: Julia Hammann (Food and Agriculture Organization of the United Nations)

Fellows: Claude Mbarga Ella (IFORD), Zhuang Han (Cornell University/The London School of Economics and Political Science)

Credit: Anna_Om/Envato

Chapter summary

Credit: leungchopan/Envato

Global decision makers need a systemic approach to address the global environmental crises of climate change, biodiversity loss, land degradation and desertification, pollution and waste, and their intersections. The economic and financial, energy, food, material resources and environmental systems driving these environmental crises are interconnected and therefore require integrative and systemic transformation. Such a transformation of the current systems would alleviate their adverse effects on the environment and the human population, while further improving their sustainability and resiliency to future shocks and disruptions. The transformation needs to effectively integrate, among other factors, knowledge about climate change, including scenarios, trajectories, and adaptation options. This chapter proposes a 7-step methodology to guide such a system transformation {13.8}.

The proposed methodology addresses a pressing policy need to accelerate the pace of change *(well established but incomplete)*. It supports a paradigm shift from evolution to transformation, at a time when environmental crises are deepening, in part because past methods have failed to yield the desired results. These past failures have been tied to a lack of strong institutions and legislation, insufficient financial resources and infrastructure, weak enforcement capacity, difficulties in changing habits, values and lifestyles towards sustainable consumption patterns, and vested interests {13.2.1,13.2.2}. Breaking away from the past, this chapter presents a new framework for designing and implementing interventions to drive system transformations. Developing transformative solution pathways requires fundamentally new ways of thinking and acting. For this reason, operational steps for the roll out of solution pathways were developed, based on theoretically grounded requirements for system transformation (12.3). This framework is designed to be future-proof, anticipating challenges, complexities, and the implications of system transformations.

This 7-step methodology is adaptive and integrates interdependencies – synergies and trade-offs – between and within systems. Through an iterative, holistic decision-making process, it attends to the possible effects of resistance, shocks and risks, and provides guidance in designing transformative solution pathways. It is organized to identify the system goals, solutions, levers, actors, and actions to be taken. **Figure 13.1** illustrates how principles and steps are jointly articulated to serve these purposes {13.6}.

The proposed methodology accommodates operational environment uncertainty. Given the current global instability and the decline of democratic institutions, the governance of system transformations cannot rely unconditionally on strong institutions, democracy, stable economies, and peace. Systems transformations must be able to operate under shocks and crises {13.2}.

The methodology underscores the benefits of action, which largely exceed the costs of inaction *(well established)*. The costs of inaction in addressing the climate change, biodiversity loss, land degradation and desertification, and pollution crises are immense. Without accelerated mitigation efforts, such as the rapid deployment of offshore wind farms, and adaptation measures, such as fast-tracking a programme to retrofit cities with nature-based solutions against floods, the world is on track to breach the temperature limits set by the Paris Agreement. Global gross domestic product (GDP) is likely to decrease by 2.6 to 4.2 per cent by 2050 in pathways that fail to limit warming to 1.5°C above pre-industrial levels. Air pollution is responsible for approximately 6.7 million premature deaths annually, with annual health costs of around 6.1 per cent of global GDP. Global land degradation continues unabated and is estimated to cost more than 10 per cent of the annual global GDP in terms of the loss of biodiversity and ecosystem services. While there are winners and losers in any system transformation at different temporal scales, society as a whole will benefit in the long-term more from transformation than not. This methodology addresses the complexity of the actors involved and strives to ensure that no one is left behind {13.2, 13.8.7}.

The methodology links theory to practice *(well established)*. It does so by linking the six principles outlined in the theory chapter to the 7-step methodology clustered into three groups that closely match the three phases of the X-curve (**Figure 13.2**), that is, activation, acceleration, and completion of the transformation, and the seven steps in the Goal-Solution-Lever framework. Specifically, the first phase in the X-curve, where levers are activated and barriers to transformation are removed up to a tipping point, is linked to the methodology's cluster of levers/actions/actors (L) that activate the transformation process. The second phase in the X-curve of transformation, where positive change is accelerated and the old system breaks down, is linked to the methodology's cluster that is about finding solutions (S). It includes a turnover point when the new system overtakes the old. The third phase in the transformation, which is about the stabilization of the new/phase-out of the old system, is linked to the methodology's steps that are about setting goals (G). Ultimately, the methodology links a theoretical understanding of the transformation process to the practical design of solution pathways that accelerate sustainable systems and destabilize unsustainable ones. In particular, it shows how transformation is activated by a systematic inventory of solutions from multiple and complementary sources, and it specifically informs the activation of the process with the full range of possible levers, actors, actions and their interactions {13.3, 13.6, 13.7, 13.8}.

The methodology recognizes interdependencies across systems and interactions within systems *(well established)*. The sustainable development goals (SDGs) are by nature designed for systemic interactions. Integrating these interactions – including trade-offs and co-benefits – in policymaking can reduce costs by selecting the most efficient policy options, in which trade-offs are minimized, and co-benefits are maximized. For example, making renewable energy accessible to all can help alleviate poverty as a co-benefit. We make interdependencies a central element in our methodology. We consider within-system interactions in the selection of actions and solution pathways. Yet we also consider interdependencies across systems, with vicious cycles or trade-offs having a destabilizing effect and virtuous cycles or co-benefits a reinforcing one {13.4, 13.5, 13.8}.

The methodology facilitates systemic planning by addressing all aspects of a system's complexity *(well established)*. It helps plan differently, in ways that are systemic, holistic, adaptive, multi-scalar, multi-temporal, and inclusive. Systemic and holistic planning means recognizing current environmental crises as multidimensional and interconnected. Adaptive planning means anticipating and nimbly addressing

the likely resistances and new challenges throughout the implementation phases of the solution pathways; multi-scalar planning connects local actors to global actors and their institutions, and multi-temporal planning recognizes the need to address short- and longer-term processes. Finally, inclusive planning means reconciling the contributions, competing interests, and diverse views of multiple actors in society, including Indigenous Peoples, local communities, vulnerable populations, and the younger generation. This implies incorporating those actors in the co-creation and use of knowledge {13.6, 13.8}.

The methodology recognizes the contribution of Indigenous Knowledge and Local Knowledge, as well as their own decision-making practices in understanding and addressing environmental challenges *(well established)*. The solution pathways for transformation require consideration of the specific knowledge, worldviews, values, ethics, and long-term practices of Indigenous Peoples and communities which have a historical connection with place and nature. Indigenous Peoples govern formally or customarily at least a quarter of the world's terrestrial surface. When designing solutions for system transformation, it is essential to respect their territorial rights, values and practices {13.4}.

The methodology embeds adaptivity to future-proof transformation pathways against unexpected shocks *(well established)*. Our ensemble of solution pathways is geographically nuanced and is not expected to remain static. It is designed to be flexible and adaptive, allowing for adjustments if the problem to be solved becomes more complex over time or if unexpected shocks and crises arise. For example, agricultural intensification was the model implemented in many countries in the past to increase productivity and feed a growing population. The concept of food security, however, has since evolved beyond intensification towards quality, affordable and nutritious food for all, while conserving soil and the environment. Intensification alone, with the use of pesticides, fertilizers and mechanization, is no longer enough to address the complex food challenges of today. Transforming the food system in the 21st century requires seeking new solution pathways that address a complex set of interdependent challenges. Transformative solutions also consider the accelerating adverse effects, risks, and adaptation needs associated with climate change {13.8}.

The methodology proposes a sequential but adaptive 7-step process. It includes setting goals, reviewing past solutions, identifying the set of solution pathways to be designed, evaluating the identified solutions considering the local context, defining the combination of levers, identifying the options for short- and medium-term actions, and defining actors, their roles and interactions. The 7 steps have an integrated time sequence: as challenges change, the solution pathways adapt to the new realities, ensuring that goals are attained. The inclusion of adaptable responses to shocks of any sort, for example, pandemics, conflicts, economic, and environmental, must be part of the design of the solution pathways {13.6, 13.8, 13.9}.

The methodology proposes a built-in process of continuous evaluation *(well established)*. The methodology begins with a rigorous ex-ante evaluation of solutions, based on the 6 principles (Chapter 12), and integrates monitoring and evaluation throughout the process, allowing for the necessary changes to achieve the proposed goals. Policy makers are invited to test their ensemble of solution pathways ex-ante in order to future-proof them against shocks and anticipate the need to make changes during the process. For instance, the COVID-19 pandemic severely affected the world economy, significantly slowing down progress towards the SDGs. Other shocks for which an adaptive methodology is needed include the increased intensity and frequency of climate extremes that continue to affect billions of people globally with recurrent hazards {13.5, 13.6, 13.8, 13.9, Appendix 13.1}.

The proposed methodology is applied in Chapters 14–18, which focus on economics/finance, materials and waste, energy, food and environment *(well established)*. It is also applied to transforming the way the environment is managed to create resilient environmental systems for nature, energy, food and materials. The goal is to demonstrate how these systems can be transformed simultaneously while leveraging synergies and minimizing unintended consequences {13.8, 13.9}.

Credit: JuiceFlair/Envato

13.1 Introduction

This chapter proposes a methodology for solution pathways towards transformation designed to structure the report's progression from theory to solutions. It serves four main purposes, namely to: a) guide the subsequent systems chapters' efforts to identify viable pathways to transformation; b) build consistency across system chapters in their identification and description of solutions; c) link the proposed solutions to the theory of transformation, based on the 6 principles, outlined in Chapter 12; and d) support policy makers in building their own solution pathway in a specific context.

Abstracting from its details, the X-curve presented serves as a visual model of the transformation processes for raising desirable systems and destabilizing undesirable ones. It breaks down the transformation process into three stages, namely: activation, take-off (metamorphosis), and completion. For the sake of consistency, this three-stage description of theory is also adopted in the description of the methodology. Thus, in linking transformation theory to solutions, this methodology is built around these three stages of transformation:

- Stage I – referred to as the Levers, including the conditions, levers, and actors
- Stage II – referred to as the Solution, is about the form, momentum, and pace of transformation
- Stage III – referred to as the Goal, is about the outcomes of the transformation.

This framework is used to discuss not only the key steps but also the tools and basic principles to follow in designing a viable solution pathway (13.8).

The rest of the chapter progresses as follows. Key concepts and processes, including solution pathways, levers, actions, and policies, are defined. Then the methodological framework, specifically how the steps, tools, and common principles are considered in the design of solutions, is presented and discussed. This is then followed with a stage-by-stage description of the 7-step methodology. The first stage receives the most extensive discussion, especially in reviewing the key actors, levers, and enabling conditions. Specific examples are provided, including international successes and failures, and their contextual conditions. Evaluation criteria are provided in the last methodological step, to

assess whether a solution pathway is plausible, feasible and effective, meaning it will accomplish the proposed goals. This ex-ante evaluation will assess the solution's capacity to deliver results and to navigate the social, political, economic, and technological tensions and trade-offs expected.

In order to establish the 7-step methodology and how actors, levers, solutions, and actions interplay, certain foundational assumptions must be laid out to facilitate the logical flow of this chapter. Among these, adoption and uptake mechanisms are reviewed, including the costs of inaction and the benefits of action. By costing some of the global environmental crises, and putting a monetary value on them, awareness can be raised among actors and policy makers, strengthening the commitment towards transformative change. Finally, having a clear vision of policy effectiveness is also key to looking back at policy implementation mechanisms to identify opportunities for improvement and lessons learned.

Changing people's perceptions, attitudes and value preferences towards the environment and development is key to inducing a transformative change that achieves both the sustainable development goals (SDGs) and the internationally agreed global environmental goals (Sunstein and Reisch 2014; Blackenberg and Alhusen 2019; Haddock, Thorne and Wolfe 2020; Sockhill et al. 2022; Verplanken and Orbell 2022). However, it is important to note that behavioural change cannot happen overnight, and lasting behavioural changes take time (Bhandari 2023; Merz et al. 2023). Current environmental and development policies primarily focus on market-based values, neglecting other values such as relational, intrinsic, and non-market instrumental values (Pascual et al. 2023). Cultural values and cultural heritage must be an integral part of the transformation process, requiring special attention and prioritization (United Nations Educational, Scientific and Cultural Organization [UNESCO] 1972; Nocca 2017; Seekamp and Jo 2020; Fusco and Vecco 2021;). Understanding the diverse values of nature, including those promoted by Indigenous philosophies, the ecocentric approach, and incorporating them in decision-making will lead to better outcomes for nature and the environment (Pascual et al. 2023; Kopnina et al. 2024). Promoting empowerment, gender equality, and both inter- and intra-generational equity can help to expand people's choices and achieve sustainable development (United Nations Development Programme [UNDP] 2011).

13.2 Background

13.2.1 The causes for failed transformation

According to the United Nations (2023b), after 8 years of implementation, only about 15 per cent of the SDG targets are on track, approximately half show some progress while being moderately off track, and more than 30 per cent have not progressed or have even regressed below the 2015 baseline. The SDGs trailing behind include environmental goals such as SDG 6 Clean water and sanitation, SDG 12 Responsible consumption and production, SDG 13 Climate action, SDG 14 Life below water and SDG 15 Life on land (United Nations 2023b). The main causes identified are a lack of strong institutions, legislation and infrastructure, weak enforcement capacity, ingrained habits and lifestyles that are resistant to sustainable consumption, and vested interests (Filho et al. 2023a; Malekpour et al. 2023; Klees 2024). In terms of finance, there are still limited applications and efficient mechanisms to promote private investment, such as green credit, bonds, carbon markets, and biodiversity offset (Deutz et al. 2020; Finance Earth 2021; United Nations Environment Programme [UNEP] 2021; Caldwell, Alayza and Larsen 2022). The distribution of international official support in many cases is uneven. It usually gives less priority to natural resources use, environmental pollution, and climate change, regardless of the vulnerability of the recipient country (Massa and Díaz 2023), and it is unequally spread among developing countries (Rickman et al. 2022).

Other barriers include challenges in mobilizing collective action, trade-offs between goals, difficulties in establishing accountability and commitment, lack of technology and data, implementation capacity, and policy actors operating in silos (Filho et al. 2020; Moors et al. 2022). Gender inequalities also have adverse effects and are a major impediment to the achievement of the SDGs (Filho et al. 2023b; Jeevanasai et al. 2023). In addition, the confluence of the COVID-19 pandemic, regional conflicts and wars, rising inflation and living costs, and natural disasters further exacerbated the slow implementation of the SDGs (Filho et al. 2023a; Malekpour et al. 2023; United Nations 2023b).

The Global Sustainable Development Report (United Nations 2023b) report and related studies found that to achieve the SDGs, it is necessary to carry out holistic

system transformations enabled by governance, economy and finance, individual and collective action, science and technology, and capability actions (Moors et al. 2022; United Nations 2023b).

13.2.2 The need for urgent action and accelerated change

The costs of inaction in addressing the rising emissions exacerbating climate change, as well as the continuous loss of soil and biodiversity, have reached an alarming rate as shown in Chapter 4. While the effect of economic growth on environmental degradation is established, recent studies (Acheampong and Osei Opoku 2023) show that environmental degradation significantly slows economic growth, mainly through effects on health, foreign direct investments and technological innovation. The costs of inaction in addressing the global environmental crises are incalculable. Without accelerated mitigation efforts, the world will breach the temperature limits set by the Paris Agreement. Global GDP is likely to decrease by 1.3–2.7 per cent by 2050 in pathways that fail to limit warming to 2°C, and 2.6-4.2 per cent in pathways that fail to limit warming to 1.5°C above pre-industrial levels (Intergovernmental Panel on Climate Change [IPCC] 2023a; IPCC 2023b). This, combined with biodiversity loss, will make us more vulnerable to disasters and weather extremes as well as jeopardizing human well-being and achievement of the SDGs (Nabuurs et al. 2023). Climate change leads to disproportionate adverse effects on women, youth, the rural poor, and Indigenous Peoples (Food and Agriculture Organization [FAO] 2024; Filho et al. 2021; Reyes-García et al. 2024). A survey of rural households in 24 low- and middle-income countries from the five world regions notes that heat stress widens the income gap between female-headed and male-headed rural households by US$ 37 billion a year, and floods by US$ 16 billion a year (FAO 2024). Only 1–6 per cent of the 4,164 climate actions in these countries were focused on women, youth and the rural poor, which highlights the need for more climate action programmes that specifically cater to women, youth and the impoverished. The cost of

Credit: wirestock/Envato

air pollution is vast, with estimates suggesting that air pollution is responsible for approximately 6.7 million premature deaths globally every year, entailing annual health costs of around 6.1 per cent of global GDP, equivalent to more than US$ 8.1 trillion in 2019 alone (World Health Organization [WHO] 2023). An estimated 400,000–1,000,000 people die every year due to plastic pollution and other mismanaged wastes (Tearfund 2019). Approximately 100,000 marine mammals and 1,000,000 sea birds die every year for the same reason (Darrah 2023; Ocean Blue Project 2021). Global land degradation is estimated to cost more than 10 per cent of the annual global GDP in terms of the loss of biodiversity and ecosystem services (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES] 2018).

The benefits of action generally exceed the costs of inaction (Global Commission on Adaptation [GCA] 2019; IPCC 2023b; International Union for the Conservation of Nature [IUCN] 2020; Nabuurs et al. 2023; UNEP and Food and Agricultural Organisation [FAO] 2020; UNEP 2021; IPCC 2023c; Verdone and Seidl 2017). The global economic benefits of climate mitigation exceed the cost of mitigation (IPCC 2023b; Nabuurs et al. 2023; IPCC 2023c). Ecosystem restoration of 350 million hectares of degraded lands by 2030 is projected to yield ecosystem benefits worth over US$ 9 trillion for an investment of US$ one trillion or about 0.1 per cent of global GDP, that is, a benefit-cost ratio of 9:1, plus the removal of an additional 13–26 gigatons of greenhouse gases (GHGs) from the atmosphere (Verdone and Seidl 2017; IUCN 2020; UNEP and FAO 2020; UNEP 2021). The health co-benefits of reducing GHGs and air pollutants are estimated at US$ 54 trillion compared with global costs of around US$ 22 trillion (UNEP 2019). According to another UNEP report, the annual social and environmental costs of plastic pollution are projected to be from US$ 300 billion to US$ 600 billion per year, with some estimates as high as US$ 1.5 trillion per year (UNEP 2023). The report states that shifting to a circular economy and relying on the 3R strategy – Reuse, Recycle, and Reorient – and diversification, as well as tackling the legacy of plastic pollution, could lead to an 80 per cent reduction in plastic pollution, a net increase of 700,000 jobs by the year 2040, as well as improving livelihoods and encouraging innovation. Apart from reducing annual GHG emissions, it could lead to savings of US$ 1.3 trillion in direct public and private costs over the period 2021–2040 and avoid US$ 3.3 trillion of environmental and social costs due to plastic pollution. Another report notes that investing US$ 1.8 trillion globally in five areas – early warning systems, climate-resilient infrastructure, improved dryland crop production, global mangrove protection and making water resources more resilient – over the period 2020–2030 could generate US$ 7.1 trillion of total net benefits, a benefit-cost ratio of 3.9:1 (GCA 2019). A scenario analysis of plausible plastic futures up to 2060 suggests that a global action scenario with stringent policies implemented worldwide would likely reduce plastic waste by a third, almost eliminating plastic leakage into the environment while lowering global GDP by about 0.8 per cent (Organisation of European Co-operation and Development [OECD] 2022). However, this likely decrease in global GDP overlooks the tangible and intangible benefits of the avoided damages caused by plastic pollution.

13.3 Evaluation of theories of development and environmental change and embracing complexity

Over the last couple of decades, a renewed focus on system transitions and resilience thinking has brought the scholarship on systems thinking to the forefront of efforts to embrace complexity (Chapter 12). Classic theories on economy, society and the environment are no longer viewed as appropriate in addressing the complexities of today's world. New theories to address these challenges must cover multi-dimensionality, multi-actor perspectives, uncertainty and non-linearity of system dynamics. Recent theories on system transformation already capture these principles, but the methodologies and methods to guide system transformations lag behind. The operationalization of system transformations requires carefully designed transformation processes that consider multi-actor perspectives, are socially acceptable, politically, economically and financially feasible, consider equity, distribution and diversity impacts, and pay special attention to the effects on Indigenous Peoples as well as local communities. Step-by-step methodologies that can guide decision makers to operationalize the transformation processes are very much needed.

13.4 Incorporation of Indigenous Knowledge and Local Knowledge

The contribution of Indigenous Knowledge and Local Knowledge to understanding and addressing environmental challenges is increasingly acknowledged

Credit: emirkoo/Envato

(Brondízio et al. 2021), and these types of knowledge are now included in global assessments, such as IPCC and IPBES (Tengö et al. 2017). Based on a recent review of the literature, Brondízio et al. (2021) identify 6 pathways through which Indigenous Peoples and other societies with deep historical connections to place engage with the management of and relationships with nature. These pathways include:

- territorial management practices and customary governance
- nature conservation and restoration efforts with regional to global implications
- knowledge co-production for assessments and monitoring
- countering the drivers of unsustainable resource use and resistance to environmental injustices
- role in environmental governance across scales
- and alternative conceptualizations of the interrelations with nature.

The solution pathways for transformation require consideration of Indigenous Peoples and other societies with deep connections to nature's specific knowledge, worldviews, values, and perspectives on desired futures (IK&LK Dialogues 2025). Most Indigenous cosmologies do not consider nature as separate from humans and promote values of reciprocity and care in relationships with non-humans (Brondízio et al. 2021; IK&LK Dialogues 2025). In all systems, Indigenous Knowledge and Local Knowledge is a crucial solution lever. The role of Indigenous women in climate change adaptation and environmental sustainability is highly recognized. They are often at the forefront of defence, adaptation, and transformation initiatives, leading community-driven projects and movements (Singh et al. 2022; Yadav and Shekhawat 2024). The importance of Indigenous Knowledge and Local Knowledge is evident in environmental and energy systems (IPBES 2019a; Estrada et al. 2022; Pörtner et al. 2022), in the transformation of the food system (Argumedo 2021), or in waste management (Madonsela, Semenya and Shale 2024). Indigenous Peoples account for 6.2 per cent of the global population (estimation of International Labour Organisation [ILO] 2020 p. 52), govern either formally or customarily at least a quarter

of the world's terrestrial surface (Garnett et al. 2018) in 90 countries and also monitor 80 per cent of the world's biodiversity (Convention on Biological Diversity [CBD] 2022). The good-to-moderate condition of 92 per cent of native lands shows a solid understanding of ecosystem management (Das et al. 2022; Garnett et al. 2018; Sangha et al. 2025). When designing solutions for system transformation, it is essential to respect their territorial rights, values and practices. Approximately 60 per cent of Indigenous Peoples' land in 37 countries is at risk due to the conversion of Indigenous land for industrial development, according to Kennedy et al. (2023). Against this background, solutions for system transformation cause more environmental and human crises if their potential negative effects are not considered. Supporting Indigenous Peoples' rights, self-determination, sovereignty and leadership is crucial, as demonstrated in projects related to energy system transformation (Zárate-Toledo, Patiño and Fraga 2019).

13.5 Policy effectiveness, coherence and decision-making

13.5.1 Policy effectiveness

The Sixth Global Environment Outlook (GEO-6) report found that the reduction of substances that deplete the ozone layer, the control of persistent organic pollutants, and the restrictions on the transnational transportation of hazardous waste have been effective policies (UNEP 2019). However, environmental policy decisions are often made in response to environmental problems, rather than taking proactive action to resolve the root causes and drivers of environmental issues (UNEP 2019; Jacob and Elkins 2020; Global Young Academy 2024). The concept of "grow first, clean up later" is still ingrained in most countries' development models and sectoral policies. It was concluded that to achieve most international agreed goals, profound systems transformations are required.

Policy plays an important role in the transformation process because of its governance function (Jacob and Elkins 2020), and transformation is usually the result of policy changes in different fields and at different levels (Berglund et al. 2022). To initiate the policy approach for transformation, it is necessary to create a knowledge base about transformation, enabling conditions for innovation and introducing experimental regulations. A vision of the shape and configuration of the new system needs to be established in order for policy to be developed and institutional reforms to be implemented. This enables different actors to deploy innovation as well as to eliminate the current system (Jacob and Elkins 2020; Independent Group of Scientists appointed by the Secretary-General, 2023; Global Young Academy 2024). Additionally, it is essential to identify winners and losers, involve them in the process, and address the barriers (López-Avilés et al. 2015). Furthermore, gender equality is critical to achieving sustainable and equitable development goals; therefore, it should be integrated in the policy design and implementation (UN Women and UNDP 2018; Filho et al. 2023b).

To achieve transformation, a package of policy instruments is often needed, which can achieve the goals that one single instrument cannot, improving the effectiveness of each individual instrument while minimizing undesired consequences. To design such a package, central and supporting instruments must be identified and their interrelationships must be considered, including preconditions, synergies, and facilitating or hindering conditions. The choice of policy instruments should be based on financial, technical, and technological feasibility, as well as preconditions, political legitimacy, institutional settings, and social acceptability, and it depends greatly on the specific context and conditions of each country (Matt et al. 2013). Some of these factors are typically the result of the ex-ante policy assessment, which sometimes employs models and techniques in the policy formulation process.

13.5.2 Policy coherence

The proper design of policies is critical for ensuring policy effectiveness. This means choosing the right mix of policy instruments and building an enabling environment and governance structures. This also means adhering to all phases of the policy cycle – agenda setting, policy design, policy implementation, and policy review – and policy coherence, as well as including an assessment of social, environmental and cultural impacts (Ferrier et al. 2016; UNEP 2019; Ninan 2020). Policy coherence is a crucial lever for achieving systemic transformations to reach the internationally agreed environmental and development goals. It refers to an effective alignment of various policies so that efforts in one policy area do not undermine

efforts in another, and if possible, even reinforce these efforts (Parsons and Hawkes 2019 cited in OECD 2021). This requires wide participation and inter-sectorality in policy design. The SDG target 17.E focuses on enhancing policy coherence for sustainable development. The OECD introduced the concept of policy coherence as an approach to systematically integrate the economic, social, environmental, and governance dimensions of sustainable development into policymaking, ensuring that they are mutually supportive (OECD 2015). A UN report emphasizes that "governments will need to prioritize policy coherence, overcome sectoral silos and align existing rules and regulations towards achieving the SDGs that are interlinked across sectors" (United Nations 2019). The whole-of-government approach seems suitable for overcoming sectoral silos. Policy coherence implies that policies should be aligned across scales, sectors and policy communities. Effective and inclusive governance mechanisms are required to address policy interactions across sectors and align actions between different levels of government (OECD 2021).

The synergies and trade-offs between different policies, as well as their transboundary effects, need to be analysed. To address the global environmental crises, it is necessary to design and select policies and instruments that yield win-win outcomes, employing an integrated approach. If trade-offs between different policy interventions cannot be reconciled, decision makers should rely on an inclusive and participatory process involving different stakeholders, including marginalized and vulnerable sections, and women, keeping in view the government's policy priorities, with special attention to environmental variables and nature-based solutions. Decision makers should assess the gains or losses of alternative solution pathways, as well as the political and societal acceptance of the intended policy interventions. Involving women in climate action and decision-making processes will help address these disparities and leverage their unique perspectives and knowledge, leading to more effective solutions.

13.5.3 Decision processes

Tools and techniques for effective and robust decision-making are improving thanks to steady developments in decision sciences (Jones et al. 2014; New et al. 2022). There are many decision-analytic methods and approaches to choose from, including Bayesian, interval methods, decision-making under deep uncertainty, cost-benefit analyses, multi-criteria decision analysis, elicitation, and general decision support tools. Multi-attribute decision-making is particularly intriguing because it offers a complete and methodical approach, such as for energy system transformation pathways. It allows for the consideration of public opinions in the decision-making process and the involvement of stakeholders (Hoek et al. 2021; Hottenroth et al. 2022). Iterative decision-making processes for solution pathways that incorporate recursive and reflexive steps help avoid linearity. Model validation, verification, and data interpretation are considered essential. The iterative decision-making process requires careful implementation, monitoring, evaluation and risk management. Iterative decision-making is context-specific and can take into consideration socioeconomic, political, cultural, and conflict-sensitive situations, as well as hazards and risks caused by modifications to the bio-physical environment (Jones et al. 2014; New et al. 2022). Combining new knowledge and technological advancements through iterative decisions enables the analysis of their effects on the environment, society, and the economy. The literature shows that ensuring strong governance grounded in local contexts, providing medium- and long-term support, including diverse knowledge systems – Indigenous, local, scientific, and citizen – in processes of knowledge co-production (Hill et al. 2020), processing technological innovations, and ensuring appropriate financing are necessary conditions to successful outcomes (Jones et al. 2014; New et al. 2022). It is important to consider local and Indigenous decision-making processes that are context specific. The decision-making process can be top-down or bottom-up, and is often a combination of both, involving multiple actors in the implementation steps (Petzold et al. 2023).

13.6 Presenting the 7-step methodology

13.6.1 Why is a new methodology needed?

As already discussed, previous solutions for agreed international goals have not delivered the desired results. With the environmental crises worsening, the global community needs to act urgently to accelerate the pace of change, from evolution to transformation. Policymakers must think differently and act systematically and holistically because the current

crises are multiple and interlinked, otherwise known as polycrises. Action must adaptively address resistance and shocks, in multi-scalar ways that connect the local and the global, the individual and society. Theories of development and environmental change increasingly embrace a systems perspective, and methods must incorporate diverse forms of knowledge, including Indigenous Knowledge and Local Knowledge.

13.6.2 What does the methodology do?

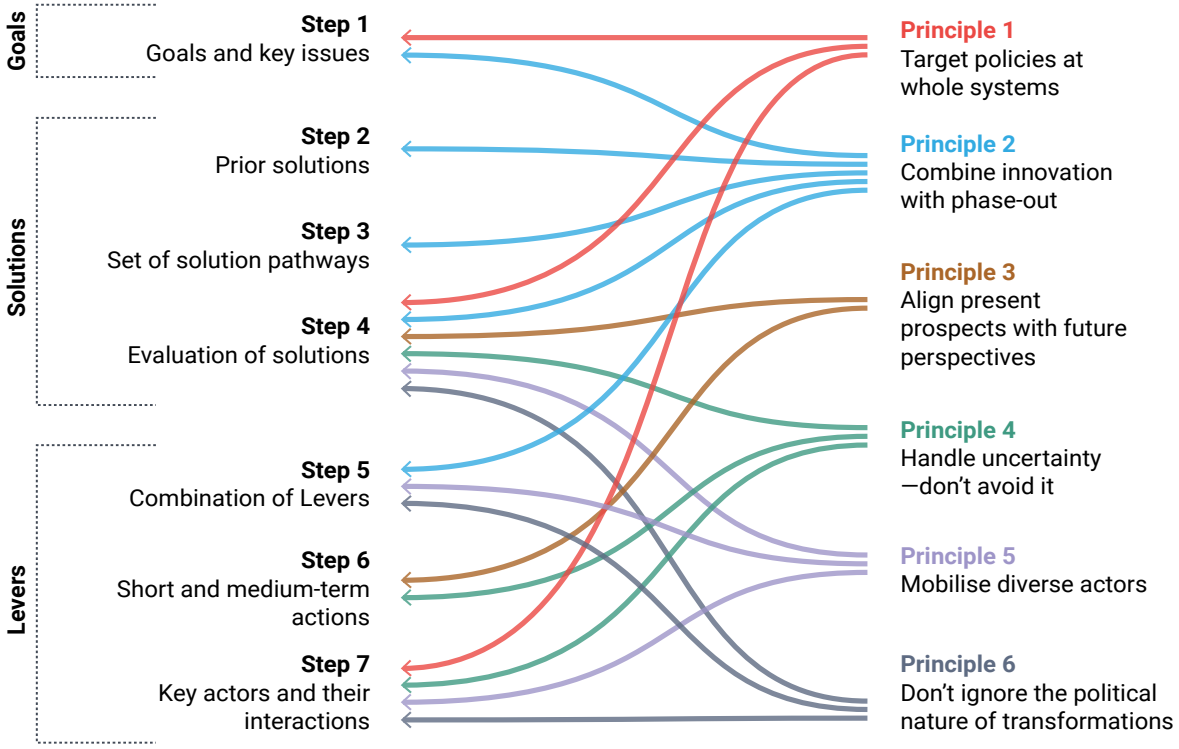
The new methodology innovates by integrating new theoretical development and contexts, for instance, shocks such as the recent pandemic. It clearly links the theory of transformation to practice, that is, the tools for finding and implementing solutions. It produces an explicit 7-step approach, theoretically based on the six principles developed in Chapter 12, to identify effective pathways towards transformation. It guides the clear and comprehensive specification of goals and the systematic identification of levers, actors and actions to be undertaken. It steers the systematic inventory of solutions from a mix of sources, including modelling exercises, past initiatives, and Indigenous Knowledge and Local Knowledge. It conducts the rigorous ex-ante evaluation of these solutions. It integrates monitoring and evaluation throughout the process. It is solution-centred and recognizes the crucial interdependencies between and within systems. It fosters policy coherence and effectiveness by supporting bottom-up approaches, and highlights the cumulative benefits of immediate action, that is, the cumulative losses of inaction.

Figure 13.1 shows the relationship between the 7 steps proposed to design a solution pathway, and the six principles developed in Chapter 12. The figure shows small boxes that contain examples of questions the policymaker should ask to ensure the proposed solutions will lead to transformative change.

13.6.3 What are the expected outcomes with this methodology?

Planners can identify a robust set of solutions derived from multiple sources and fully vetted based on multiple criteria. Solutions are grounded in a better understanding and consideration of local contexts and competing interests. The methodology provides an understanding and visualization of a process towards

Figure 13.1: Bridging principles and action: aligning steps for effective system transformation



Note: this figure shows how the 7-step methodology integrates the 6 principles for system transformation into the development of solution pathways. Each step draws on a distinct set of principles to guide effective and coherent action.

achieving a future-proof goal of transforming systems.

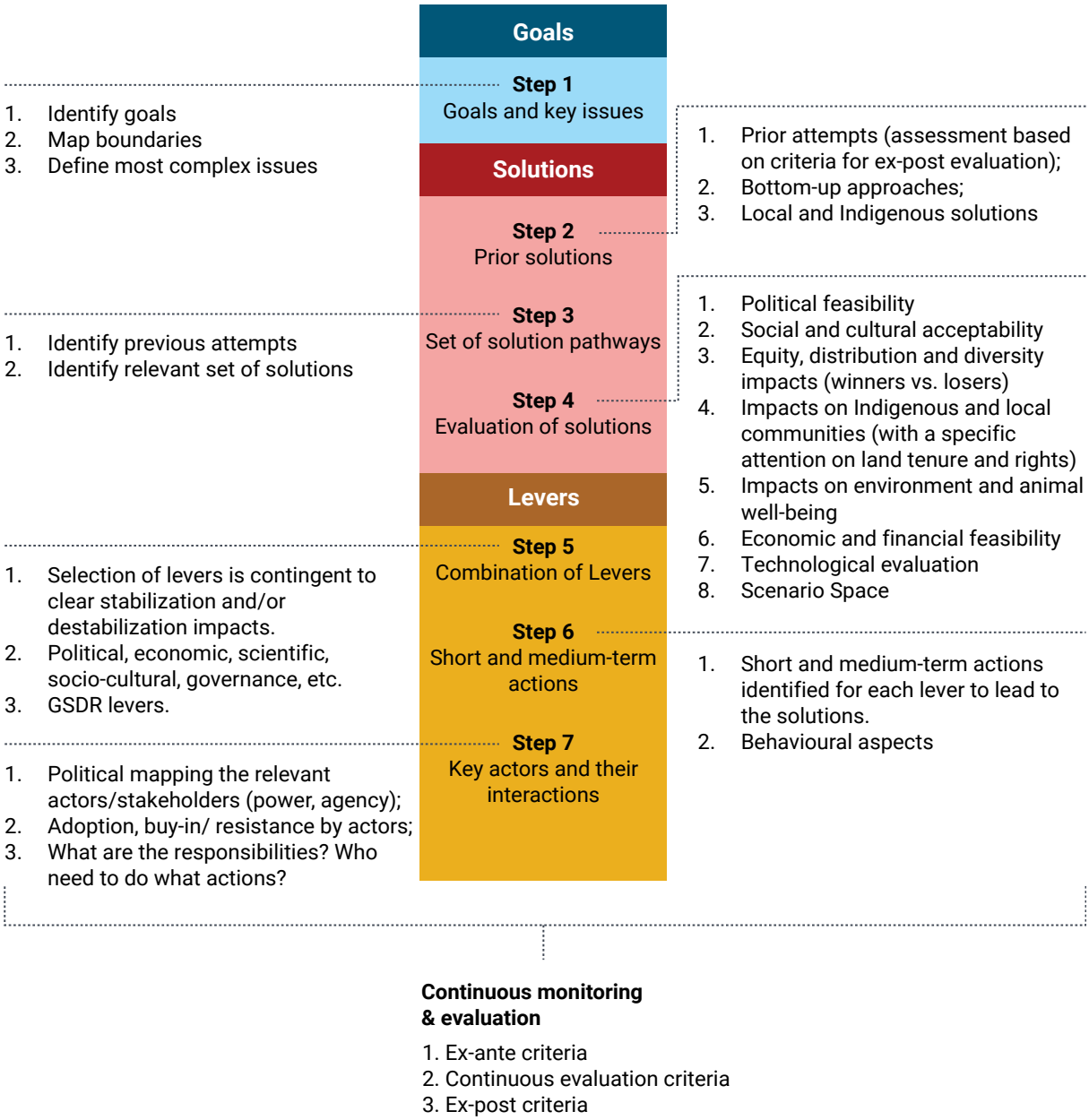
The methodology, made up of the 7 steps summarized in **Figure 13.2**, shows how it integrates the Goals, Solutions, Levers framework and the evaluation monitoring methodology.

13.7 Presenting the X-curve

The X-curve is a visual representation of a solution pathway for system transformation integrating the 7 steps, as well as the GSL framework, the evaluation, and the 6 principles (**Figure 13.3**) (Hebinck et al. 2022; Matti et al. 2022; Matti, Bontoux and Jensen 2025; Silvestri et al. 2022; United Nations 2023b).

The X-curve diagram uses the S-curve graph from the sixth Global Environment Outlook (GEO-6) report to show the greater impact on environmental sustainability of transformational actions or policies in comparison to integrated (environmental, economic, social) actions or policies, and business-as-usual actions or policies (Silvestri et al. 2022; UNEP 2019; United Nations 2023b). The sequencing of the steps is illustrated by the arrows and numbers for each action and shows the progress towards

Figure 13.2: Summarized 7 steps fit to the GSL, 6 principles and evaluation

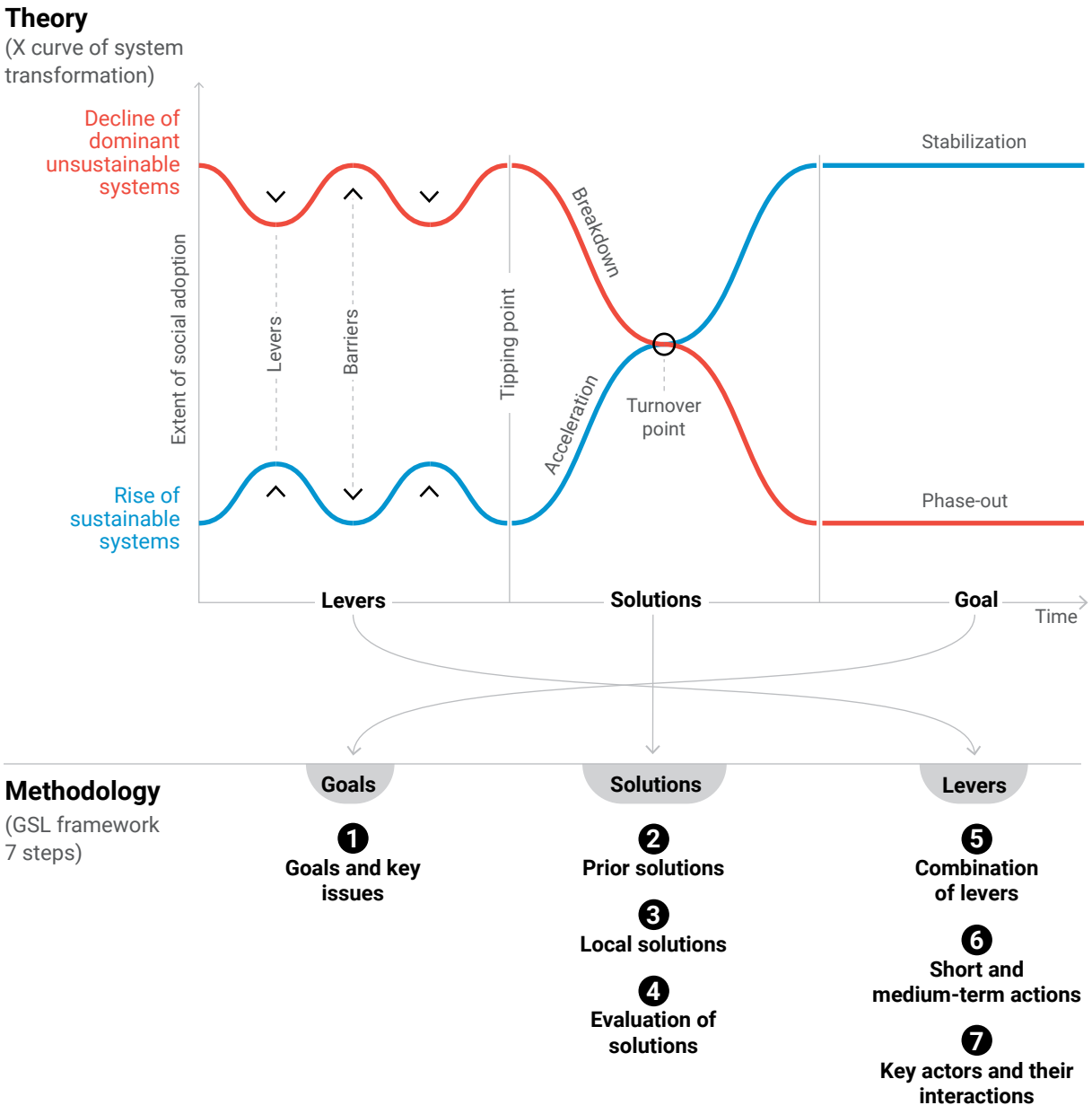


transformation as the actions progress up the S-curve. At some point – likely a critical mass or broad adoption rate – these actions are no longer necessary and there is a self-sustaining momentum towards transformation.

The X-curve depicts both solution pathways intentionally steering systems towards a) a rise of sustainable systems, and/or b) a decline of unsustainable systems. The upwards and downward tipping points cannot be methodologically identified. Rather, it is within the contextual reality of a given system that the action exerting an upward or downward infliction can be identified.

The figure describes the transformation from theory to applied methodology. Mechanically, solution pathways are selected to gradually disrupt unsustainable systems and foster the rise of sustainable ones. The x-axis is defined as time clustered in three phases: Phase 1: Activation; Phase 2: Take-off; Phase 3: Stabilization and Phase-out. The dependent variable is defined as the extent of social adoption of the solution pathway. Phase 1 Activation involves a combination of stabilizing and destabilizing levers that support or inhibit the uptake of a solution. During the take-off phase, a set of solutions is being socially adopted and sustained over time, whereas solution pathways

Figure 13.3: Curve in relation to Goals-Solutions-Levers Framework



that are considered unsustainable are being broken down and ultimately phased out.

The Goals-Solutions-Levers diagram provides a tool for building the solution pathway at the system level. The exemplified frameworks show how to define a solution pathway in each system; the system transformation would unfold in order from Levers, to Solutions, to Goal. However, to define a solution pathway strategically, the system chapters defined the Goals, Solutions and Levers as suggested in the 7-step methodology. As shown in **Figure 13.3**, the GSL Framework is presented in reverse order in the X-Curve that represents the 7-Step methodology from theory to practice. Starting with the Goal in mind as Step 1, the decision maker develops a solution pathway in Steps 2–4, while considering a set of Levers with Steps 5–7. The steps are described in detail in the following section.

13.8 Step-by-step description of the 7 steps

13.8.1 Step 1. Identify goals and define the most complex issues for the system that need to be solved to achieve transformations and the specific transformational goals.

The processes of identifying goals for system transformation must follow good governance principles, including, inclusive and participatory decision-making, co-design and co-creation of solutions, accountability, and transparency. These principles also include the active involvement of diverse actors in the process of identifying the system goals and in envisioning the desired future. They further link to the governance targets of SDG 16 on "Peace, Justice and Strong Institutions" and a transformative promise of the 2030 Agenda "To Leave No One Behind (LNOB)" (United Nations 2023a).

Thus, the process for identifying goals should:

- Map out the boundaries of a given system (e.g. temporal, geographical, etc.).
- Clearly identify the problem that requires solving (tools such as SWOT and PESTLE analysis may be useful here)
- Develop an inclusive and empowering multi-actor consultation process for the relevant actors within a system.
- Use strategic foresight when possible (Matti et al. 2025).
- Through the consultation process, identify the most pressing issues/areas within a system that need urgent attention and action.
- As a result of the iterative consultation processes, develop a list of a set of goals to address the pressing issues and for system transformation.
- Work on detailed discrepancies, align the proper wording and targets with the involved stakeholders, ensuring stakeholder commitment to the goals.
- Identify interdependencies for trade-offs and co-benefits across goals, but more so across systems, and utilize the leveraging effect if applicable.

Goals can be understood across three levels:

- **Overarching goals level**
  These are aspirational and not necessarily directly attainable goals. Actions should nevertheless carry the transformational process towards that goal and allow major progress towards it, for example:
  Sustainable life on Earth is the most overarching goal encompassing most internationally agreed goals and inspiring the 2030 Agenda. It is clearly a foundational, universal and overarching goal.
  Halting climate change is not necessarily attainable at the local level, but local mitigation projects, emission reductions, and exiting a fossil-fuel economy can significantly help limit climate change.
- **System-level goals**
  These goals are partially attainable and can be achieved within a specific timeframe. For example:
  Enhance food systems with nutritious, healthy, and affordable food, while minimizing

environmental harm through humane and sustainable agriculture and land management practices.

- **Implementation-level goals**
  These are concrete, attainable goals with clear outcomes and measurable indicators. They operate at the country, policy, project, programme, or legislative level and contribute directly to system-level and overarching goals. For example: Ensure national compliance with the 30×30 biodiversity target, whereby at least 30% of terrestrial and marine areas—prioritizing key biodiversity sites—are effectively and equitably managed through connected conservation systems; and Enhance the state or health of forests through improving the richness of plant and animal species, ecosystem services, participatory management by local communities, and adaptive and sustainable management.

13.8.2 Step 2. Review sources of solutions

Review and identify one or more examples or evidence that illustrate prior attempts to transform these systems and analyse them according to ex-post criteria.

Some actions may have already been tried and they yield lessons to be learned. Analyse these examples based on the goal, design, involved actors, instruments, tools, and achieved output and outcome, using policy analysis to understand where they succeeded and failed. Analyse the stage of maturity: sustainability transitions, including system transformations, with a broader consideration of well-being beyond humans, that is, animal well-being and nature, which are long-term processes. It takes time to destabilize a system and develop an alternative one. The evidence can also be analysed to determine whether they are in the predevelopment, take-off, acceleration or stabilization phases, to avoid hasty judgements.

Use the examples to support the proposed sequencing and timing of the proposed actions in the solution pathways.

Activating an ensemble of solution pathways for transformation should address a system sustainability problem at a given point in time. However, if not adaptive, this ensemble of solution pathways can become inappropriate in solving a problem that becomes more complex over time. For example, agricultural intensification, such as India's Green Revolution, and the utilization of pesticides and chemical fertilizers was the model implemented in many countries to increase productivity and food security (Conway 1999); Conway and Barbier 1988; Ninan 1992; Ninan 2000; Pingali 2012; Conway and Barbier 2013; John and Babu 2021; United Nations 2023b). Food security, however, has expanded to encompass quality, affordable, and nutritious food for all, while also conserving soil and the environment. Intensification alone, with pesticides, fertilizers, and mechanization, has been superseded in addressing an increasingly complex challenge (Conway 1999; Duguma 2014; Nabuurs et al. 2023). Transforming the food system in the 21st century requires seeking new solution pathways that address a complex set of interdependent challenges. The 7 steps have an integrated time sequence to ensure that as challenges change, the ensemble of solution pathways adapts constantly to the new realities in order to ensure goals are attained.

Similarly, the electrification of vehicles today to support the net-zero goal by 2050 could be an oversimplification of the problem. Transformation should include changes in all mobility behaviours including car sharing, public transport, and the use of bicycles (International Energy Agency [IEA] 2023). Further, solutions are needed for the adequate management of electrification, battery waste disposal, and a plan to reduce the extraction of rare earth materials (Li et al. 2021; Jaramillo et al. 2023). Shocks of any sort must be considered when designing solution pathways. Adaptability that allows rapid shifts in the ensemble of solution pathways to achieve a given goal is central. Policy makers are invited to test their ensemble of solution pathways to make them future-proof against shocks and anticipate the need to make changes during the process. Such shocks may be related to health, the economy, or the environment. For instance, the COVID-19 pandemic severely affected the world economy, significantly slowing achievement of SDG targets (United Nations 2023b). The increased intensity and frequency of climate extremes affect billions of people globally with recurrent hazards. The ensemble of solutions must be adaptive to respond to these shocks while maintaining progress towards

Credit: ©UNEP

the goal. The disruptions, such as migration due to climate change, can also serve as an entry point and a valuable learning opportunity to reconfigure societal systems and guide societal transformations toward the desired state.

13.8.2.1 Bottom-up approaches and solutions

The lack of representation of bottom-up approaches in global sustainability trajectories and scenarios is well-documented (Vervoort et al. 2014; IPBES 2019b; Pereira et al. 2021). Yet they can improve the exploration of scenarios for future global sustainability. They might already be practised at a limited scale, but with proper structural support, such as legal and market support, they can be scaled up to the national and regional scales (Moore, Riddell and Vocisano 2015). Failure to incorporate bottom-up perspectives into global sustainability solutions may undermine their legitimacy and render them ineffective when implemented locally. To ensure the representation of bottom-up sustainability solutions in global scenario development, it is important to explore their inventory, to consider those that might already be practised by individuals, groups or communities, and to explore how they can be scaled up. For example, a town might extensively use nature-based solutions to deal with the problems created by stormwater. A village community can reorganize itself through a social innovation to deal with a local pressing environmental issue, such as forest fires in nearby forests. Or a group of farmers might practise regenerative agricultural practices that address food sustainability in the territory. These solutions could be totally new or based on the revival of traditional knowledge and practices within a given territory. They serve as an inspiration for devising solutions at the global system level.

13.8.2.2 Restructure the models of action and the role of actors

The results review of the effectiveness of previous systems transformation solutions identifies patterns of actions and the roles of actors as the reasons for the failure of previous solutions. This is due to decision-making, governance mechanisms and the performance of actors in the execution chain of solutions (Van Vuuren et al. 2015; Turnheim and Nykvist 2019). Action refers to the mechanisms and pathways for implementing the solutions advocated. These include, for example, strategic assistance projects – both financial and technical – to NGOs and other organizations. These projects are useful for protecting the most threatened ecosystems, implementing carbon tax policies, and providing monetary incentives that aggregate market signals

to enhance the greater attractiveness of carbon reduction options.

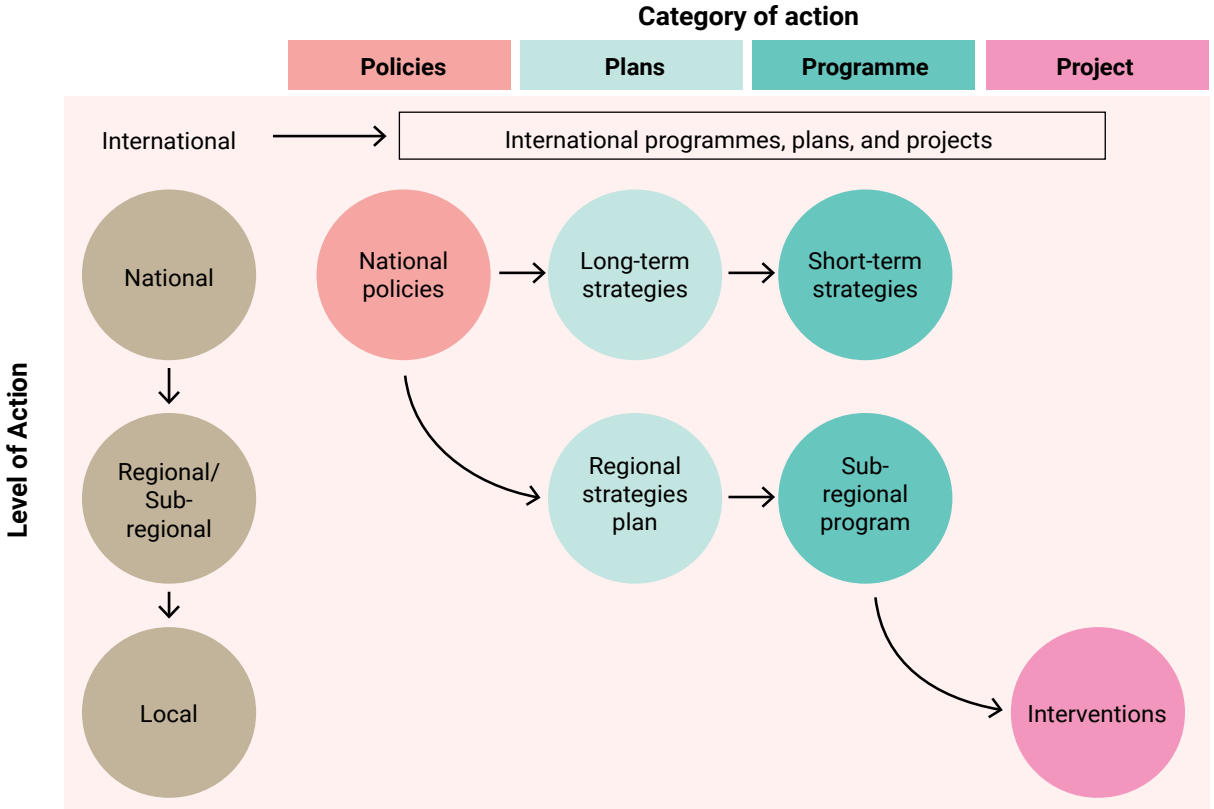
The main criticism is that effective actions must incorporate the key constraints that are most often overlooked. These include technological maturity, economic costs, infrastructure, operational and quality issues, the societal acceptability of each of the relevant technological pathways, and sociotechnical, political and cultural inertia (Clemens 2007; Haydu 2010; Haydu 1998; Mahoney 2000; Pettigrew 1997; Loftus et al. 2015). In this context, models of action should be more integrated and diverse, and reject cockpitism (Flanagan, Uyarra and Laranja 2011; Kivimaa and Kern 2016). They should focus on the governance of transition at multiple levels and scales (Nilsson, Hillman and Magnusson 2012; Raven, Schot and Berkhout 2012) and consider the multiple skills of decision makers.

This rejection of cockpitism avoids the illusion that only top-down leadership by governments and intergovernmental organizations can solve global problems (Hajer et al. 2015). It incorporates the role of other change actors, such as businesses, civil society and local authorities (Hajer et al. 2015), and other qualitative and societal aspects crucial to accelerate transition (Loftus et al. 2015). Thus, effective solutions encompass two main considerations, as follows:

- The levels of implementation of international, national, regional, or local actions according to the decision-making authority, which are the international groups, national or federal leaders, regional or state leaders, subregional or local leaders. Thus, for instance, municipal leaders may have a more or less central role, depending on national context. Indeed, strategies based on action models have been criticized for not sufficiently considering crucial aspects of governance, including the multiple levels and scales of governance involved in transitions (Nilsson, Hillman and Magnusson 2012; Raven, Schot and Berkhout 2012; Turnheim and Nykvist 2019).

- Categories of action: policies, plans, programs and projects (**Figure 13.4**). The effectiveness

Figure 13.4: Categories and levels of actions for changes



Sources: Authors, Turnheim and Nykvist 2019

Credit: YuriArcursPoepleimages/Envato

of a solution also depends largely on the type of action envisaged. Taking into account action categories makes it possible to consider the temporal sequencing of strategies – short, medium and long term – to achieve a given scenario (Nilsson and Nykvist 2016); the granularity of interventions, for example, policy combinations and the interaction of interventions (Flanagan, Uyarra and Laranja 2011; Kivimaa and Kern 2016; Rogge and Reichardt 2016); and the prioritization of resources mobilized (Tavoni et al. 2014).

These contextual and more realistic parameters determine why some solutions may be more likely to fail than others (Turnheim and Nykvist 2019)

13.8.3 Step 3. Identify a set of solutions for the system transformation and check their coverage

Solution are the way to achieve goals. Multiple solutions can contribute to achieving one goal. Solution pathways are collections of actions, sequenced and timed to achieve a particular solution, and that creates a self-sustaining momentum towards achieving recognized goals:

- Review the sources of solutions, for example, previous attempts to change the system, bottom-up approaches, and available solutions based on Indigenous Knowledge or Local Knowledge,
- Once the sources of solutions have been reviewed, list around 5–6 solutions relevant for the system that could lead to system transformation and achieve the identified goals.
- Describe the list of solutions in detail: Cross-check the coverage of these solutions against the modelling exercise (Chapter 11). For the solutions covered by the modelling exercise, draw insights in terms of quantitative projections, the specificities of a solution in terms of trade-offs, synergies, challenges and opportunities.

13.8.4 Step 4. Validate the identified set of solutions in a system context and scale (most relevant for policy makers)

Once the set of plausible solutions has been identified, their feasibility needs to be checked in a local context. Chapter 10 provides an overview of plausible solution pathways for transformation, and it can guide the choice of solutions to be identified here. The solutions include technological and behavioural solutions. These scenarios must link to a storyline reinforcing the scenarios and further justifying their connection with the goals. Thus, this validation of the solutions needs to adhere to the following checklist:

- **Political feasibility** – analysing to what extent implementation of the solutions will be politically accepted and carried out in the longer

term, avoiding incumbent or future actors' resistance to change.

- **Social and cultural acceptability** – gaining legitimacy for the proposed solutions through consent – that is, social processes through which an agreement is given to a certain phenomenon by stakeholders – is an important element in designing and implementing these solutions, to achieve collective participation in and ownership over transformations (Beetham 1991). This is also influenced by behavioural or societal and cultural norms that create this resistance to change.

- **Justice, equity, distribution and diversity effects; winners vs losers** – solutions to system transformation should consider interspecies, intergenerational and intragenerational justice issues (Gupta and Koontz 2019). Carefully mapping the winners and losers and mitigating the unfair distribution of the costs on the most vulnerable and disadvantaged communities and groups – women, the elderly, children, and people with disabilities, among others – s vital. Any societal injustices associated with the transformation should be avoided.

- **Effects on Indigenous Peoples** – placing a special focus on the effects of the proposed solutions on Indigenous Peoples and other communities that maintain historical connections with place and nature, with particular attention to land tenure and land rights, is a crucial aspect to consider. The best strategy to avoid any adverse effects is to involve these groups in the decision-making processes from the outset.

- **Effects on animal welfare and the environment** – the rights of nature and nonhumans must be considered, and their agency should be included in the process. The solutions should be assessed through rigorous environmentalm impact assessments and those with comparatively less impact should be prioritized.

- **Economic and financial feasibility** – understanding the degree to which the economic advantages of implementation are greater than the economic costs. Financial risks of implementation should also be accounted for and distributed in a fair manner.

- **Technological evolution** – anticipate potential support or push factors and constraints or pull factors that the evolution of technology can provide to support solutions at the system level.

- **Scenarios solution space** – Chapter 10 provides a clear overview of plausible solutions for system transformations. The ensemble of solution pathways must fit the scenarios solution space and their storylines.

13.8.5 Step 5. Identify the specific combination of levers that incentivize actions that lead to self-sustaining momentum towards achieving transformative goals

The theory of levers and transformation is provided in 12.5. This step involves providing clear examples for levers that lead to actions that are transformative versus those that are not, in view of the given issue in a system. Identify the forces of radical change and those of stability and path dependence that need to be addressed by the levers, as well as their interplay. Levers are domains of societal influence that share a configuration of broad types of actors, actions, and analysis. The levers as identified in the Global Sustainable Development Report (United Nations 2023b) are Governance, Economy and finance, Individual and collective action, Science and technology, and Capacity building.

13.8.6 Step 6. Identify the options for short- and medium-term actions, and how they should be sequenced. Make decisions while also considering the socioeconomic, ethical, and environmental effects of the actions

Identify 10–15 actions that would result from the application of the levers to support a given solution pathway. These can be an intermediary set of actions that create an enabling environment for other actions to come into play. The sequencing and timing of each action is hence central to creating a viable solution pathway. Research highlights that understanding the interplay of various drivers and their timing is essential for effectively managing transitions in

Credit: tampatra/Envato

food systems (Moberg et al. 2021). Sequence and timing are key factors in promoting an efficient circular economy, ensuring that recovered materials are optimally processed and reused (Andriyani et al. 2024). In the co-production of knowledge framework, particularly in the context of environmental protection and recycling within energy systems, well-defined sequences and timing ensure that all stakeholders, including Indigenous communities, are involved from the outset. This involvement is crucial for building equitable relationships and addressing systemic inequities (Yua et al. 2022). These recommendations should be actionable and implementable, allowing for intentional movement towards transformation.

Action is defined by conscious decision-making to do something in the light of attaining the goal in each system, adhering to the given and previously selected solution. However, the actor is limited in their ability to choose from the options presented and accessible in each system. It is crucial to understand that social and collective actions also have powerful transformational effects and that a careful design of governance around system transformations is essential. Governmental interventions can have a profound influence on actions; government policies can create an enabling environment and context for transformation by determining the direction of transformation – phase in or phase out – through policy priorities and resource allocation. Each system chapter should explore the literature on the success of each action, including the diversity of instruments used to implement the actions. Financial systems and vested interests, as well as other lock-ins, should be considered in this literature review. Identifying failing actions and the reasons for their failures should also be part of the literature review. Try to select shorter-term or immediate actions to help ensure policymakers are accountable for delivering these actions within their term in office. Explore the impacts of these actions on technologies, governance and behavioural change. The effectiveness and efficiency of levers, policies, or actions, as well as their co-benefits or trade-offs, should also be researched and considered. Contextual requirements for each action should be detailed – and perhaps relate these requirements to the governance contexts Literature on ex-post and ex-ante analysis of actions should also be considered here.

The sequencing and timing of actions would also likely need to include adaptive measures, so that if a conflict, disaster, shock, or other barrier arose, there would be guidance for governments or other actors on the best solution pathway for adaptation.

In defining the sequencing of actions, consider the X-curve approach, that is, consider the phasing-out actions in parallel to the phasing-in actions. Actions should be envisioned for an intentional rising path that supports a sustainable system, and an intentional declining path that destabilizes an unsustainable system towards its exit.

13.8.7 Step 7. Identify and understand the responsible actors and their roles and interactions for realizing those actions

The politics of system transformations captures how different actors, and their groups can have diverse epistemological understanding of transformative solutions, and contest or align over the desired outcomes of transformations, including the measures to achieve those outcomes (Avelino and Wittmayer 2016; Kern and Rogge 2018). This means understanding whose vision, values, and discourse dominate when deciding the direction of future pathways and who wins or loses when those pathways are taken. Thus, system transformations are not only sociotechnological changes within each system but also involve shifts in power relations and the (dis)empowerment of actors (Avelino and Wittmayer 2016). In this sense, the politics of system transformations are closely linked to issues of legitimacy, justice, agency, and power among actors.

Stakeholders are all actors affected by a project, policy, study or decision, or who have an important influence on its outcome. Stakeholder analysis usually involves four stages: 1) identification of the system, sector or project under focus for example, a special theme where we need stakeholder engagement; 2) identification of the system boundaries and overall context, for example, location, geography, and time frame); 3) identification of stakeholders, for example, which individuals and groups); and 4) mapping, analysis, and prioritization of stakeholders.

The integration of diverse actors' perspectives begins with effective stakeholder identification and engagement, and it continues with the establishment of good governance around system transformations, including environmental education. This involves being attentive to the voices of non-conventional players and integrating the perspectives of scientists, youth movements, Indigenous Peoples as rights holders, local communities, and movements that tackle issues of poverty, race, gender, age, or ethnic disparities (Pascual et al. 2023). This stems from the recognition that system transformations are highly complex, uncertain and multidimensional processes. As such, they cannot be managed solely through a top-down approach by governments, and they require the involvement of a plurality of actors. The governance of transformations must seek to understand the needs and empowerment of stakeholders, and remain accountable to them, as well as to the governance processes, instruments, and outcomes.

Thus, in this step, the decision maker needs to:

- Identify the diversity of stakeholders or stakeholder groups.
- Politically map them according to the power to affect the transformation and be influenced by its results, that is, winners and losers.
- Identify the actors that might resist the change.
- Identify and assign the roles of actors for driving transformation and ensure the uptake by society as a whole.

The literature shows the many factors influencing the actions implemented at different levels: individual, community, civil society, governance, and private sector. These factors can reveal the drivers, obstacles, and catalytic conditions that influence the implementation of specific actions in the solution pathway, as well as whether these influences are positive or negative (IPCC 2022; Pascual et al. 2023). Recent literature highlights the need to develop multi-actor actions to achieve a beneficial synergy between the positive indicators and obtain positive social tipping dynamics (Petzold et al. 2023). The 7th step highlights the importance of considering all these indicators.

13.9 Monitoring and evaluation

A continuous evaluation process must be applied to achieve transformative change. Ex-ante and ex-

post evaluations, along with permanent monitoring procedures, using key indicators, including a gender perspective, would contribute to defining realistic goals, selecting feasible solution pathways, implementing actions by committed actors across the identified levers, and being capable of adapting to unforeseen events or unexpected situations.

Monitoring and evaluation help gauge whether the solution pathways under execution are performing in a way that aligns with the achievement of the proposed goals (Marwedel 2021). If not, the reasons for underperformance, for instance, due to unexpected scenarios, must be identified and understood before adjusting the actions (Luederitz et al. 2017). These processes need to be constant and dynamic (van den Berg, Magro and Salinas Mulder 2019) to stay on the correct path for a transformative change, but also to make effective use of scarce resources. Flexibility in actions and indicators is a prerequisite for a dynamic and continuous monitoring and evaluation process.

Thus, the continuous monitoring and evaluation process runs parallel to the implementation of the solution pathways and the GSL framework. It starts at the goal level, analysing if the goals are determined using participatory methods (FAO et al. 2023), and if measurable indicators of progress are defined (United Nations Framework Convention on Climate Change [UNFCCC] 2010; Turnheim and Nykvist 2019; UNEP 2019; OECD 2020; United Nations 2023a). Next, an ex-ante evaluation of the solution pathways under analysis needs to be performed, based on strong qualitative and quantitative data. Based on the top-down and bottom-up approaches used in the GEO-6 report and other evaluations experiences (van den Berg, Magro and Salinas Mulder 2019), the criteria to evaluate the alternative solution pathways are:

- effectiveness and goal achievement
- unintended effects
- setting of a baseline
- coherence and convergence and synergy
- co-benefits
- equity, and winners and losers
- enabling and constraining factors
- cost and cost-effectiveness
- time frames
- feasibility
- acceptability
- stakeholder involvement

The potential solution pathways need to be evaluated in the local context regarding their political feasibility, social and cultural acceptability, economic and financial feasibility, and distributional impacts on, for example, Indigenous Peoples as well as local communities (Turnheim and Nykvist 2019), among others, using credible data.

After Step 4, the selected solution pathway will be evaluated, regarding its capacity to address the relevant levers: Governance; Individual and collective action; Economy and finance; Science and technology, and Capacity building (United Nations 2023a).

For the sequence of actions that the selected solution pathway integrates, a proportionate monitoring and evaluation process needs to be designed and implemented. First, we need to conduct a quantitative-qualitative baseline analysis of the proposed indicators at the goal level, including gender disaggregation. Next, a monitoring procedure and intermediate evaluation of the actions for the solution pathway will be designed. The objective of the monitoring process is not only to measure progress, but also to learn from the experience, identifying changes or detours (van den Berg, Magro and Salinas Mulder 2019), to ensure that the transformative change is taking place. Additionally, the inclusion, role, and commitment of each of the relevant actors in the solution pathway should be evaluated (Fisher and Newig 2016). This continuous monitoring and evaluation process should be proportionate to the level of actions implemented. Finally, a systematization process should be designed to highlight the lessons learnt, the good practices implemented, and the improvements that can be made in future interventions. All these processes constitute the evaluation in the GSL framework. In the Appendix 13.1, a checklist of questions is included to help with the design and development of the evaluation process.

13.10 Concluding thoughts

This chapter proposes a significant advance in the field of systemic transformation by introducing a new methodology for developing solution pathways. The method's key strengths are innovation, integration, and adaptability.

The methodology is integrative in both scientific and social terms. Scientifically, it links abstract theories of transformation with concrete planning steps, thereby operationalizing complex concepts into actionable processes. Its 7-step approach offers a practical toolkit for overcoming deep-seated policy and systemic failures that continue to hinder progress on the SDGs. It is solution-centred and focuses on identifying system goals, solutions, levers, actors, and actions to be undertaken. The inventory of solutions includes modelling exercises, past initiatives, existing bottom-up solutions, Indigenous Knowledge and Local Knowledge. It reflects the six principles of transformation (12.4) and integrates monitoring and evaluation throughout the process, recognizing the need to constantly assess and adapt to stay on track for transformative change.

Socially, the model recognizes and integrates diverse knowledge systems, particularly Indigenous Knowledge and Local Knowledge, which are often marginalized in formal policy design. By placing these epistemologies on an equal footing with scientific and technical knowledge, the methodology fosters more legitimate, equitable and culturally grounded solutions. An inclusive engagement of all stakeholders must be sought at all phases of the effort to ensure broad-based ownership and political legitimacy. Absent such inclusion, the proposed solution pathways may simply maintain or reinforce existing systemic injustices. Inclusion is also important to gain legitimacy, achieving societal support and maintaining it over a long period (Beetham 1991).

The model is also adaptive, both internally and externally. Internally, it considers various interdependencies, including trade-offs, synergies and feedback loops. In so doing, it provides a more realistic account of the dynamics of systemic change while also facilitating the coherence of multiple policy interventions. Externally, the methodology can be adapted to address shocks and uncertainties. This feature, which facilitates response to emerging challenges, is vital in today's world where environmental, social and economic systems are susceptible to sudden disruptions. Overall, the methodology supports continuous monitoring, evaluation, and timely recalibrations that maximize the likelihood of transformative success.

Ultimately, the methodology's dominant feature is to be innovative. It advances the use of systems thinking at a time when the world must move beyond incrementalism and transform rapidly to address our global environmental crises in ways that are socially just, ecologically sound, and resilient to future shocks. Transforming systems means breaking away from business-as-usual, including in the realm of policy theory and methodology. The proposed 7-step methodology represents a significant step toward methodological innovation.

Appendix 13.1 Guidelines for the evaluation process in the GSL Framework

Steps	GSL Framework	Evaluation of Step or Procedure Check List	Literature
S1: Goals	Goals	• Are the goals defined using participatory methods? • Are the country/region priorities aligned with the selected goals? • Are there indicators and procedures to measure the progress and achievements of the goals for transformative change defined? • How are the goals connected to explicit representations of the system (configuration and boundaries) and structural sources of lock-in? • What needs to be removed, changed or maintained?	(FAO et al. 2023) (OECD 2020; UNFCCC 2010; Turnheim and Nykvist 2019)

S2: Source of solution:
• Prior attempts
• Local solutions
 	
S3: Set of selected solution pathways
 	
S4: Evaluation of the selected solution pathways in the local context.
• Political feasibility
• Social and cultural acceptability
• Economic and financial feasibility
• Equity, distribution and diversity impacts (winners vs losers)
Impacts on Indigenous Peoples as well as local communities.
	Solution pathways (SP)	Questions that may help S2–S4:
		
		• Are the solution pathways (SP) leading to transformative change?
		• Are there evidence-based evaluations of policies, actions or programmes that explain the results of the prior attempts?
		• Do models and scenarios provide feasible targets, considering time frames (i.e. 2030, 2050)
		• Are there literature or data that support the effectiveness or co-benefit of transformative actions, policies and programmes implemented for the solution pathway in a similar context? In different contexts?
		• Does the SP include intermediate results or targets to reach for getting the identified goal?
		• Are all potential actors involved identified?
		• Has the SP been validated considering multiple perspectives and approaches?
		• Does the political context facilitate implementation of the SP in the short and long term? Are there many actors capable of promoting the SP?
		• Are social and cultural actors interested in implementing the SP? Do these actors propose an active participation in the development of the SP?
		• Are financial resources available for funding the SP?
		• Are all actors informed about potential positive and negative effects of the SP selected (specifically, those who would be the losers in the SP)
		• Pre-defined criteria to evaluate the potential SP:
		
		  • Cost effectiveness and cost-benefit analysis for goal achievement; nintended effects; setting of a baseline;
		  • Coherence, convergence and synergy; co-benefits;
		  • Equity, winners and losers; enabling/ constraining factors;
		  • Cost; cost-effectiveness; time frames; technical feasibility; acceptability; stakeholder involvement
			(Turnheim and Nykvist 2019 p. 777-778)
			
			(Luederitz et al. 2017; van den Berg, Magro and Salinas Mulder 2019)

Steps	GSL Framework	Evaluation of Step or Procedure Check List	Literature
S5: Levers	Levers	Does the SP selected include notions of the following levers: • Governance • Economics and finance • Individual and collective action • Knowledge and innovation • Capabilities If the answer is no, the SP needs to be revised to make sure all the levers are included.	(Lamhauge, Lanzi, and Agrawala 2012)
S6: Sequence of actions	Levers	After the SP to be implemented is selected, the sequence of actions should be developed. Parallel to the definition of these sequences, a monitoring and evaluation process needs to be designed. 1. Ex-ante evaluation of the sequence of actions of the SP selected: • Is there an approved procedure to measure the defined indicators? • Is the SP economically feasible? Are the externalities and co-benefits of the SP included in the evaluation? 2. Monitoring: • Are there indicators (short and medium term) that can measure the progress of the proposed actions? • Is it possible to define a procedure to gather information for measuring the progress on the selected indicators? • Are there resources (funding, human resources) to periodically perform the monitoring actions? 3. Ex-post evaluation: • - Are there resources (e.g. human, financial, • technical) available to perform the ex-post evaluation?	(Lamhauge, Lanzi, and Agrawala 2012)
S7: Actors	Levers	• Are different types of actors involved in the design and implementation of the proposal government (at multilevel: local, regional, federal), private sector, consumers/producers, NGOs, international agencies, organized civil society? • Are there actors who support vs. oppose (e.g. funding, advocacy) the SP/actions proposed? • Is the plurality of actors hf? • Is a systematization process designed to highlight the lessons learned, the good practices implemented, and the improvements required for future interventions?	(UNFCCC 2010; Fisher and Newig 2016) (OECD 2020)

Note: The evaluation process is permanent and must consider the step in which it is located. For example, in Step 4, the solution pathway is evaluated in terms of how to achieve transformative change, while in Step 6, the evaluation focuses on determining whether the sequence of actions guarantees the achievement of the solution pathway.

References

Acheampong, A.O. and Osei Opuko, E.E. (2023). Environmental degradation and economic growth: investigating linkages and potential pathways. Energy Economics 123. 106734. https://doi.org/10.1016/j.eneco.2023.106734

Andriyani, N., Suprobo, P., Adi, T.J.W., Aspar, W.A.N., Jatmiko, A.D. and Santoso, A.D. (2024). Integrating urban building information modeling and circular economy framework for green sustainability. Global Journal of Environmental Science and Management 10(3), 1313-1332

Argumedo, A., Song, Y., Khoury, C. K., Hunter, D., Dempewolf, H., Guarino, L. et al. (2021). Biocultural diversity for food system transformation under global environmental change. Frontiers in Sustainable Food Systems 5, 685299. https://doi.org/10.3389/fsufs.2021.685299

Avelino, F. and Wittmayer, J.M. (2016). Shifting power relations in sustainability transitions: a multi-actor perspective. Journal of Environmental Policy & Planning 18(5), 628-649. https://doi.org/10.1080/1523908X.2015.1112259

Beetham, D. (1991). Max Weber and the Legitimacy of the Modern State. Analyse & Kritik 13(1), 34-45. https://doi.org/10.1515/auk-1991-0102. doi:10.1515/auk-1991-0102

Berglund, O., Dunlop, C.A., Koebele, E.A. and Weible, C.M (2022). Transformational change through Public Policy. Policy & Politics 50(3), 302–322. https://doi.org/310.1332/030557322X16546739608413 10.1332/030557322X16546739608413

Bhandari, S. T. (2023). Promoting gender equality across the sustainable development goals Environment. Development and Sustainability 25, 14177–14198. https://doi.org/10.1007/s10668-022-02656-1

Blackenberg, A.K. and Alhusen, H. (2019). On the determinants of pro-environmental behaviour: a literature review and guide for the empirical economist. CEGE 350. University of Gottingen. https://www.econstor.eu/handle/10419/204821

Brondízio, E.S., Aumeeruddy-Thomas, Y., Bates, P., Carino, J., Fernández-Llamazares, Á., Ferrari, M. F. et al. (2021). Locally based, regionally manifested, and globally relevant: Indigenous and local knowledge, values, and practices for nature. Annual Review of Environment and Resources 46(1), 481-509. https://doi.org/410.1146/annurev-environ-012220-012127

Caldwell, M., Alayza, N., and Larsen, G. (2022). Paying for the Paris Agreement Report. Washington, DC: World Resources Institute. https://doi.org/10.46830/wrirpt.21.00150

Clemens, E.S. (2007). Toward a Historicized Sociology: Theorizing Events, Processes, and Emergence. Annual Review of Sociology 33, 527-549. https://doi.org/https://doi.org/10.1146/annurev.soc.33.040406.131700

Convention on Biological Diversity (2022). Indigenous Communities Protect 80% Of All Biodiversity. Convention on Biological Diversity. https://www.cbd.int/kb/record/newsHeadlines/135368

Conway, G. (1999). The Doubly Green Revolution: Food for All in the Twenty-First Century. Cornell University Press. https://www.jstor.org/stable/10.7591/j.ctvtv9340

Conway, G.A. and Barbier, B.E. (1988). After the green revolution: Sustainable and equitable agricultural development, Futures 20 (6), 651-670. https://doi.org/10.1016/0016-3287(88)90006-7

Conway, G.A. and Barbier, B. E. (2013). After the Green Revolution-Sustainable Agriculture for Development. Abingdon: Routledge. https://www.routledge.com/After-the-Green-book/9780415845946?srsltid=AfmBOoqwGNo5YMoEdKzyWGrwXw9dNgSjzR9oxZ39HkmqLZsI70KNghpH

Darrah, P. (2023). How Many Marine Animals die due to Marine Pollution. Global Vision International (GVI) UK. https://www.gvi.co.uk/blog/smb-how-many-marine-animals-die-from-plastic-pollution

Das, M., Das, A., Seikh, S. and Pandey, R. (2022). Nexus between indigenous ecological knowledge and ecosystem services: a socio-ecological analysis for sustainable ecosystem management. Environmental Science and Pollution Research 29(41), 61561-61578. https://doi.org/10.1007/s11356-021-15605-8

Deutz, A., Heal, G.M., Niu, R., Swanson, E., Townshend, T., Zhu, L., et al. (2020). Financing Nature: Closing the global biodiversity financing gap. Paulson Institute, the Nature Conservancy, and Cornell Atkinson Center for Sustainability. https://doi.org/10.13140/RG.2.2.26226.32968

Duguma, L.A., Minang, P.A. and van Noordwijk, M. (2014). Climate change mitigation and adaptation in the land use sector: from complementarity to synergy. Environmental Management 54, 420-432. https://doi.org/10.1007/s00267-014-0331-x

Eckerberg, K. (1997). National and Local Policy Implementation as a Participatory Process. International Governance on Environmental Issues. M. Rolén, H. Sjöberg and U. Svedin. Dordrecht, Springer Netherlands: 119-137. https://doi.org/10.1007/978-94-015-8826-3_8

Eckerberg, K., et al. (2020). "Devolving power from the state: local initiatives for nature protection and recreation in Sweden." Local Environment 25(6): 433-446. https://doi.org/10.1080/13549839.2020.1760226

Estrada, A., Garber, P.A., Gouveia, S., Fernández-Llamazares, Á., Ascensão, F., Fuentes, A. et al. (2022). Global importance of Indigenous Peoples, their lands, and knowledge systems for saving the world's primates from extinction. Science advances 8(31), eabn2927. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9365284/

Ferrier, S., Ninan, K.N., Leadley, P., Alkemade R. et al. (2016). The Methodological Assessment Report on Scenarios and Models of Biodiversity and Ecosystem Services, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). Bonn: United Nations. https://digitallibrary.un.org/record/3793989?ln=en

Filho, W.L., Wolf, F., Lange Salvia, A., Beynaghi, A., Shulla, K., Kovaleva, M. et al. (2020). Heading towards an unsustainable world: some of the implications of not achieving the SDGs. Discover Sustainability 1(2). https://doi.org/10.1007/s43621-020-00002-x

Filho, W.L., Matandirotya, N. R., Lütz, J. M., Abate Alemu, E., Brearley, F.Q., Baidoo, A.A., et al. (2021). Impacts of climate change to African indigenous communities and examples of adaptation responses. Nature Communications 12, 6224. https://doi.org/10.1038/s41467-021-26540-0

Filho, W.L., Trevisan, L.V., Rampasso, I.S., Anholon, R., Dinis, M.A.P. and Brandli, L.L. et al. (2023a). When the alarm bells ring: Why the UN sustainable development goals may not be achieved by 2030. Journal of Cleaner Production 407. 137108. https://doi.org/10.1007/s43621-020-00002-x

Filho, W.L, Kovaleva, M., Tsani, S., Țîrcă, D.M., Shiel, C., Dinis M.A.P. et al. (2023b). Promoting gender equality across the sustainable development goals. Environment, Development and Sustainability 25, 14177–14198. https://doi.org/10.1007/s10668-022-02656-1

Finance Earth (2021). A Market Review of Nature-Based Solutions: An Emerging Institutional Asset Class. The Green Purposes Company, Finance Earth. https://finance.earth/wp-content/uploads/2021/05/Finance-Earth-GPC-Market-Review-of-NbS-Report-May-2021.pdf

Fisher, L. and Newig, J. (2016). Importance of Actors and Agency in Sustainability Transitions: A Systematic Exploration of the Literature. Sustainability 8, 476. https://doi.org/10.3390/su8050476

Flanagan, K., Uyarra, E. and Laranja, M. (2011). Reconceptualising the 'policy mix'for innovation. Research Policy 40(5), 702-713. https://doi.org/10.1016/j.respol.2011.02.005

Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, World Food Programme, and Consortium of

International Agricultural Research Centers Gender Impact Platform (2023). Guidelines for measuring gender transformative change in the context of food security, nutrition and sustainable agriculture. Rome: FAO. https://www.fao.org/3/cc7940en/cc7940en.pdf

Food and Agriculture Organization of the United Nations (2024). The Unjust Climate: Measuring the Impacts of climate change on the rural poor, women and women, youth. Rome: FAO. https://www.fao.org/socioeconomic-research-analysis/resources/unjust-climate/the-unjust-climate/en

Fusco, G.L. and Vecco, M. (2021). The "intrinsic value" of cultural heritage as driver for circular human-centered adaptive reuse. Sustainability 13(6), 3231. https://www.mdpi.com/2071-1050/13/6/3231

Garnett, S.T., Burgess, N.D., Fa, J.E., Fernández-Llamazares, Á., Molnár, Z., Robinson, C.J. et al. (2018). A spatial overview of the global importance of Indigenous lands for conservation. Nature Sustainability 1(7), 369-374. https://doi.org/310.1038/s41893-41018-40100-41896

Global Commission on Adaptation (2019). Adapt Now: A Global Call for Leadership on Climate Resilience. September 2019. Global Centre on Adaptation and World Resources Institute. https://gca.org/reports/adapt-now-a-global-call-for-leadership-on-climate-resilience/

Global Young Academy (2024). Young researchers and scholars' proposals for action for a sustainable present and future. 4. GYA. https://globalyoungacademy.net/wp-content/uploads/2024/11/GYA-Statement-for-COP29-2024.pdf

Gupta, D. and Koontz, T.M. (2019). Working together? Synergies in government and NGO roles for community forestry in the Indian Himalayas. World Development 114, 326-340. https://doi.org/310.1016/j.worlddev.2018.1009.1016

Haddock, G., Thorne, S. and Wolfe, L. J. (2020). Attitudes and Behavior. Oxford Research Encyclopaedia. https://doi.org/10.1093/acrefore/9780190236557.013.449

Hajer, M., Nilsson, M., Raworth, K., Bakker, P., Berkhout, F., De Boer, Y. et al. (2015). Beyond cockpit-ism: Four insights to enhance the transformative potential of the sustainable development goals. Sustainability 7(2), 1651-1660. https://doi.org/10.3390/su7021651

Haydu, J. (2010). Reversals of fortune: path dependency, problem solving, and temporal cases. Theory and Society 39(1), 25-48. https://doi.org/10.1007/s11186-009-9098-0

Hebinck, A., Diercks, G., von Wirth, T., Beers, P.J., Barsties, L., Buchel, S. et al. (2022). An actionable understanding of societal transitions: the X-curve framework. Sustainability Science 17(3), 1009-1021. https://doi.org/10.1007/s11625-021-01084-w

Hill, R., Walsh, F. J, Davies, J., Sparrow, A., Mooney, M., Central Land Council et al. (2020). Knowledge co-production Indigenous adaptation pathways: Transform post-colonial articulation complexes to empower local decision-making. Global Environmental Change 65, 102161. https://doi.org/10.1016/j.gloenvcha.2020.102161

Hoek, A. C., Malekpour, S., Raven, R., Court, E. and Byrne, E. (2021). Towards environmentally sustainable food systems: decision-making factors in sustainable food production and consumption. Sustainable Production and Consumption 26, 610-626. https://doi.org/10.1016/j.spc.2020.12.009

Hottenroh, H., Sutardhio, C., Weidlich, A., Tietze, I., Simon, S., Hauser, T. et al. (2022). Beyond Climate Change. Multi-attribute decision making for a sustainability of energy system transformation pathways. Renewable and Sustainable Energy Reviews 156, 111996. https://doi.org/10.1016/j.rser.2021.111996

IK & LK Dialogues (2025). Indigenous Knowledge and Local Knowledge Dialogues. Global Environment Outlook 7. Mexico City: CopIt-arXives, 2025. https://copitarxives.fisica.unam.mx/SC0011EN/SC0011EN.php

Intergovernmental Panel on Climate Change (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FullReport.pdf

Intergovernmental Panel on Climate Change (2023a). Climate Change 2022: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Sixth Assessment Report of the of the Intergovernmental Panel on Climate Change (IPCC). Portner, H.O., Roberts, D.C. et al. (eds.) Intergovernmental Panel on Climate Change, WMO and UNEP. Geneva: Cambridge University Press. https://report.ipcc.ch/ar6/wg2/IPCC_AR6_WGII_FullReport.pdf

Intergovernmental Panel on Climate Change (2023b). Climate Change 2022: Mitigation of Climate Change, Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Shukla, P.R., Skea, J., et al. (eds.) Intergovernmental Panel on Climate Change, WMO and UNEP. Geneva: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf

Intergovernmental Panel on Climate Change (2023c). Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009157926

Intergovernmental Science-Policy Framework on Biodiversity and Ecosystem Services (2018). Summary for Policy Makers of the Thematic Assessment on Land Degradation and Restoration of the Inter-governmental Science-Policy Framework on Biodiversity and Ecosystem Services. Edited by Scholes, R. https://www.researchgate.net/publication/348845184_Summary_for_policymakers_of_the_global_assessment_report_on_biodiversity_and_ecosystem_services_of_the_Intergovernmental_Science-Policy_Platform_on_Biodiversity_and_Ecosystem_Services

Intergovernmental Science-Policy Framework on Biodiversity and Ecosystem Services (2019a). Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Edited by Diaz, S., Settele, J. et al. https://doi.org/10.5281/zenodo.3553579

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019b). The global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. https://www.researchgate.net/publication/348845184_Summary_for_policymakers_of_the_global_assessment_report_on_biodiversity_and_ecosystem_services_of_the_Intergovernmental_Science-Policy_Platform_on_Biodiversity_and_Ecosystem_Services

International Energy Agency (2023). Global EV Outlook 2023-Catching up with Climate Ambitions. International Energy Agency. Paris: IEA. https://www.iea.org/reports/global-ev-outlook-2023

International Labour Organisation (2020). Implementing the ILO Indigenous and Tribal Peoples Convention No. 169: Towards an inclusive, sustainable and just future. International Labour Organisation. https://www.ilo.org/publications/implementing-ilo-indigenous-and-tribal-peoples-convention-no-169-towards

International Union for the Conservation of Nature (2020). Restore Our Future, Bonn Challenge, Impact and Potential of Forest Landscape Restoration. https://www.bonnchallenge.org/sites/default/files/resources/files/%5Bnode%3Anid%5D/Bonn%20Challenge%20Report.pdf

Jacob, K. and Elkins, P. (2020). Environmental Policy, Innovation and Transformation: Affirmative or disruptive? Journal of Environmental Policy and Planning 22(7), 1-15. https://doi.org/10.1080/1523908X.2020.1793745

Jaramillo, P., Ribeiro, S.K., Newman, P. et al. (2023). Transport Chapter 10. In: Climate Change 2022-Mitigation of Climate Change, Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Shukla, P.R., Skea, J. et al. (eds.). WMO and UNEP, Geneva: Cambridge University Press.

Jeevanasai, S.A., Saole, P., Rath, A.G., Singh, S., Rai, S., Kumar, M. (2023). Shades & shines of gender equality with respect to sustainable development goals (SDGs): The environmental performance perspectives. Total Environment Research Themes 8, 100082. https://doi.org/10.1016/j.totert.2023.100082

John, G.A. and Babu, G.R. (2021). Lessons from the aftermaths of the green revolution on food system and health. Frontiers in Sustainable Food Systems 5, 644559. https://doi.org/10.3389/fsufs.2021.644559

Jones, R.N., Patwardhan, A., Cohen, S.J., Dessai, S., Lammel, A., Lempert, R.J. et al. (2014). Foundations for decision making. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Working Group II Fifth Assessment Report of the IPCC. 195-228. Cambridge: Cambridge University Press. https://www.researchgate.net/publication/269696848_Foundations_for_Decision_Making

Kennedy, C.M., Fariss, B., Oakleaf, J.R., Garnett, S.T., Fernández-Llamazares, Á., Fa, J.E. et al. (2023). Indigenous Peoples' lands are threatened by industrial development; conversion risk assessment reveals need to support Indigenous stewardship. One Earth 6(8), 1032-1049. https://doi.org/1010.1016/j.oneear.2023.1007.1006

Kern, F. and Rogge, K.S. (2018). Harnessing theories of the policy process for analysing the politics of sustainability transitions: A critical survey. Environmental innovation and societal transitions 27, 102-117. https://doi.org/10.1016/j.eist.2017.11.001

Kivimaa, P. and Kern, F. (2016). Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. Research Policy 45(1), 205-217. https://doi.org/10.1016/j.respol.2015.09.008

Klees S.J. (2024). Why SDG4 and the other SDGs are failing and what needs to be done. International Journal of Educational Development 104. https://doi.org/10.1016/j.ijedudev.2023.102946

Kopnina, H., Zhang, S. R., Anthony, S., Hassan, A. and Maroun, W. (2024). The inclusion of biodiversity into Environmental, Social, and Governance (ESG) framework: A strategic integration of ecocentric extinction accounting. Journal of Environmental Management 351, 119808. https://www.semanticscholar.org/paper/The-inclusion-of-biodiversity-into-Environmental%2C-A-Kopnina-Zhang/3c1ef765980ff9440736af51d2f0be209b955c28.

Lamhauge, N., Lanzi, E. and Agrawala, S. (2012). Monitoring and Evaluation for Adaptation: Lessons from Development Co-operation Agencies. OECD Environment Working Papers N°38. https://dx.doi.org/10.1787/5kg20mj6c2bw-en

Li, S., Wang, B., Yang, M., Zhang, F. (2021). The Global Diffusion of Electric Car-Lessons from the First Decade. World Bank Policy Research Working Paper 9882. Washington D.C.: World Bank. https://documents1.worldbank.org/curated/en/225111639490843204/pdf/The-Global-Diffusion-ofElectric-Vehicles-Lessons-from-the-First-Decade.pdf

Loftus, P.J., Cohen, A.M., Long, J.C., and Jenkins, J.D. (2015). A critical review of global decarbonization scenarios: What do they tell us about feasibility? Wiley Interdisciplinary Reviews: Climate Change 6(1), 93-112. https://doi.org/10.1002/wcc.324

López-Avilés, A., Chenoweth, J., Druckman, A., Morse, S., Kauffmann, D., Hayoon, L. et al. (2015). Servicizing Policy Packages for the Water Sector. SPREE Project Servicizing Policy for Resource Efficient Economy. http://www.spreeproject.com/wp-content/uploads/2013/04/Deliverable-8.2.1_Servicizing-PP-in-the-Water-Sector_FULL_3.pdf. Accessed: 27 June 2017

Luederitz, C., Schapke, N., Wiek, A., Lang, D., Bergmann, M., Bos, J. et al. (2017). Learning through evaluation - A tentative evaluative scheme for sustainability transition experiments. Journal of Cleaner Production 169, 61-76. https://doi.org/10.1016/j.jclepro.2016.09.005

Madonsela, B.S., Semenya, K. and Shale, K. (2024). A review of indigenous knowledge systems and their application in sustainable solid waste management. World 5(2), 219-239. https://doi.org/10.3390/world5020012

Mahoney, J. (2000). Path Dependence in Historical Sociology. Theory and Society 29(4), 507-548. https://www.jstor.org/stable/3108585

Malekpour, S., Allen, C., Sagar, A., Scholz, I., Persson, A., Miranda, J.J. et al. (2023). What scientists need to do to accelerate progress on the SDGs. Nature 621, 250. https://www.nature.com/articles/d41586-41023-02808-x

Marwedel, P. (2021). Embedded System Design: Embedded systems foundations of cyber-physical systems, and the internet of things. Cham: Springer

Massa, I. and Díaz, L.B. (2023). SDG financing needs an urgent global reboot. https://sdg-action.org/sdg-financing-needs-an-urgent-global-reboot/. Accessed: 12 May 2024

Matt E., G.M., Epstein B., Feitelson, E. (2013). Methodology Development for the Evaluation of Policy Instruments to Promote Servicizing. FP7 Project: SPREE Servicizing Policy for Resource Efficient Economy. https://cordis.europa.eu/project/id/308376

Matti, C., Rissola, G., Martinez, P., Bontoux, L., Joval, J., Spalazzi, A. et al. (2022). Co-creation for policy: Participatory methodologies to structure multi-stakeholder policymaking processes. Luxembourg: Publications Office of the European Union. https://doi.org/10.2760/495731

Matti, C., Bontoux, L. and Jensen, K. (2025) Strategic foresight framework for addressing agency in sustainability transitions: a co-creation approach. Frontiers in Sustainability 6, 1507708. https://doi.org/10.3389/frsus.2025.1507708

Merz, J.J., Barnard, P., Rees, W.E., Smith, D., Maroni, M., Rhodes et al. (2023). World scientists' warning: The behavioural crisis driving ecological overshoot. Science Progress 106(3), 00368504231201372. https://mahb.stanford.edu/wp-content/uploads/2023/09/merz-et-al-2023-world-scientists-warning-the-behavioural-crisis-driving-ecological-overshoot-1.pdf

Moberg, E., Allison, E.H., Harl, H.K., Arbow, T., Almaraz, M., Dixon, J. et al. (2021). Combined innovations in public policy, the private sector and culture can drive sustainability transitions in food systems. Nature Food 2(4), 282-290. https://doi.org./10.1038/s43016-021-00261-5

Moore, L., Riddell, M.D. and Vocisano, D. (2015). Scaling out, scaling up, scaling deep: strategies of non-profits in advancing systemic social innovation. Journal of Corporate Citizenship 67-84. https://www.jstor.org/stable/jcorpciti.58.67

Moors E., C.J.V., Jewitt, G. and Cak, A.D. (2022). Accelerating Toward Water Security. https://eos.org/science-updates/accelerating-toward-water-security

Nabuurs, G.J., Mrabet, R., Hatab, A., Bustamante, M., Clark, H., Havlík, P., House, J. et al. (2023). Agriculture, Forestry and Other Land Uses (AFOLU). In Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate, C. (ed.) 747-860. Cambridge: Cambridge University Press. https://www.cambridge.org/core/books/climate-change-2022-mitigation-of-climate-change/agriculture-forestry-and-other-land-uses-afolu/465B45B2DF3F9DF46468F1445DBBE985

New, M., Reckien, D., Viner, D., Adler, C., Cheong, S. M., Conde, C. et al. (2022). Decision-making options for managing risk. In Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II, Sixth Assessment Report of the IPCC. 2539-2654. Cambridge: Cambridge University Press. https://research.utwente.nl/en/publications/climate-change-2022-impacts-adaptation-and-vulnerability-contribu/publications/

Nilsson, M. and Nykvist. B. (2016). Governing the electric vehicle transition – Near term interventions to support a green energy economy. Applied Energy 179, 1360-1371. https://doi.org/10.1016/j.apenergy.2016.03.056

Nilsson, M., Hillman, K. and Magnusson, T. (2012). How do we govern sustainable innovations? Mapping patterns of governance for biofuels and hybrid-electric vehicle technologies. Environmental Innovation and Societal Transitions 3, 50-66. https://doi.org/https://doi.org/10.1016/j.eist.2012.04.002

Ninan, K.N. (1992). The green revolution, dryland agriculture and sustainability-Insights from India, in G.H. Peters and B. F. Stanton (Eds.) Sustainable Agricultural Development - The Role of International Co-operation. Proceedings of the Twenty First International Conference of Agricultural Economists held at Tokyo, Japan during August 22-29, 1991. Hant: Dartmouth Publishing. 102-114. https://doi.org/10.22004/ag.econ.183240

Ninan, K.N. and Chandrasekhar, H. (2000). Economic Reforms in India: Impact on the Poor and Poverty Reduction. IDS Working Paper 102. Brighton: University of Sussex, Institute of Development Studies. https://www.ids.ac.uk/download.php?file=files/Wp102.pdf.

Ninan, K.N. (2020). Environmental Assessments: Scenarios, Modelling and Policy. Cheltenham, UK and Northampton, USA: Edward Elgar. https://www.elgaronline.com/edcollbook/edcoll/9781788976862/9781788976862.xml

Nocca, F. (2017). The role of cultural heritage in sustainable development: Multidimensional indicators as decision-making tool. Sustainability 9(10), 1882. https://www.mdpi.com/2071-1050/9/10/1882

Ocean Blue Project (2021). Plastic Pollution in the Ocean-How Many Marine Animals die from Pollution. https://oceanblueproject.org/wp-content/uploads/2023/02/how-many-animals-die-from-plastic-pollution-ocean-blue-report.pdf

Organisation for Economic Co-operation and Development (2015). Better Policies for Development 2015-Policy Coherence and Green Growth. Organisation of European Co-operation and Development. Paris: OECD Publishing. https://doi.org/10.1787/9789264236813-en

Organization for Economic Co-operation and Development (2020). Improving Governance with Policy Evaluation Lessons from Country Experiences. Paris: OECD. https://doi.org/10.1787/89b1577d-en

Organization for Economic Co-operation and Development (2021). Making Better Policies for Food Systems. Organisation of European Co-operation and Development. Paris: OECD Publishing. https://doi.org/10.1787/ddfba4de-en

Organisation of European Co-operation and Development (2022). Global Plastics Outlook-Policy Scenarios to 2060. Organisation of European Co-operation and Development. Paris: OECD Publishing. https://doi.org/10.1787/aa1edf33-en

Pascual, U., Balvanera, P., Anderson, C.B., Chaplin-Kramer, R., Christie, M., González-Jiménez, D. et al. (2023). Diverse values of nature for sustainability. Nature 620, 813-823. https://doi.org/10.1038/s41586-023-06406-9

Pereira, L., Asrar, G.R., Bhargava, R., Fisher, L. H., Hsu, A., Jabbour, J. et al. (2021). Grounding global environmental assessments through bottom-up futures based on local practices and perspectives. Sustainability Science 16(6), 1907-1922. https://doi.org/10.1007/s11625-021-01013-x

Pettigrew, T.F. (1997). Personality and Social Structure: Social Psychological Contributions. In Handbook of Personality Psychology. Hogan, R., Johnson, J. and Briggs, S. (Eds.). Chapter 12, 417-438. Academic Press. https://doi.org/https://doi.org/10.1016/B978-012134645-4/50018-4

Petzold, J., Hawxwell, T., Jantke, K., Gonçalves Gresse, E., Mirbach, C., Ajibade, I. et al. (2023). A global assessment of actors and their roles in climate change adaptation. Nature climate change 13(11), 1250-1257. https://doi.org/10.1038/s41558-023-01824-z

Pingali, P.L. (2012). Green Revolution: impacts, limits, and the path ahead. Proceedings of the National Academy of Sciences (PNAS) 109(31), 12302-12308. https://pnas.org/cgi/doi/10.1073/pnas.0912953109

Pörtner, H.O., Roberts, D., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A. et al. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg2/

Raven, R., Schot, J. and Berkhout, F. (2012). Space and scale in socio-technical transitions. Environmental Innovation and Societal Transitions 4, 63-78. https://doi.org/10.1016/j.eist.2012.08.001

Reyes-García, V., García-Del-Amo, D., Porcuna-Ferrer, A., Schlingmann, A., Abazeri, M., Attoh, E.M.N.A.N. et al. (2024). Local studies provide a global perspective of the impacts of climate change on Indigenous Peoples and local communities. Sustainable Earth Reviews 7 (1). https://doi.org/10.1186/s42055-023-00063-6

Rickman J., Kothari, S., Larosa, F. and Ameli, N. (2022). The Unequal Distribution of International Climate Finance Flows and Its Underlying Drivers. Research Square. https://doi.org/10.21203/rs.3.rs-1188981/v1

Rogge, K.S. and Reichardt, K. (2016). Policy mixes for sustainability transitions: An extended concept and framework for analysis. Research Policy 45(8), 1620-1635. https://doi.org/https://doi.org/10.1016/j.respol.2016.04.004

Sangha, K.K., Ahammad, R., Russell-Smith, J. and Wolley, L.A. (2025). A Nature-Based Solutions Assessment Framework Integrating Indigenous Biocultural and Ecosystem Services Perspectives: An Australian Example. Ecological Indicators 172, 113230. https://doi.org/10.2139/ssrn.5037713

Seekamp, E. and Jo, E. (2020). Resilience and transformation of heritage sites to accommodate loss and learning in a changing climate. Climatic Change 162(1), 41-55. https://link.springer.com/article/10.1007/s10584-020-02812-4

Silvestri, G., Diercks, G. and Matti, C. (2022). X-Curve: A Sense Making Tool to Foster Collective Narrative on Systems Change. DRIFT, EIT Climate-KIC Transition Hub. Netherlands. https://drift.eur.nl/app/uploads/2023/08/X-Curve-booklet-DRIFT-EIT-Climate-KIC-2022-1.pdf

Singh, R., S., Dahiya, B., Singh, A. K. and Poudel, P. C. (2022). Practising Cultural Geographies: Essays in Honour of Rana P.B. Singh. Advances in 21st Century Human Settlements series. Singapore: Springer Nature Pte Ltd. 3-24. https://doi.org/10.1007/978-981-16-6415-1_1

Sockhill, N.J., Dean, A.J., Oh, R.R.Y. and Fuller, R.A. (2022). Beyond the ecocentric: diverse values and attitudes influence engagement in pro-environmental behaviors. People and Nature 4, 1500-1512. https://doi.org/10.1002/pan3.10400

Sunstein, C.R. and Reisch, L.A. (2014). Automatically green: behavioural economics and environmental protection. Harvard Environmental Law Review 38(1), 127-158. https://dx.doi.org/110.2139/ssrn.2245657

Tavoni, M., Kriegler, E., Aboumahboub, T., Calvin, K., DeMaere, G., Jewell, J., et al. (2014). The distribution of the major economies' effort in the Durban platform scenarios. Climate Change Economics 4. https://doi.org/10.1142/S2010007813400095

Tearfund (2019). No Time to Waste-Tackling the Plastic Pollution Crisis before it's too late. Tearfund. Teddington. https://learn.tearfund.org/-/media/learn/resources/reports/2019-tearfund-consortium-no-time-to-waste-en.pdf

Tengö, M., Hill, R., Malmer, P., Raymond, C. M., Spierenburg, M., Danielsen, F. et al. (2017). Weaving knowledge systems in IPBES, CBD and beyond—lessons learned for sustainability. Current opinion in environmental sustainability 26, 17-25. https://doi.org/10.1016/j.cosust.2016.12.005

Turnheim, B. and Nykvist, B. (2019). Opening up the feasibility of sustainability transitions pathways (STPs): Representations, potentials, and conditions. Research Policy 48(3), 775-788. https://doi.org/10.1016/j.respol.2018.12.002

United Nations Educational, Scientific and Cultural Organization (1972). Convention Concerning the Protection of the World Cultural and Natural Heritage. UNESCO. https://whc.unesco.org/en/conventiontext/

United Nations (2019). Global Sustainable Development Report 2019-The Future is Now: Science for Achieving Sustainable Development. New York: United Nations. https://sdgs.un.org/gsdr/gsdr2019

United Nations (2023a). The Sustainable Development Goals Report 2023: Special edition -Towards a Rescue Plan for People and Planet. New York: United Nations. https://sdgs.un.org/sites/default/files/2023-07/The-Sustainable-Development-Goals-Report-2023_0.pdf

United Nations (2023b). Global Sustainable Development Report 2023: Times of Crisis, Times of Change. Science for Accelerating Transformations to Sustainable Development. New York: United Nations. https://sdgs.un.org/sites/default/files/2023-09/FINAL%20GSDR%202023-Digital%20-110923_1.pdf

United Nations Development Programme (2011). Human Development Report 2011. United Nations. https://www.un-ilibrary.org/content/books/9789210549448

United Nations Environment Programme (2019). Global Environment Outlook – GEO-6: Healthy Planet, Healthy People. Cambridge: Cambridge University Press. https://www.cambridge.org/core/books/global-environment-outlook-geo6-healthy-planet-healthy-people/8FE2F127F310561C679B620F1D2EDBA6

United Nations Environment Programme (2021). State of Finance for Nature 2021. Nairobi: UNEP. https://www.unep.org/resources/state-finance-nature-2021

United Nations Environment Programme (2023). Turning off the Tap - How the World can end plastic pollution and create a circular economy. https://www.unep.org/resources/turning-off-tap-end-plastic-pollution-create-circular-economy

United Nations Environment Programme and Food and Agricultural Organisation (2020). The UN Decade of Ecosystem Restoration 2021-2030. UNEP/FAO Fact Sheet https://atthebirdhouse.org/wp-content/uploads/2021/06/UNDecade.pdf

United Nations Framework Convention on Climate Change (2010). Synthesis Report on Efforts Undertaken to Monitor and Evaluate the Implementation of Adaptation Projects, Policies and Programmes and the Costs and Effectiveness of Completed Projects, Policies and Programmes, and Views on Lessons Learned, Good Practices. Bonn: UNFCCC. https://unfccc.int/documents/6094

United Nations Women and United Nations Development Programme (2018). Gender Equality as an Accelerator for Achieving the Sustainable Development Goals. New York: UN Women and UNDP. https://www.undp.org/publications/gender-equality-accelerator-achieving-sdgs

Van Vuuren, D.P., Kok, M., Lucas, P.L., Prins, A.G., Alkemade, R., van den Berg, M. et al. (2015). Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. Technological Forecasting and Social Change 98, 303-323. https://doi.org/https://doi.org/10.1016/j.techfore.2015.03.005

Van den Berg, R., Magro, C. and Salinas Mulder, S. (2019). Evaluation for Transformational Change: Opportunities and Challenges for the Sustainable Development Goals. Exeter: IDEAS

Verdone, M. and Seidl, A. (2017). Time, space, place and the Bonn challenge global forest restoration target. Restoration Ecology. The Journal of the Society for Ecological Restoration 25 (6), 903-911. https://doi.org/10.1111/rec.12512

Verplanken, B. and Orbell, S. (2022). Attitudes, Habits and Behavior Change. Annual Review of Psychology 73, 327-352. https://doi.org/10.1146/annurev-psych-020821-011744

Vervoort, J.M., T.P., Kristjanson, P. et al. (2014). Challenges to scenario-guided adaptive action on food security under climate change. Global Environmental Change 28, 383–394. https://doi.org/310.1016/j.gloenvcha.2014.1003.1001

Yadav, S. and Shekhawat, S. (2024). Indigenous women as agents of environmental change: a study of selected Indian ecodocumentaries. Feminist Media Studies 1-19. https://doi.org/10.1080/14680777.2024.2395973

Yua, E., Raymond-Yakoubian, J., Daniel, R.A. and Behe, C. (2022). A framework for co-production of knowledge in the context of Arctic research. Ecology and Society 27(1), 24. https://doi.org/10.5751/ES-12960-270134

Wood, C. and M. Dejeddour (1992). Strategic Environmental assessment: EA of policies, plans and programmes Impact Assessment. 10(1): 3-22. https://doi.org/10.1080/07349165.1992.9725728

World Health Organization (2023). Air Pollution: The Invisible Death Threat. https://www.who.int/news-room/feature-stories/detail/air-pollution--the-invisible-health-threat

Zárate-Toledo, E., Patiño, R. and Fraga, J. (2019). Justice, social exclusion and indigenous opposition: A case study of wind energy development on the Isthmus of Tehuantepec, Mexico. Energy Research & Social Science 54, 1-11. https://doi.org/10.2139/ssrn.5037713

14 Solution Pathways for the Transformation of Economic and Financial Systems

Co-ordinating Lead Authors: Pierre Failler (University of Portsmouth), Adina Relicovschi (European Investment Bank), David C. Broadstock (National University of Singapore and The Lantau Group)

Lead Authors: Juliana Subtil Lacerda (European Environment Agency), Patricia Maccagno (Moreno National University), Ronaldo Seroa da Motta (State University of Rio de Janeiro), Nkechi Owoo (University of Ghana), Kamaljit K Sangha (Charles Darwin University), Stella Tsani (National and Kapodistrian University of Athens), Jianhua Xu (Peking University)

Fellows: Tegan Evans (University of Portsmouth, Centre for Blue Governance), Laura Fanciulli (Italian Ministry of Environment and Energy Security), Kelo Uchendu (Students Organising for Sustainability)

Image credit: GoldenDayz/Envato

Chapter summary

Credit: leungchopan/Envato

The current global economic and financial systems have inadvertently fostered economic activities that cause significant environmental and social harm (*well established*). In recent years, many efforts have focused on prioritizing more sustainable development principles. Nonetheless, environmental harm from economic activities is pervasive and insufficient action is being taken to address the adverse environmental effects. These trends exacerbate the global environmental crises. Scientific evidence confirms that the world is not on track to achieve the Sustainable Development Goals (SDGs). {14.2}

A well-informed, scientifically driven transformation of our economic and financial systems is necessary to meet the 2030 SDGs and targets (*well established*). Building upon growing interest in transforming our current economic and financial systems to balance the well-being of people and nature presents an opportunity to implement specific solution pathways (SP). Alternatives already exist for driving change and putting the economic and financial systems on a sustainable path. Public and private finance can play a crucial role in reorienting capital flows toward sustainable endeavours. {14.1}

Four solution pathways are identified to facilitate a timely, equitable, and steady transformation of the economic and financial systems (*established but incomplete*). These pathways emerge from a long-standing scientific debate on economic and financial policies and mechanisms to enable a sustainability transition. They explore the economic and financial system changes required to achieve the SDGs. To this end, a timely, just and equitable transformation is discussed within a framework that respects planetary boundaries and considers deep and complex interactions across multiple socioeconomic and environmental issues. Solution Pathway 1 concentrates on the actions required to price externalities adequately. Solution Pathway 2 relates to making sustainability mainstream in multilevel and multilateral governance, as well as in macroeconomic and fiscal policy considerations. Solution Pathway 3 concerns the financial sector, with an emphasis on tools and frameworks that can unlock private financial capital for environmental sustainability projects. Solution Pathway 4 considers the role and use of non-price instruments to engender pro-sustainable norms, attitudes and behaviours. The

numbering of these pathways in no way reflects either their relative importance, or sequencing. {14.2–14.5}

Some solution pathways are already implemented and need scaling up, while others have been tested and have not yet reached the desired outcomes, thus calling for a thorough consideration and update to achieve the desired socioeconomic and environmental goals (*well established*). Certain pathways and actions are based on promising experiences that need to be scaled up, for example, green finance. Others, such as pricing externalities, have had mixed successes, with some carbon markets not fully meeting their objectives. There is no ambiguity or contestability that pricing externalities is necessary for valuing externalities in environmental policy frameworks, hence its retention as a solution pathway. Yet the associated actions can be framed more concretely around the implementation barriers that still need to be overcome, particularly around public policy, awareness and institutional impediments. Ways of avoiding these barriers include redirecting subsidies, implementing higher taxes on polluting activities, offering tax incentives for non-polluting activities, and supporting investment in necessary future technologies. These solutions require data availability, improved socioeconomic and environmental models, big data analysis, machine learning, and artificial intelligence, among others. Transparency in framing and presenting these options is still crucial to attract political and public approval. {14.2}

Economic and policy targets and assessment must be framed within comprehensive principles (*well established*). The economic system needs to move beyond traditional measures of economic activity, such as gross domestic product, by setting up integrated socioeconomic and environmental accounting systems, such as building on existing approaches for natural capital accounting, to reflect a broader notion of progress for policy decision support (SP1– SP4). Lessons can be learned by understanding the links between the environment, sustainability, and well-being from many Indigenous Peoples as well as local communities across the globe. {14.2, 14.3.2, 14.3.3}

Environmentally harmful subsidies must be phased out or drastically reduced, depending on each country's circumstances (*well established*). Existing subsidies, such as for fossil fuels, agriculture and fisheries, which directly favour activities that have significant harmful effects on the environment, including on biodiversity, must be removed through a timely, planned process. Funds from the redirection of subsidies should be used to create innovative financing mechanisms, such as low-interest loans, more autonomous food systems, the use of renewable energy, less agrochemical-intensive agricultural production, nature restoration, and support for low-income local populations, among other initiatives. This approach will benefit the environment and improve the socioeconomic conditions of the most disadvantaged populations, for example, by strengthening Indigenous systems. (SP1) {14.3.1}

Externalities must be integrated into the pricing system that signals the efficient allocation of resources (*well established*). Environmental costs that are not captured in market prices when producing and consuming goods and services must be internalized in economic transactions to make market forces work in favour of sustainable pathways. For instance, the external costs of industrial air pollution from large industrial operators is equivalent to approximately 2 per cent of the European Union's gross domestic product (GDP), while at the global level, costs of fine-particle (PM2.5) air pollution reach 6.1 per cent of GDP, with estimates varying from 1.7 per cent in North America, to 9.3 per cent in East Asia and the Pacific, and 10.3 per cent in South Asia. Water pollution, the leading cause of waterborne and childhood diseases, but also of poisoning and cancer, represents 2.5 per cent of all deaths and 2.9 per cent of all lost days globally. Electricity systems could generate US$11.644 trillion in annual externalities, while transport could generate another US$13.018 trillion; when combined, this is equivalent to 28.7 per cent of global GDP.

From a climate change perspective, the social cost of carbon emissions is US$1,056 per ton of CO2, which is about 15 times the price of a ton of CO2 on the European Carbon Credit Market. Concerning food, at US$19.8 trillion, the current externalities are estimated to be more than double the current total global food consumption cost of US$9 trillion. This means that food is roughly a third cheaper than it would be if these externalities were included.

Internalizing externalities can be realized through both pricing and non-pricing approaches (*well established*). Efficiency in resource utilization can be improved through promoting circularity, restructuring fiscal systems, and fostering sustainable governance (SP1, SP2, SP4). For instance, a circular economy model, where waste generation and economic growth are decoupled by

adopting waste avoidance, sustainable business practices, and full waste management, could avert social costs of more than US$110 billion a year.

Revenues raised through pricing externalities can be used to promote system transformation and minimize distributional impacts (*well established*). Mechanisms such as carbon taxes and carbon markets, water charges, or fees for single use-plastics, as a few examples, contribute to promote the transition to more sustainable economic activities. If well managed fiscally, they can be used to offset distributional effects, funding green activities or reducing the tax burden on labour and capital elsewhere. (SP1)

The estimation of external costs and benefits and their pricing are not trivial processes (*well established*). Different pricing tools may be better suited than others. Appropriateness depends on the policy aim, the nature and scale of the externalities, data and expertise availability, the distribution of the degradation sources, and inequality repercussions. Local institutional capacities and implementation costs must be considered when pricing externalities. (SP1)

Participation and communication strategies in different forms and from diverse sources cannot be neglected (*well established*). Proposed pricing policies and instruments must be well communicated, with a clear and coherent presentation of the total expected benefits and costs, in both the short and long run. More importantly, it should be clear to whom benefits will accrue and how distributive and competitive effects will be addressed, to engage the public and private sectors and, consequently, policymakers and legislators, in support of these policies.

Non-pricing approaches are a necessary complement to price-based instruments for shaping pro-environmental behaviours (*well established*). While price is a powerful force in coordinating economic activity, decision makers also base their actions on other factors – such as preferences, habits, norms and cultures and corrective pricing may not be feasible or fully effective in all cases. Non-pricing tools are therefore necessary, which may include regulatory approaches, soft approaches such as eco-labelling, research and development, and self-regulation or governance and should take into consideration people's ethics and moral values towards ecosystems, which is particularly relevant for Indigenous Peoples as well as local communities (SP4). The suitability and performance of each approach need to be carefully weighed when choosing among them. {14.3.4}

The economic transformation must integrate a nature-positive economy approach, recognizing that long-term prosperity depends on ecosystem health (*established but incomplete*). Policies should prioritize investments in biodiversity, ecosystem restoration, and nature-based solutions to foster a regenerative, resilient, and inclusive economic future. Initiatives such as the Kunming-Montreal Global Biodiversity Framework and the Taskforce on Nature-related Financial Disclosures offer vital guidance for embedding biodiversity considerations into economic governance.

Sustainable finance is an essential enabler and cultivating tool for sustainable economic activity (*well established*). To foster green finance, there is a need to reorient public funds and steer the private sector to place value on the environment, including biodiversity and avoidance of environmental-related risks (SP2, SP3). The estimated cost of delivering net zero GHG emissions by 2050 is US$ 150- 200 trillion (approximately 8 trillion per year). Fragmented sustainable finance frameworks have emerged, with incomplete coverage or implementation within countries and incoherent connections across countries. Reducing fragmentation and enhancing compatibility is required through, for example, the adoption of a common taxonomy to achieve interoperability around the world. Coordinated action across different levels and spaces is required to make the most of the globally mobilized capital that supports the sustainability transition (SP1, SP2, SP3). {14.5.1, 14.5.2}

Making sustainability central to governance, global coordinated action, risk evaluation and management (*well established*). Governance should evolve at local, regional, transnational, and global levels to facilitate coordinated action for the sustainability transition at various levels (SP2). Core actors, especially those that can financially propel the sustainability transition need to be identified, interconnected and jointly mobilized to serve the transition in a timely, just and equitable manner (SP2, SP3). Recognition and strengthening of local governance structures, and Indigenous Peoples and local communities, is necessary to achieve social and environmental sustainability. Revised perceptions of risk are needed, taking a holistic approach to quantifying environmental and sustainability-linked risks connected with business and investment decisions (SP2, SP3).

Accounting for all financially material effects, risks, and opportunities will ensure the confident inclusion of sustainability in financial decision-making. This will also enhance the overall resilience of the financial sector to a more comprehensive array of physical and transitional risks and shocks, by centralizing sustainability within risk management frameworks (SP3).

The undue pressure for short-term performance in financial and economic decision-making must be reduced for finance to prioritize environmental sustainability effectively (*established but incomplete*). Investments in environmental objectives require a long-term orientation that contrasts with the prevailing short-term high-return practices (SP2, SP3). This requires a balanced and transparent approach that utilizes the most effective levers across the system, including capital providers, capital seekers, policymakers and regulators. {14.4.4, 14.5.4}

Actions, such as overall capacity expansion and preparedness steps, are shared priorities for all solution pathways (*established but incomplete*). Achieving the goals of the solution pathways will involve actions common to all, for example, capacity expansion in terms of both the quantity and quality of relevant human capital to deliver the pathways. Preparatory steps will have similar attributes for each pathway, including reviews of existing mechanisms, laws, regulations and policies, as well as engagement with all members of society on the ways in which they are both necessary and exciting opportunities to embrace transition in the economic and financial systems. {14.4}

System transformation will only be achieved through combining solution pathways to achieve the desired socioeconomic and environmental goals (*well established*). The co-development of other complementary pathways strengthens individual pathways. Focusing solely on an individual solution pathway risks adverse side effects on the other three pathways or forgoing potential synergies, thereby missing multiple co-benefits. A holistic perspective based on the joint implementation of these pathways increases efficacy, prevents lock-ins and mobilizes opportunities to accelerate and leverage the transformation towards a sustainable economic system. Adaptive management and implementation of solution pathways can address evolving country conditions, by switching between, or rebalancing focus among the different solution pathways. To this end, various synergies among the solution pathways are not only recognized but should be exploited. For instance, revenues from the internalization of externalities (SP1) can be used to support green financing instruments (SP3), tools such as environmental, social, and governance ratings, and also addressing growing consumer demand for greener products (SP4), all facilitated through well-structured macro-governance systems (SP2). {14.4}

Important synergies exist between the economic and financial systems, as well as with other connected systems for food, energy, circularity and environment (*established but incomplete*). Broadening the scope of economic and financial systems is essential to ensuring that they are based on valuation frameworks that account for a wider and more inclusive range of societal and ecological values. These values are fundamental to Indigenous Peoples as well as local communities and their significant contributions to managing natural systems and ecosystem services in the context of circularity principles and restoring the natural cycle. Promoting such synergies and values will enable a more balanced allocation and use of resources to maintain ecosystems, people's well-being, and societal resilience. {14.4}

14.1 Introduction

Economic and financial systems exist to help organize markets for goods and services and to facilitate the efficient use and allocation of typically finite, and often non-renewable, resources. Through their roles in pricing and facilitating the exchange of resources, these systems shape the boundaries of economic transition and development pathways. Yet the current economic paradigm, with economic activity being exploitative and fossil-fuel intensive, is contributing pollution pressure and accelerating the unsustainable use of air, land, and water, among other natural resources (World Bank 2023), and creating systematic risks for investors, businesses, the financial system, governments and society. The benefits and consequences of the unsustainable use of these systems are unequally shared among human societies across global, regional and local scales, with disproportionate effects on many Indigenous Peoples, as well as local communities. There is a need to recalibrate the economic paradigm to be less dependent on extractive resources and more integrative of environmental limitations and social development needs across sectors and activities. This is a precondition for the transformations that need to be achieved in efficient circular systems of resource use, and in the energy, food and environment systems.

The key features of a well-functioning modern economic system include people, as residents, decision makers, entrepreneurs and the providers of labour, as well as physical resources, including land and natural resources. There are also several necessary institutions, including governments, legal and regulatory systems, and financial markets, to steer capital flows efficiently. These institutions serve an important purpose in providing critical economic infrastructures of common societal value, but they are either undervalued by individuals, as in the case of education or the environment, and cannot realistically

Credit: StructuredVision/Envato

be provided by private parties, for example, transport and communication networks.

Economic systems can be broadly characterized as either a market economy or a planned economy. In a pure market economy, the choice is made to rely on unfettered market forces, that is, the actions of sellers and buyers of goods and resources to determine how resources are allocated. In contrast, a pure planned economy approach would see resource-allocation decisions determined centrally by governments. There are compelling reasons for placing trust in market forces, yet in real-world settings there are many instances where markets, left to their own devices, fail to allocate resources as desired, for example, as a result of negative externalities and information asymmetry, among others. In such conditions, government intervention can be pivotal to achieving well-functioning markets, particularly where private and social costs or benefits of resource use diverge, as has been the case with environmental resources. In practice, most economies operate somewhere between the two extremes of market and planned configurations, balancing the efficient allocation of resources and equity in the distribution of wealth and welfare, and tailoring them to local conditions.

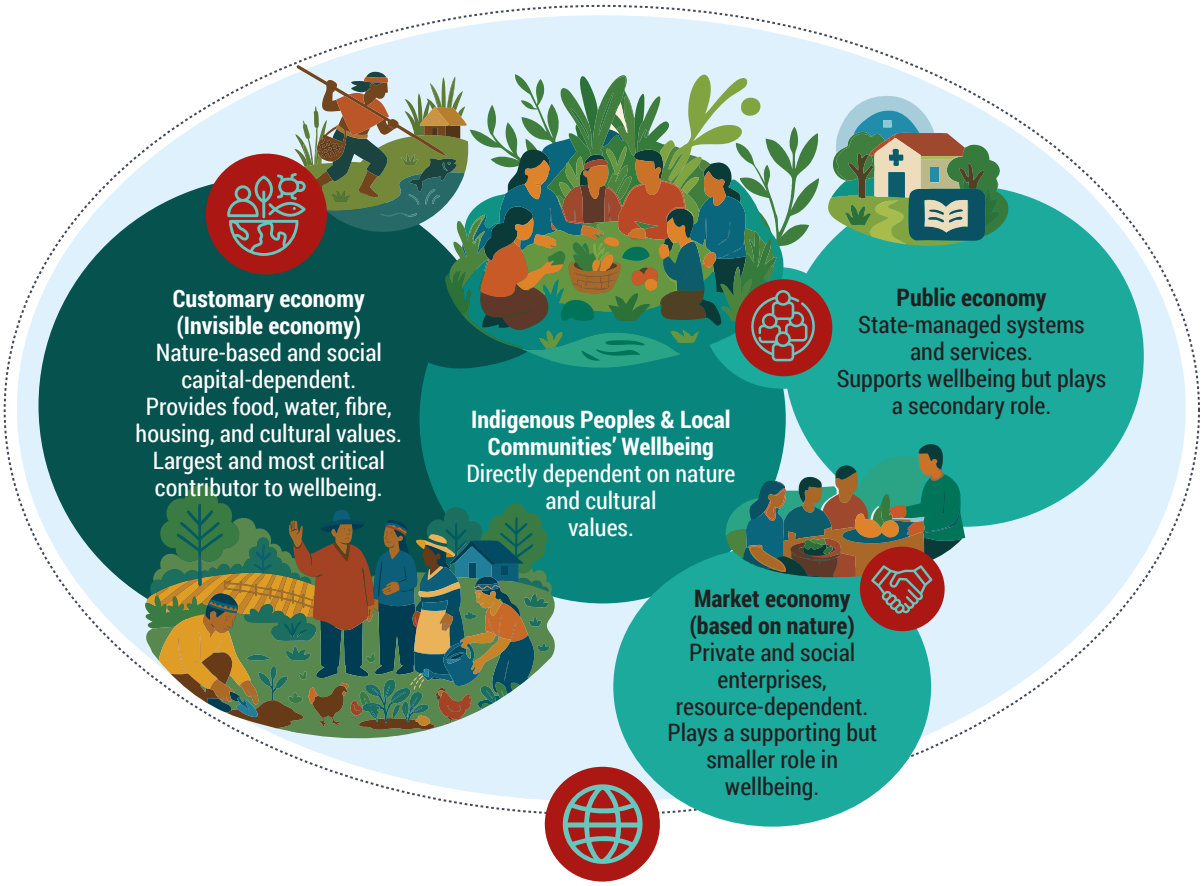
Current economic and financial systems are built on a set of values and valuation methods that are applicable to mainstream society and consider only the instrumental and monetary values of nature (Dasgupta 2021; Intergovernmental Platform for Biodiversity and Ecosystem Services [IPBES] 2022). There is a growing awareness that our modern economic systems depend heavily on nature (Costanza et al. 1997; Costanza et al. 2014), with around 50 per cent of global gross domestic product (GDP) originating from sectors moderately or heavily dependent on nature (United Nations Environment Programme [UNEP] 2022; PricewaterhouseCoopers [PwC] 2023). In supporting the growth of these systems, our activities have transgressed six out of nine planetary boundaries (Richardson et al 2023), with an estimated loss of US$7 trillion in externalities each year through the loss of pollinators and other biodiversity, land degradation, greenhouse gas emissions and pollution, among others. Moreover, global, regional and national sustainability agendas take little account of the fact that natural resources are finite and non-substitutable (UNEP 2024). Indigenous Peoples and many local communities often adhere to value systems that are embedded in nature. Their resource utilization from natural systems applies integrated and relatedness perspectives, such as Mother Earth or Mother Nature (Sangha and Russell-Smith 2017; IK & LK Dialogues 2025). Their worldviews, which encompass the intrinsic and relational values of nature, and focus on social-environmental balance, local economies, and environmental justice, contrast with the mainstream economic thinking that has become reliant on extractivism, extended value chains and perpetual growth (Sangha 2020; IK & LK Dialogues 2025).

Indigenous Peoples as well as local communities comprise about 2.5 billion people, with 476 million Indigenous People from 50 countries (International Labour Organization 2020; Rights and Resources Initiative 2023) and they depend closely on nature and its services to support their well-being and livelihoods. However, their economies are largely invisible to the modern economy (**Figure 14.1**). Traditional ecological knowledge, cultural practices and values are key to sustaining and regenerating biodiversity and nature's services (IK & LK Chapeau D). Deliberate integration of the capabilities, skills, knowledge and related cultural practices used by Indigenous Peoples, as well as some local communities, into mainstream economic systems, governance and policy design can help the transition towards sustainability. As a co-benefit, this integration will pay dividends in the future management of nature's resources at a global scale (Sangha and Russell-Smith 2017; Sangha et al. 2021; Balasubramanian and Sangha 2021).

At a broader level and to maximize effectiveness, the required range of policies and practices needed to implement the solution pathways and support transformative change in the economic and financial systems must be inclusive. These policies and practices need to place greater emphasis and attention on integrating the role of Indigenous People, communities and local knowledge. Similarly, integrating gender perspectives is also essential for achieving inclusive and equitable development. Economic transformation must account for gender disparities to ensure equitable benefits for both men and women from economic growth and sustainability initiatives. This includes promoting women's participation in green jobs and ensuring that economic policies do not disproportionately disadvantage women.

The financial system includes macroeconomic finance and central-banking systems together with traditional banking systems, insurance providers and pension

Figure 14.1: An outline of the Indigenous Economy



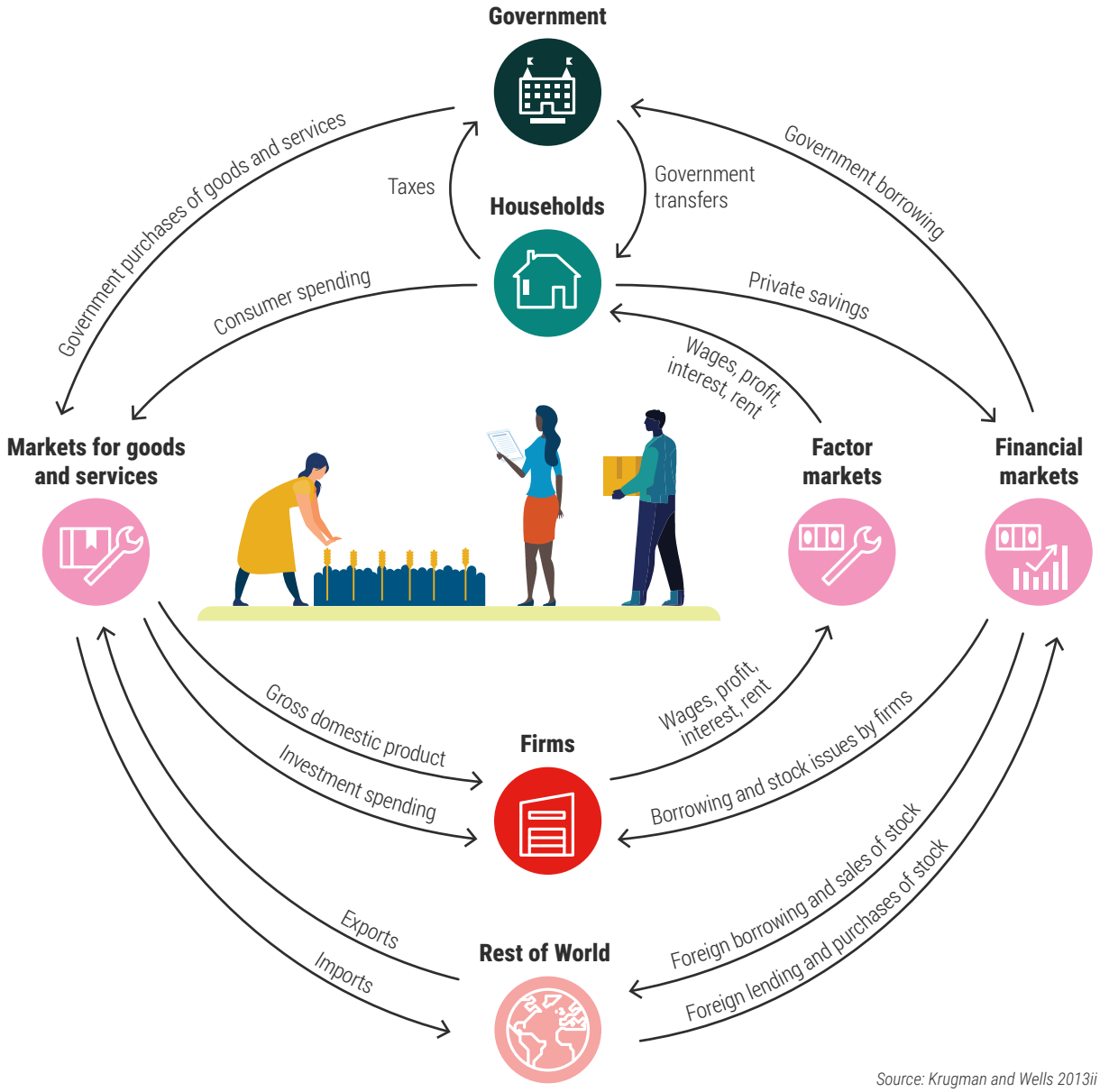
Note: This figure highlights Indigenous Peoples and local communities' direct dependence on nature. They operate in a hybrid economy comprising: 1. Customary economy – mostly based on nature and social capital, comprising the largest part; 2. Public economy – managed by the State governments; 3. Market economy – managed and run by the private sector, including local and/or social and private enterprises. Among these, the customary economy is the largest and plays a critical and direct role in people's well-being, followed by the public and private sectors (the thickness of the arrows corresponds to importance). The outer circle denotes the broader State/Regional level socioeconomic, cultural and political systems that shape and impact Indigenous economies.

funds, equity and commodity markets among others. The financial system operates as an enabler of the economic activity through its crucial role in facilitating the allocation of resources by enabling economic transactions that are fairly and consistently priced with diligent consideration of the risks attached to investments (**Figure 14.2**). In so doing, they increase trust and enable capital allocation to occur with greater confidence while offering fair compensation. The financial system promotes stability and confidence within an economy.

The current economic and financial systems have underdelivered on the SDGs. There are several reasons for this, including:

- Societal and environmental costs and benefits in producing and consuming goods are not fully captured in market prices as a result of market, government, and/or incompatible behaviours;
- Incompatibility between incentives for directing capital flows and SDGs;
- Limited monitoring and accountability for environmental externalities and risk perception biasing measures;
- Short-termism and increasing levels of speculation in financial markets;
- Markets heavily discounting future cash flows, demagnifying the effects on future generations;
- Normative and cultural institutions fail to instil green awareness in daily, corporate, and national decision making; and
- Failure to apply ethics principles to market and financial systems.

Figure 14.2: Finance and the economy - an extended circular flow diagram of an economy



Source: Krugman and Wells 2013ii

The incumbent economic and financial systems display a low awareness of, and in many countries a high level of inaction for, normalizing environmental sustainability. Current systems must also be overhauled to match the ideals and values propagated by sustainable development. Procrastination only serves to exacerbate the global environmental crises, with major and enduring adverse effects on society, including human well-being and capabilities, food systems and food patterns. including human well-being and capabilities, food systems and food patterns.

Transformation in the structure and use of our economic and financial systems is urgently needed on a global scale. An expanded economic toolkit, built upon comprehensive measures of economic progress, must prioritize a more balanced definition of prosperity. The traditional leading economic indicator, GDP, in its broadest sense reflects how much monetary income or output a country generates within its fixed borders and is usually measured across a given year or quarter (World Bank 2021). However, GDP accounting does not capture resource use and degradation, nor does it account for the externalities associated with economic actions, that is, it does not reflect all the social benefits and costs of economic activity (Costanza et al. 2014). To solve such problems, the UN developed the System of

Environmental-Economic Accounting in 2012 and the System of Environmental-Economic Accounting: Ecosystem Accounting in 2021. A significant number of countries have implemented these systems through systematic accounts or registries that organize information on the state and dynamics of ecosystems, as well as their interaction with the economy. However, not all these countries have fully implemented all environmental accounts or registries. To this end, taking into account the literature (Our Common Agenda 2023; Stiglitz et al. 2018), this approach proposes supplementing GDP with a panel of indicators to include metrics that assess ecosystem health, biodiversity integrity, and natural capital value, recognizing that both systems can complement each other.

Natural systems contribute to human well-being, not only as inputs to the production of consumer goods, but also through combinations of use and non-use values, including flood protection provided by mangroves to coastal cities, the sequestration of CO2 by forests, and the maintenance of biodiversity. However, since they are often not priced in nor their contributions accounted for in modern economic and financial systems, these benefits can be difficult to realize (Bastien-Olvera and Moore 2022).

There is increasing consensus around the need to replace the goal of unlimited increase of economic growth as it is not achievable, given the planet's environmental limits (Kallis et al. 2025). As a result, global sustainable development is being constrained as rapid economic growth leads to resource scarcity and environmental degradation (Lv et al. 2022). In addition, the consequences of our unsustainable systems are unequally shared across different countries and within national populations, with the worst consequences for vulnerable societies in developing countries (International Federation of Red Cross [IFRC] 2018; FAO, UNDP, and UNEP, 2021; Damania et al. 2023).

The ultimate goal of economic development is to enable fair living standards for present and future generations on a shared planet with other living species. Realizing this goal requires continuing to use land and natural resources, labour, and capital to produce goods, while maximizing the efficiency of resource utilization, minimizing the emissions of pollutants and greenhouse gases, and balancing other social objectives such as equity. A paradigm shift is needed for the transition towards more resilient, healthier and inclusive economies (UNEP and International Resource Panel [IRP] 2024). A more sustainable and equitable path forward requires the following:

- Redesign of our economic system and development paradigm, placing environmental costs and benefits, and ethical principles of justice and equity at its core;
- Reorientation of capital flows towards environmental sustainability; and,
- Reshaping normative and cultural values to realize a thorough green transformation.

Achieving transformative change requires understanding key actors in the economic system, and their roles in decision-making regarding resource allocation, production organization, and goods and services distribution. Market failures cannot be solved purely with market-based solutions; governments, markets, and society all play important roles. There is an urgent need to rebalance the playing field with favourable institutional conditions that account for economic, environmental, and social effects on people and the planet, while fostering sustainable production and consumption patterns. Further, changes must recognize and address information asymmetries that lead to different decisions and opportunities among economic agents. Acknowledging that "…contributing to and achieving the SDGs offer a compelling growth strategy for businesses and for the world economy as a whole" (Business and Sustainable Development Commission 2017) renders sustainability-oriented transformation attractive. As a way forward, considerations should include:

- In current economic systems, natural resources are massively undervalued, ecosystem services are not paid for or are underpaid, and the rights of using common resources are not clearly defined, making the formation of price signals impossible. Barriers to transformation need addressing,and favourable institutions should be created or strengthened to facilitate the formation of optimal prices for, or to recognize the value of natural resources and ecosystem services.

- Beyond using pricing, a green mentality is also needed to drive transformation, requiring fundamental change in our normative and cultural value systems. Both coercive and incentive approaches, such as regulation and exhortation, are needed to facilitate green behaviours and to revolutionize the current value system regarding our relationship with nature.

- A more holistic and less transactional approach from the financial system requires a focus on making all business and investment decisions more sustainable, enhancing advisory services, and accounting for all detrimental and beneficial effects on people and environment. This approach will be aided by utilizing the most effective levers across the system, including capital providers, capital seekers, policymakers and regulators.

Moving away from the linear economic model and transitioning to a regenerative growth model that gives back to the planet more than it takes is essential to keep resource consumption within planetary boundaries (Raworth 2017). The current linear pattern continually increases its demands on scarce natural resources. Committing to circular economy principles ensures that sustainable products, services and business models become the norm, and catalyses the transformation of consumption patterns.

Transformation requires multiple actions, utilizing the structure and workings of economic systems based on their first principles. Many actors will need to cooperate in driving forward one or more actions in tandem to ensure transformative change in economic and financial systems. These actions are described within four solution pathways aimed at recalibrating central attributes of the supporting systems (**Figure 14.3**).

- SP1: the revised use of pricing mechanisms to internalize the externality

- SP2: reconstituting macro-level governance architectures

- SP3: accelerating and expanding the deployment of green and climate finance mechanisms for steering private sector capital

- SP4: making more extensive use of non-pricing mechanisms to guide our consumption choices and broader economic actions.

These solution pathways have been selected on the basis of their policy relevance and actionable system features. Another reason is their capacity to change the current situation due to their incremental and innovative conception of how economic activity can be organized, such as promoting circularity. Finally, they represent necessary solutions such as pollution taxes that, despite mixed successes, remain an essential component of future policy and have irrefutable scope for scaling up and duplication to different contexts.

These pathways can be conveyed cumulatively through the lens of two overarching goals for achieving transformative change in the economic and financial systems, as follows.

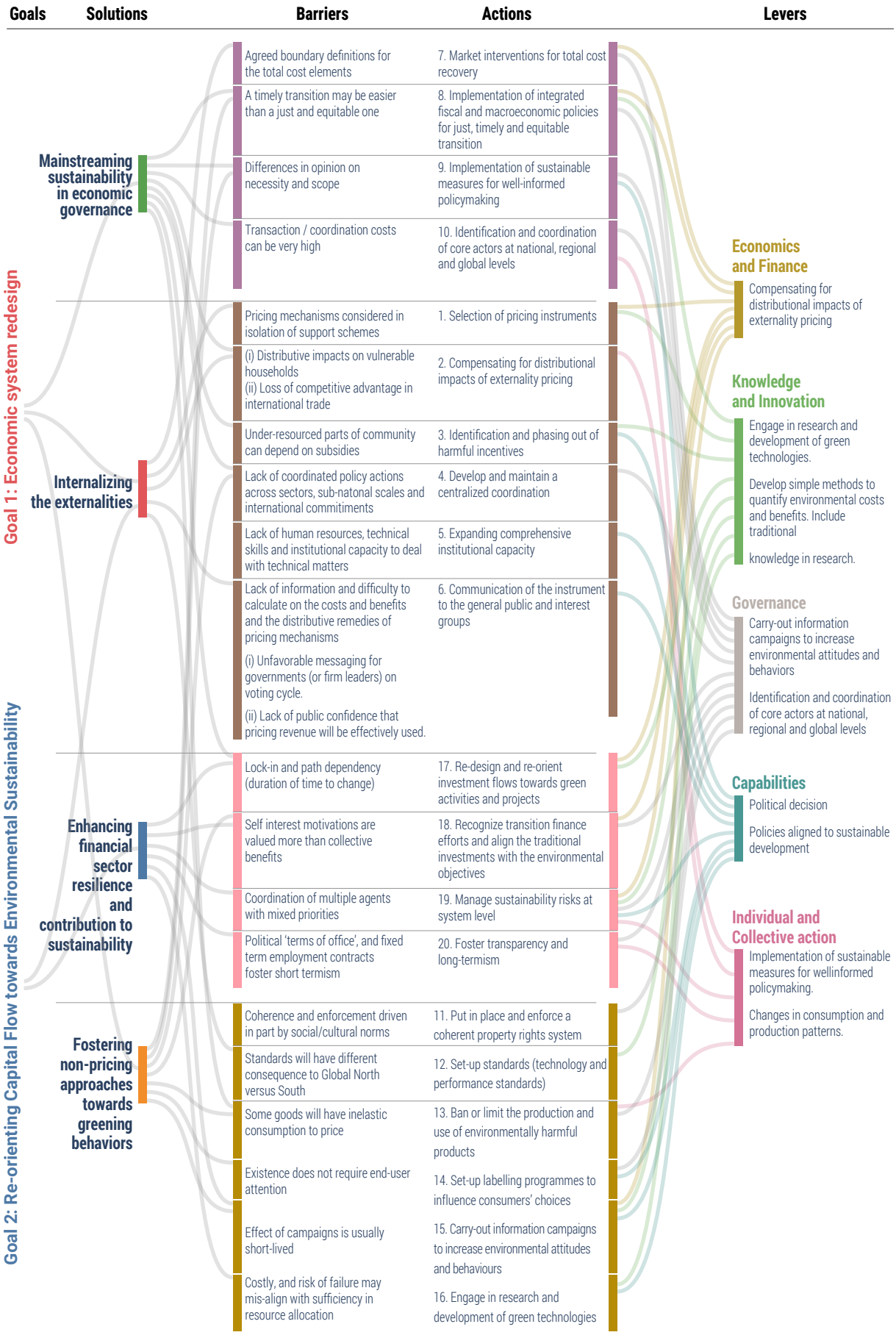
14.1.1 Goal 1: Economic system redesign

The economic system transformation required to achieve the SDGs, providing a just and equitable future for all on a stable and resilient planet, involves deep and complex interactions across multiple socioeconomic and environmental issues. Focusing on any individual solution pathway entails the risk of missing out on benefits unique to a given pathway or forgoing potential synergies. The four solution pathways proposed here are integrated and complementary, with multiple parallels and co-benefits available through their joint implementation. For instance, internalizing externalities (SP1) through taxes, charges and tradable permits can generate a flow of funds to support green financing/projects (SP3), favouring more sustainable production that meets growing consumer demand for greener products (SP4), supported by economic governance with coordinated policies at national and international levels (SP2).

14.1.2 Goal 2: Reorienting capital flows towards environmental sustainability

Steering capital flows towards addressing the global environmental crises is a key enabler of the transformation towards sustainable economic systems. Easing access to capital in the right place and at the right time will foster innovation, scale up low-carbon technologies, and accelerate the transition to a greener global economy. To this end, there are

Figure 14.3: Goals, solutions, barriers and levers diagram to show combination of solutions and levers to achieve goals for the economic and financial systems



important synergies among the solution pathways presented here and other systems. For example, a measure such as policy support to research and development of low-carbon technologies may tackle the internalization of externalities (SP1), green financing (SP3) and the needed behaviour changes towards higher sustainability (SP4).

14.2 Solution Pathways to achieve transformative change

Economic activity and sustainable development are not mutually exclusive and must be achieved in parallel and along the same trajectory, not in competing or opposing directions. A range of options is available for driving transformative change and placing the economic system on a more sustainable path, integrating renewed public investment strategies with increased efforts to direct private capital, while avoiding lock-in to unsustainable practices. These include both direct controls, such as pollution limits and quotas, and market-based instruments, including charges, taxes, fees, the redirection of harmful subsidies, tradable emissions permits, and payments for environmental services. Other examples are given in the Organisation for Economic Co-operation and Development (OECD) Policy Instruments for the Environment Database (OECD 2023a).

Four solution pathways are proposed to address existing market failures and re-optimize investment incentives for the private sector. Because many natural assets are public goods, the undervaluation of inherent environmental benefits in investments, and information asymmetries, the market alone cannot deliver optimum environmental benefits. Public sector intervention is warranted to mitigate such market failures, particularly for projects that offer positive environmental benefits. The delivery of environmental benefits most often hinges on public sector intervention, whether through regulation, incentives, taxation or even provision of goods and services. Without these, private sector stakeholders are unlikely to engage in reducing pollution, their environmental footprint, or soil and water conservation.

In addition to market failures, both private and public sector promoters face numerous barriers that hinder the design and implementation of investments. There are common financial market barriers to redirecting capital towards sustainable investment consistent with those that limit the development of and access to financial markets more broadly (Intergovernmental Panel on Climate Change [IPCC] 2023):

- There are varying levels of country indebtedness, economic vulnerability, regulatory uncertainty and fragmentation, perverse incentives and subsidies, as well as differences in administrative procedures. Coupled with this is a lack of international assistance and coordination, resulting in slow uptake for green de-risking facilities. Particularly among low-income countries with low credit ratings, sometimes below investment grade and unattractive risk-return profiles, underpinned by missing or weak regulatory environments or misaligned ambitions (Matthews and Karousakis 2022).

- Market infrastructures are sometimes improperly implemented, inhibiting a well-functioning banking system, leading to inefficient capital markets such as regional mismatch between available capital and investment needs, higher cost for sustainability products, and prevent sustainability-related impacts from being accurately reflected in traditional financial statements.

- Market size and structure affect the financial viability of investments. Different structures and standards between countries can make investments more difficult.

- A lack of budgetary resources to design and implement investments is a common problem for public sector investment promoters, as are weak planning and preparation capacity, especially for complex investments.

- Limited choice and access to affordable finance are barriers frequently encountered in the private sector, particularly among small to medium-sized enterprises (SMEs). Many firms in low-income countries and SMEs struggle to find sustainable finance instruments that apply to their primary industries, and SMEs often lack the expertise and sufficient capital to access green loans or green bonds market.

- Limited institutional capacities make it challenging to ensure safeguards or provide adequate assessment of climate-related and pollution or biodiversity-related impacts, risks and opportunities.

- There is low investment due to a risky environment with increasing severity, unpredictability and frequency of risk events. Related risks include political risks such as conflicts, climate risks like drought, geo-physical risks such as earthquakes, and pollution risks, as well as epidemics and disease outbreaks.

The proposed solution pathways not only need to address multiple market failures, but also to overcome or circumvent the need to face the various barriers described above. **Figure14.4** presents an overview of how these are linked with supporting actions that are required to be taken.

Solution pathways must also be nature-positive, ensuring that economic and financial systems actively contribute to ecosystem regeneration. Leveraging biodiversity-inclusive financial instruments and nature-based solutions (NbS) will create economic value while preserving planetary health. Governments, businesses, and financial institutions must work together to align investments with nature-positive objectives, fostering long-term resilience and prosperity.

Growing awareness of society's dependence on natural resources has elevated the importance of locally led adaptation to address climate risks, especially those faced by Indigenous Peoples as well as local communities. (Coger et al. 2022) highlight examples of how the local knowledge of communities and institutions can provide more coherent, flexible and cost-effective adaptation solutions. Indigenous Peoples as well as local communities, have been operating their nature-based economies for millennia and hold enormous potential to contribute towards developing and redesigning innovative, solution-focused approaches to modern economic and financial systems.

Indigenous and local communities' economies hold enormous potential to drive solutions-focused approaches that both grow Indigenous economies and increase well-being. The Periyar Tiger Reserve in the Western Ghats of India is a notable example, spanning an area of 777 km² in the state of Kerala. Credit: wirestock/Envato. The Indigenous Adivasi communities, comprising over 225,000 people, have been living in harmony with tigers and other wildlife for millennia, contributing to the state conservation economy while preserving their own. Due to its high conservation value, the area was declared a reserve in 1978 under India's Wildlife Protection Act (1972), which affected the Adivasi economies and rights. However, in 1996, India's State Forest Department, together with the World Bank, implemented an eco-development project in the tiger reserve. The project supported Adivasi communities in developing alternative livelihood-related economic opportunities and reduced their economic dependence on natural resources within the reserve. Village-level eco-development committees were established with Adivasi communities given key roles in informing forest management and advancing their aspirations, in collaboration with the Forest Department (Bhardwaj 2023).

Supported by the eco-development committees and project initiatives, Adivasi people from Periyar Tiger Reserve and nearby conservation areas grew local economies through cultivating local crops, ecotourism, employment as forest watchers, forest guides, and revival and recognition of tribal culture. The government allocated land for cropping to Adivasi families living within the reserve, who cultivated a variety of crops organically without clearing the land. Organically grown pepper and cardamom are of a higher quality that fetches better prices in the market. This initiative generated income and sustained more than 200,000 person-days of employment, while also boosting the state's tourism economy, conservatively estimated at roughly US$300,000 per annum, with over 600,000 visitors per year (information obtained from the Forest Department). Gender equality was also supported through the active participation of women in crop cultivation and management, as well as the establishment of a specially designated eco-development committee, Vasantha Sena, where more than 60 Adivasi women volunteer to protect the local sandalwood forest, previously a target for illegal harvesting (Bhardwaj 2023).

Another relevant example includes Lattu Lifespring, a community-based organization in Isiolo County in northern Kenya with support from the PAWANKA Fund (2021). Through community dialogues, Elders

Figure 14.4: Solution Pathways for Transforming Economic and Financial Systems

Making prices reflect true costs (Internalizing the Externalities)

Objective: Incorporate environmental and social costs into pricing systems to incentivize sustainable production and consumption while addressing market failures.

Strengthen government capacity to design, enforce, and monitor pricing policies.

Apply taxes, charges, or cap-and-trade systems to correct the price of goods and services that generate pollution, biodiversity loss and land degradation.

Promote Payments for Environmental Services (PES) to support carbon sequestration, watershed protection, and biodiversity conservation — including Indigenous and local conservation systems that sustain these ecosystem services.

Phase out environmentally harmful subsidies and redirect funds to sustainable alternatives.

Clearly communicate the benefits of these pricing policies to build public and industry support.

Mainstreaming sustainability in economic policies

Objective: Make sustainability a core part of national and global economic governance, ensuring inclusive and coordinated transitions.

Align government budgets and economic policies with sustainability goals.

Ensure businesses and industries cover the full costs of environmental damage through policy interventions.

Ensure economic policies consider both environmental and social fairness.

Improve coordination between local, national, and international policymakers.

Ensure inclusive economic governance by actively engaging Indigenous Peoples and Local Communities in decision-making processes, recognizing their governance systems and knowledge.

Strengthening the financial sector's role and resilience in sustainability

Objective: Align financial systems with sustainability goals by directing investments toward environmentally responsible projects and reducing financial risks linked to climate change.

Increase transparency in financial markets and promote long-term decision-making over short-term profits.

Improve international cooperation to set common financial rules and sustainability standards.

Support industries transitioning to sustainable practices while ensuring traditional investments align with climate goals.

Shift investments toward green technologies, clean energy, and low-carbon solutions.

Encouraging sustainable choices beyond pricing

Objective: Promote environmentally friendly behaviors through laws, education, and technology, to complement pricing mechanisms.

Establish clear property rights and standards for resource use, technology, and pollution limits.

Run awareness campaigns to encourage responsible consumption and sustainable lifestyles.

Ban harmful products and promote eco-labeling programs to guide consumer choices.

Invest in research and innovation to develop green technologies and make sustainable choices easier.

Integrate Indigenous and local knowledge systems into sustainability efforts, recognizing cultural values and ethics as essential drivers of behavioral change.

Achieving transformation through synergy

These four strategies are interconnected. Focusing on just one solution is not enough—a balanced approach ensures greater impact and avoids unintended consequences. Combining smart pricing, strong policies, responsible finance, and supportive regulations creates a faster, fairer, and more sustainable transformation of our economic and financial systems.

passed on knowledge and practical skills on resource management, including their observations about environmental change, while also learning about climate change from younger generations and surrounding communities. This facilitated a convergence of traditional and contemporary understandings of climate change, where aspects of Indigenous resource management, land rights, and reduction of climate change impact on their environment as well as resilience-building.

To give a sense of the scale of the value of Indigenous economies, in Canada it is estimated to contribute US$32 billion, with small and medium-sized enterprises, largely nature-based, contributing US$927 million in 2015 (T.D. Economics 2015). In north Australia, on a parcel of land representing less than 1 per cent (29 million ha) of Australia's land area, Indigenous Peoples generated more than US$100 million worth of carbon abatements using their unique knowledge to improve fire management practices (Sangha et al. 2021; Indigenous Carbon Industry Network 2024).

Important messages from these examples include:

- Indigenous economies and conservation can go hand in hand if developed inclusively in participation with locals, in line with local values.
- The value of Indigenous economies is largely invisible, partly because the technical mechanisms for valuing personal, business and national finances do not adequately account for self-management or auto-consumption, nor for exchange or trade through barter, nor for the exchange of knowledge.
- The well-being of Indigenous Peoples – including availability of food, employment, and connections to the landscape is significantly enhanced with the implementation of the solutions-based approach.

Importantly, such a solutions-based approach delivers on 11 SDGs, including reducing hunger and inequity, enhancing incomes, improving health, supporting communities, supporting life on land and shifting local development pathways towards sustainability in the near and long term. In contrast to the Periyar Tiger Reserve example, the general population are reliant on modern economic and political systems. Indigenous value systems and cultural practices can help the wider population enhance their well-being beyond the limits of the current market economy.

14.3 Solution Pathway 1: Internalizing the externalities – correcting pricing

The goal of this pathway is to incorporate external social and environmental costs and benefits into market prices, thereby transforming market forces towards sustainable and circular practices in the production and consumption of goods and services.

Prices are crucial within economic systems, serving as a mechanism to guide resource allocation, shape incentives and behaviours, promote market efficiency, and signal important information that maximizes opportunities for buyers and sellers without increasing transaction costs while fostering competition. This has not, however, been the case for environmental goods and services where supply and demand outcomes often with excessive production and consumption levels have not always reflected the full social costs and values to consumers or producers, otherwise known as the negative externality problem. To enable a sustainable pathway, proper pricing of resources, materials, goods and services should reflect the value and/or costs to those that directly consume them, as well as the indirect value to other parties that demand and supply interactions fail to incorporate. A simple example would be the burning of coal for energy. The direct value for producers and consumers derives from the energy itself. Yet, there is negative value generated to the environment due to the pollution from burning coal. This includes consequences for the environment that affect people´s well-being in the short and long term that need to be incorporated into the prices to ensure sustainable pathways and reflect the true costs and benefits of burning coal, thereby eliminating market distortions.

The magnitude of the externalities is reflected in the following figures. Current food externality costs are estimated to be almost double (US$19.8 trillion) the current total global food consumption (US$9 trillion). These externalities account for US$7 trillion in environmental costs, US$11 trillion in costs to human life and US$1 trillion in economic costs. As such, food

is roughly a third cheaper than it would be if these externalities were included (Hendriks et al. 2023). In the fisheries sector, depending on the practice, the societal costs reflected by the price of fish vary from 1, for a handline on non-motorboat, to ten times, for industrial bottom trawling (Failler et al. 2022).

The external costs of industrial air pollution from the large industrial operators are equivalent to two per cent of the European Union's (EU) GDP, or US$4.3 trillion (Sovacool et al. 2021). Electricity systems generate US$11.644 trillion in annual externalities and transport another US$13.01l trillion. Combined, this US$24.662 trillion in externalities is equivalent to almost twenty-nine per cent of global GDP. Estimation of the global health cost of mortality and morbidity caused by exposure to $PM_{2.5}$ air pollution is about US$8.1 trillion (World Bank 2022), was an amount equivalent to 6.1 per cent of global GDP, with estimates varying from 1.7 per cent of North American GDP, to 9.3 per cent of the GDP in the East Asia and Pacific regions, and 10.3 per cent in South Asia. Although industrial air pollution in the EU has decreased by about 33 per cent in the last decade, partly due to environmental policies that have placed prices and costs on industrial pollution, industrial air emissions still had an estimated external cost, averaging between US$255–4078 billion per year (European Environmental Agency [EEA] 2024). Social externalities due to water pollution, the main cause of waterborne and childhood diseases, but also poisoning and cancer, correspond to 2.5 per cent of all deaths and 2.9 per cent of all lost days globally (Wolf et al. 2023 and World Health Organization [WHO] 2023). Thus, safe drinking water, sanitation and hygiene could have prevented at least 1.4 million deaths and 74 million days lost to illness, disability and death. Examining the externalities from a climate change perspective reveals that the social cost of carbon emissions is US$1,056/ton CO_2, six times greater than previously thought (Bilal and Kanzig, 2024). The influence of global as opposed to local climate shocks is higher in warm countries that are more vulnerable than temperate ones. Tourism contributes significantly to the generation of externalities. In Australia, tourism taxes also generate externalities, estimated at US$35 per external visitor to Australia, while the visitor tax contribution is only US$25 (Ihalanayake 2013). For the Pacific Island countries, tourism externalities outweigh their net contribution to their GDP (Amardeep et al. 2023).

Hence, the costs generated by the pollution of water, soil, air, flora, and fauna and their global effects, such as ozone depletion, the greenhouse effect, and biodiversity loss, should be incorporated into prices throughout the entire product life cycle (UNEP 2023). Despite this, **Figure 14.5** shows that tax revenue on pollution is low in the selected countries.

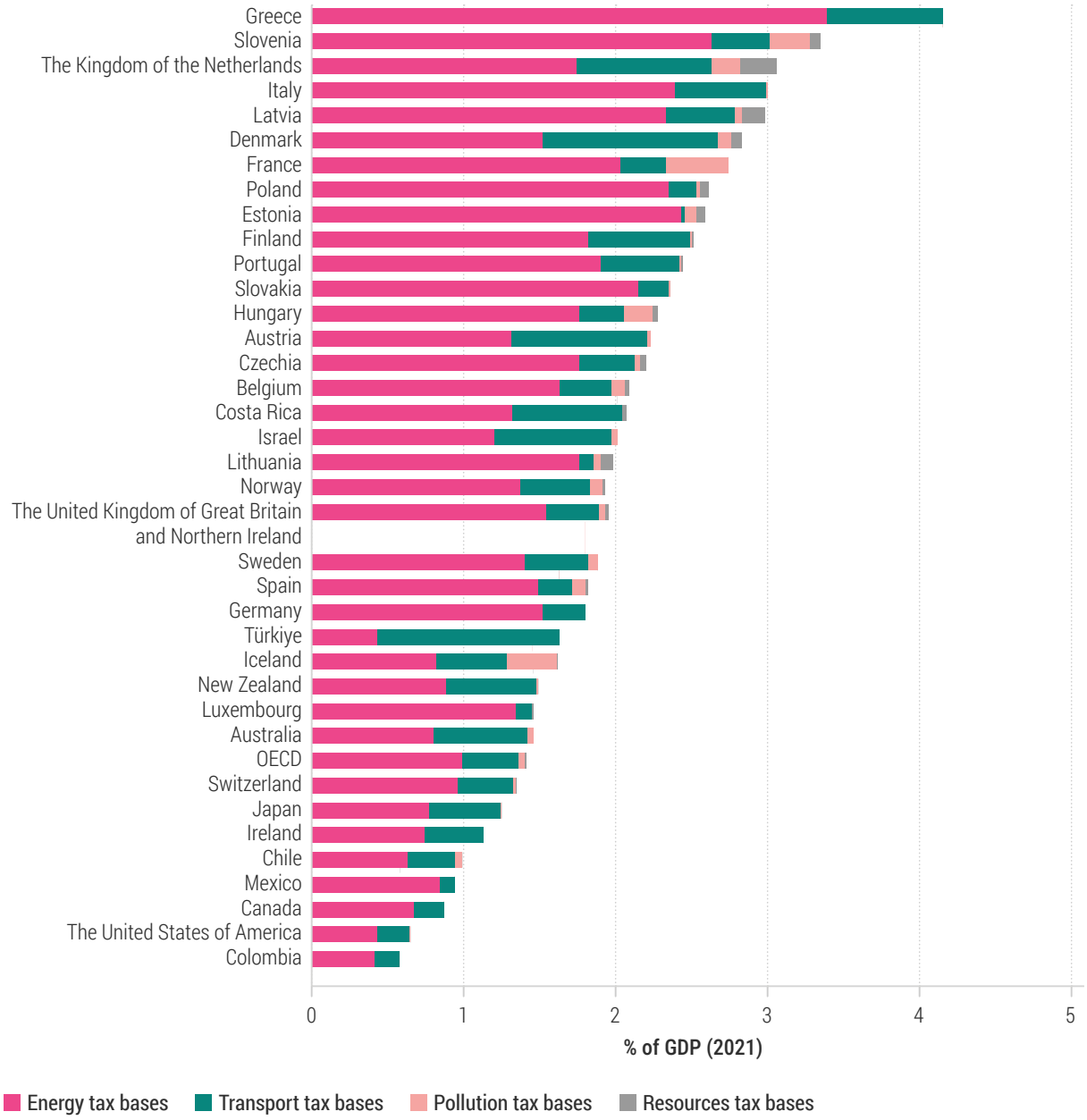
Environmental externalities cause direct effects on human health, property destruction, production disruption, and others, including some irreversible consequences for historical and cultural heritage and increased risk of species extinction, which indirectly affect the rest of the economy and human well-being. Price adjustments can be used to correct the value of goods for externalities, and secure progress towards sustainable consumption and production pathways. Pricing adjustments also decentralize decision-making to a degree that allows the polluter or resource user to have maximum flexibility in selecting an appropriate technology for optimizing environmental quality.

14.3.1 Action 1: Selection of the pricing instruments for a policy in development

Prices have a direct influence over consumers, with higher prices deterring consumption and lower prices making consumption easier. Pricing instruments should cover external costs or benefits. In the case of negative externalities, they can be in the form of a tax or charge per unit of either output or pollution, levied according to the external cost imposed on society (an idea originally due to Pigou (1920)), or with market creation approaches where market-wide pollution levels are set and economic agents compete for rights or allowances of units of the aggregate level. Pricing a positive externality can be implemented with direct payments to the providers of environmental services to reflect the external benefit, for example through payment for environmental services (Jayachandran et al. 2016; Wunder et al. 2020). These instruments must also take gender issues into account, as women, along with other marginalized groups, typically have less access to land ownership (Food and Agriculture Organization [FAO], United Nations Development Programme [UNDP] and UNEP 2021), lower incomes (Budina et al. 2023), and less access to technology (Vaishnav 2023).

Externality pricing is applied in a wide range of contexts, including energy production, vehicles and

Figure 14.5: Environmentally related tax revenues in OECD countries



Source: OECD (2024)

transport services; air pollution, ozone-depleting substances, waste management and noise; resource management for water, land, soil, forests, biodiversity, wildlife and fish stocks; and climate adaptation and mitigation. Examples of instruments in practice are captured in the OECD's Policy Instruments for the Environment Database (OECD 2023a). The challenge remains to account for the externalities of illegal activities, such as illegal mining in forested areas in Africa or Latin America, or the effect of groundwater pollution in agricultural areas around the world. More international pressure may be needed from markets that buy, process, or use these minerals, or that engage in intensive agricultural practices.

Transaction and implementation costs are also a parameter for instrument selection. Benchmarking international experiences is important, but application must be tailored to a jurisdiction's unique economic, social and institutional settings. The cost of measuring emissions or the use of emissions creating/reducing services by regulated sources can be high and technically challenging, for example transportation emissions. Consequently, pricing may not always

directly target usage or emissions but instead target the level of an input related to these environmental outcomes, as is the case with fuel and fertilizer taxes. Under such conditions, consumption can proxy for total emission and the effectiveness of the instrument is limited and must be complementary. The required level of externality pricing is determined by the environmental objective and social costs associated with meeting this objective (Bowen and Fankhauser 2017). Action 4 will discuss the institutional setting for such pricing development.

Monitoring and implementation costs may vary across jurisdictions but will be similar for different instruments since each is based on the same pollution levels and effects. In the case of taxation or charges, the fiscal structure is already in place and will need limited legal and institutional intervention to implement new sustainability-focused instruments. In some cases, such as water charges applied by a river basin authority or waste fees introduced by municipal authorities, additional legal and institutional frameworks can be required. There are several variations for each pricing instrument (Baumol and Oates 1988; European Union [EU] 2013; IPCC 2014; Sterner and Robinson 2018; van Essen et al. 2020; World Bank 2023). Taxes may be in the form of either emission taxes, or when emission measurement is difficult, based on input/resource or product taxes, as in the case of automobile emissions and agricultural emissions, with different balances of each used in different jurisdictions (**Figure 14.2**). In some instances, for resource distributors in markets with a concentration of firms for example, taxation downstream of the supply chain can be an option to reduce compliance and monitoring costs. Pricing instruments can also be combined into tax-subsidy combinations, such as fees and rebates, where sales taxes on automobiles can be reduced when vehicle emissions are below a threshold, or deposit-refund schemes, where purchase deposit fees are refunded when item packaging is returned to avoid waste generation. Such schemes can also be fiscally neutral as tax collection equalizes rebates.

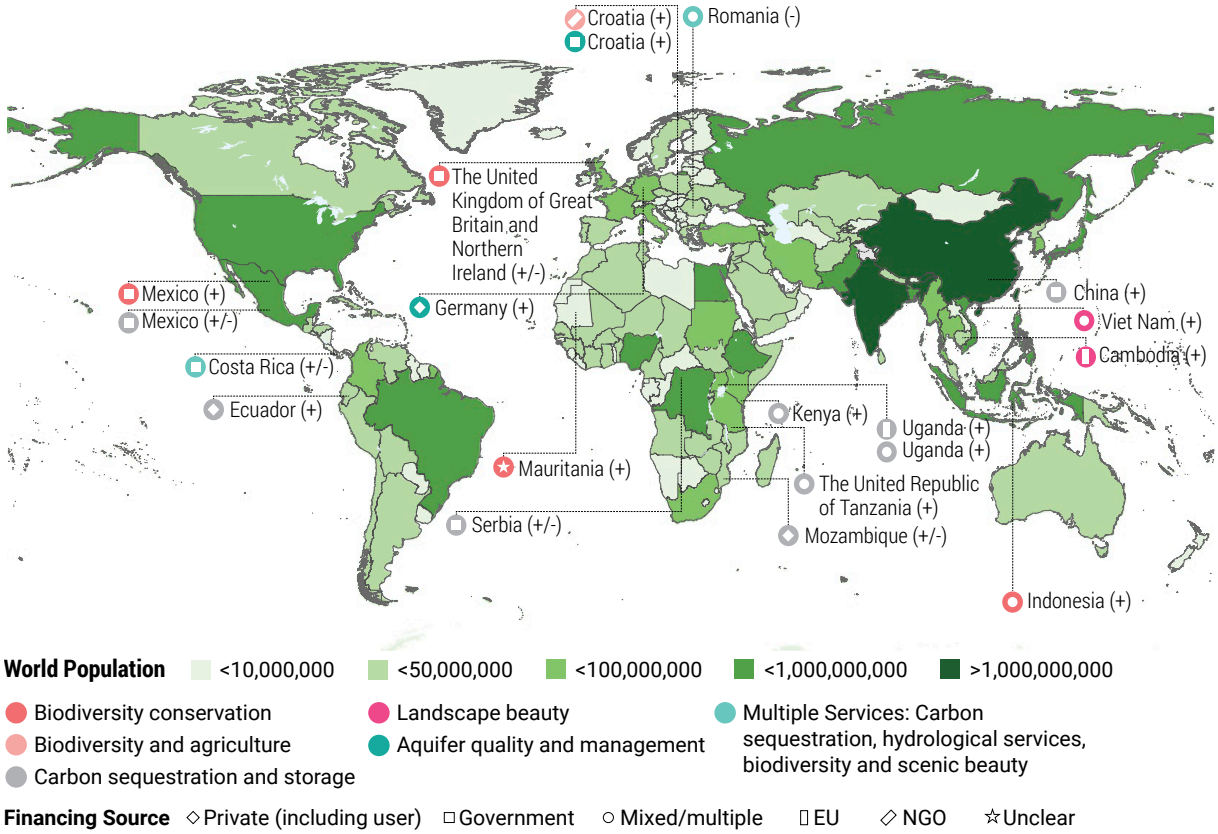
Market creation approaches will require developing market infrastructures, regulatory institutions, and legal frameworks to secure trade rights, otherwise economic agents may avoid trading. A cap level on available tradable permit schemes is usually set according to absolute aggregate emission targets. Emission intensity targets can also be an option. Pricing a positive externality via payments for environmental services has been used to target carbon sequestration, watershed services, biodiversity conservation, and scenic beauty (Salzman et al. 2018). Payments for environmental services can be essential to compensating Indigenous systems for their conservation outcomes yet may be reliant on public funding for implementation (**Figure 14.6; Appendix 14.1**). . Participation in these programmes is conditioned by the opportunity cost, direct and indirect, of the financial commitment made by suppliers to offer these services, although uncertainty regarding programme implementation, inertia in changing production modes, and knowledge of the environmental impact from services provided are also important (Grosjean and Kontoleon 2009; Cranford and Mourato 2011; Krishna et al. 2013; Seroa da Motta and Oritz 2018; Aguilar-Gómez et al. 2020; Wunder et al. 2020). In some cases, as the payments for reducing emissions from deforestation and forest degradation in developing countries, the REDD+ programme that targets jurisdictional results over the territory, and not for an individual project, have been adopted to increase the permanence of results and avoid leakage effects of moving deforestation or degradation elsewhere (Angelsen et al. 2018).

14.3.2 Action 2: Compensating for distributional impacts of externality pricing

When environmental services are accurately priced to reflect externalities, unintended consequences for poor households will still need to be addressed. A review of evidence on distributional outcomes of carbon pricing revealed progressive outcomes (Ohlendorf et al. 2021), that is, repercussions that are proportionally higher for lower income groups. The review authors draw attention to the fact that certain approaches can also increase consumer prices and the risk of poverty for low-income households, so revenue recycling schemes should be used to minimize such impacts (Woerner et al. 2024). Evidence of unequal distributional effects due to an inability to pay is also found, for example, in increasing water prices to account for the adverse externalities related to water use (Leflaive and Hjort 2020).

Economic trade and competitiveness concerns must be taken into account when developing environmental regulations and externality pricing. The pollution-haven

Figure 14.6: Examples of payment for ecosystem services implementation in selected countries



Source: See Appendix 14.1

hypothesis argues that firms may prefer to locate in jurisdictions with less stringent environmental regulations where there are lower costs attached to foreign direct investment and business operations. Studies tend to find a minimal adverse effect of environmental regulation on trade and foreign direct investment (Shahbaz et al. 2015; Dechezleprêtre and Sato 2017; Rey and Madiès 2021), while some argue the pollution-halo hypothesis, where foreign direct investment is generally based on clean technology (Mert and Bölük 2016; Gill et al. 2018; Nguyen-Thanh et al. 2022) in a potentially non-linear way (Wang and Wang 2020). Meanwhile equity markets are also displaying increasing sensitivity to emissions trading schemes (Broadstock et al. 2025), even for firms and sectors not directly participating in emissions trading. Despite mixed evidence, concerns about trade competitiveness play an important role in public acceptability of externality pricing (Stiglitz et al. 2017). Therefore, acceptability concerns should be addressed at the instrument design stage and can be managed in different ways, from exemption schemes for externality taxation or some level of free allocation of tradable permits in emissions trading systems or even by increasing the cost of imported goods via border adjustments as taxation and duties. For example, carbon border adjustment mechanisms, which aim to reduce the risk of carbon leakage and to articulate climate policies across jurisdictions, have raised concerns in developing and least-developed countries. The EU introduced a carbon border adjustment mechanism from 2023 and then updated it in 2025 through an associated Simplification Package, which makes it easier for small importers and commits to supporting countries interested in introducing or improving their carbon pricing systems (European Commission 2025a; European Commission 2025b).

Carefully implemented instrument design will require a pragmatic balance between theoretically desirable and practically feasible solutions to increase the probability that these instruments pass into legislation (Schmalensee and Stavins 2017) and also to smooth the structural adjustments in the economy that reduce jobs in high emission sectors that are losing market share in favour of clean activities. It is also important to appreciate that implementation will require a phased approach accommodating what is economically and politically feasible over time. Gradual implementation of externality pricing may be needed to allow market forces to smoothly realign investment and consumption

decisions, with the added benefit of increasing social and political acceptability.

14.3.3 Action 3: Identification and phasing out of harmful incentives

Phasing out and redirecting environmentally harmful subsidies is crucial for the sustainable use of pricing instruments and can also free up a large share of public resources. In today's economies, subsidies have been used to promote consumption patterns aimed at economic goals and unrelated to environmental sustainability objectives, requiring vast amounts of money and favouring environmentally damaging activities (Parry, Black and Vernon 2021). For example, fuel subsidies are used to artificially lower fuel costs so that lower-income households or smaller businesses can afford energy to accelerate their economic growth. Such incentives unfairly distort prices, increasing consumption of environmentally harmful products in direct contradiction to the objective of progressing towards more sustainable economic systems. In short, correcting pricing also requires the removal of some existing incentives that pervert and distort economic activity (Matthews and Karousakis 2022; OECD 2024).

Removing perverse incentives is politically challenging because of the effects on low-income vulnerable households. Such distributive impacts must be fully mitigated, for example, by recycling fiscal revenues from the removal of energy subsidies to compensate vulnerable households (Rentschler and Bazilian 2016; Adekunle and Oseni 2021). Successful experiences of subsidy reform have occurred in the Middle East and north Africa (Rentschler and Bazilian 2016; Adekunle and Oseni 2021).

14.3.4 Action 4: Develop and maintain a centralized coordination of estimated damage and compliance costs associated with the externality to calibrate the pricing levels.

Estimating external costs and benefits is not trivial and requires a substantial amount of data and a varied application of methodological approaches based on predefined assumptions regarding the scope of costs and benefits (Freeman 1979; Bennett 2013). Furthermore, mechanisms to compensate for unintended distributional effects and the removal of harmful subsidies must be integral to the instrument design and will necessitate complementary policy actions. A consistent and validated development framework must be agreed in advance. The framework needs to be designed within a centralized institutional setting to achieve convergence among representatives of civil society affected by the externalities, the private sector, academia and policy-making agencies. Further, the framework should care not only for the design phase, but also the monitoring and evaluation of pricing instruments when in place.

Actions supporting the implementation of the solution pathways for the internalization of externalities will have different time frames, depending on the economic, environmental and social structures of each country. It is recommended that they be implemented sequentially, considering each country's objectives and assessment of the effects of measures on sectors of society, especially the poorest. All this needs to be supported by science and technology, which will help to design projects that use resources more sustainably. For this, governments must make progress in environmental regulation and monitoring (Jayachandran 2022).

14.3.5 Action 5: Expanding comprehensive institutional capacity and preparedness required to implement changes, improvements and coordination among public agencies.

International experiences on externality pricing have demonstrated that the success and permanence of these instruments require early and sustained engagement between government, civil society and impacted stakeholders during the development and design of the instrument. Communication between the fiscal and environmental sectors also needs to be strengthened, not only to ensure proper implementation, but also to ensure that revenues from economic instruments are used to support incentives that benefit the environment (IPCC 2014; Sterner and Robinson 2018; World Bank 2023).

Once the policy objective has been defined and agreed to through engagement with the relevant government agencies and ministries, a possible efficient course of action may be to seek input from international organizations. These may support

the development and implementation of specific policy instruments through the provision of financial and human resources. Environmental agencies could request technical and financial assistance from international agencies to introduce economic instruments, emphasizing the phases and stages where such assistance will accelerate policy adoption.

There is also evidence indicating that women are more likely to engage in pro-environmental actions than men and policy design should take this into account (Zelezny et al. 2000; Berger and Wyss 2021; Tisserand et al. 2022).

Coordinated action within the government and with society, with requested and previously defined cooperation from international agencies, can create the necessary conditions to guarantee the institutional capacity that the use of economic instruments for environmental policies requires. Such coordination and institutional setting are further explored in Solution Pathway 4 on governance.

14.3.6 Action 6: Communication of the instrument to the general public.

Despite its theoretical effectiveness in leveraging the economic system onto a sustainable pathway (Chen, Jiandong and Saleem 2022), there are public concerns about externality pricing coming from firms and individuals. Major public concerns include that pricing externalities may increase production and consumption costs, damaging the economy by decreasing growth and employment, particularly among low-income households and marginalized groups. Some raise concerns that carbon taxes are implemented only for revenue-raising goals. Nonetheless, sometimes, such resistance can be driven by vested interests to limit public intervention in pricing (Hammar, Löfgren and Sterner 2004; Van Asselt and Brewer 2010; Carattini, Carvalho and Fankhauser 2018).

Communication and engagement strategies are crucial for engaging civil society and the private sector, as well as policymakers and legislators, thereby helping to cultivate demand for change in support of proposed policies (Drews and van den Bergh 2016; Baranzini et al. 2017; Carattini, Carvalho, and Fankhauser 2018). Communication strategies to help voters and policymakers understand the social and environmental benefits, including ecosystem services from pricing policies can also nurture people's pro-societal and environmental attitudes and cooperative tendencies, as already shown in studies in behavioural economics and explored further under Solution Pathway 2.

Communication of externality pricing policies must contain clear and coherent information on the total expected benefits and costs, in the short and long run, to whom the benefits will accrue and how distributive repercussions will be alleviated. The rights of local communities must be secured, and their interests must follow equitable, accountable and transparent procedures. For example, asymmetric bargaining power in the voluntary carbon credits market for nature-based projects has adversely affected just and equitable agreements on the sharing of benefits of trade revenues (Healy et al. 2023).

Part of the communication and engagement strategy may include alternative approaches to education. The concept of externalities should be more universally taught, from primary education to higher education, regardless of the specialty chosen at university, and not just reserved for those studying economics courses or for later stages of education.

14.4 Solution Pathway 2: Making sustainability core in economic governance

More than half, or 55 per cent, of the world's GDP, equivalent to US$58 trillion, is moderately or highly dependent on nature (PwC 2023), highlighting a material GDP-nature risk exposure. Healthy ecosystems provide essential services such as clean water, food, climate regulation, and disaster risk reduction. By ensuring ecosystem resilience, humanity can achieve significant cost reductions related to climate change, environmental degradation, and resource scarcity. Additionally, healthy ecosystems come with net social benefits related to human well-being and support of vulnerable communities, such as access to resources, local employment and job creation, community engagement and recreational activities. The unique characteristics of ecosystems and environmental resources, such as water as a public good, and of market failures, such as externalities and information asymmetries, render market-based mechanisms alone unable to achieve an efficient allocation of

resources and effective ecosystem management. Chronic environmental failures necessitate a comprehensive approach that extends beyond market-based management of natural resources and ecosystems. Sustainable economic governance, as it has been applied to date, has proven detrimental to the equitable and efficient allocation of environmental resources in an intra-generational, cross-sectoral, and intergenerational manner. Economic governance encompasses market interventions, that is, efficient pricing, the regulatory, oversight and management layers of resource management, the regional, local, and global socioeconomic policies that set the agenda for environmental management in the decades to come, as well as the national, regional, and global actors and the coordination of their actions to support the sustainability transition (OECD 2021). Inclusive governance structures that actively involve Indigenous People, local communities, women and marginalized genders in decision-making processes are essential for normalizing sustainability in economic governance. Inclusive policies can enhance the effectiveness and fairness of governance systems.

Modern economic governance is often characterized by inefficient market interventions such as taxes and subsidies, fragmented policies, and poor coordination at national and international levels. A set of actions is required to achieve sustainable economic governance, as follows.

14.4.1 Action 1: Market interventions for total cost recovery

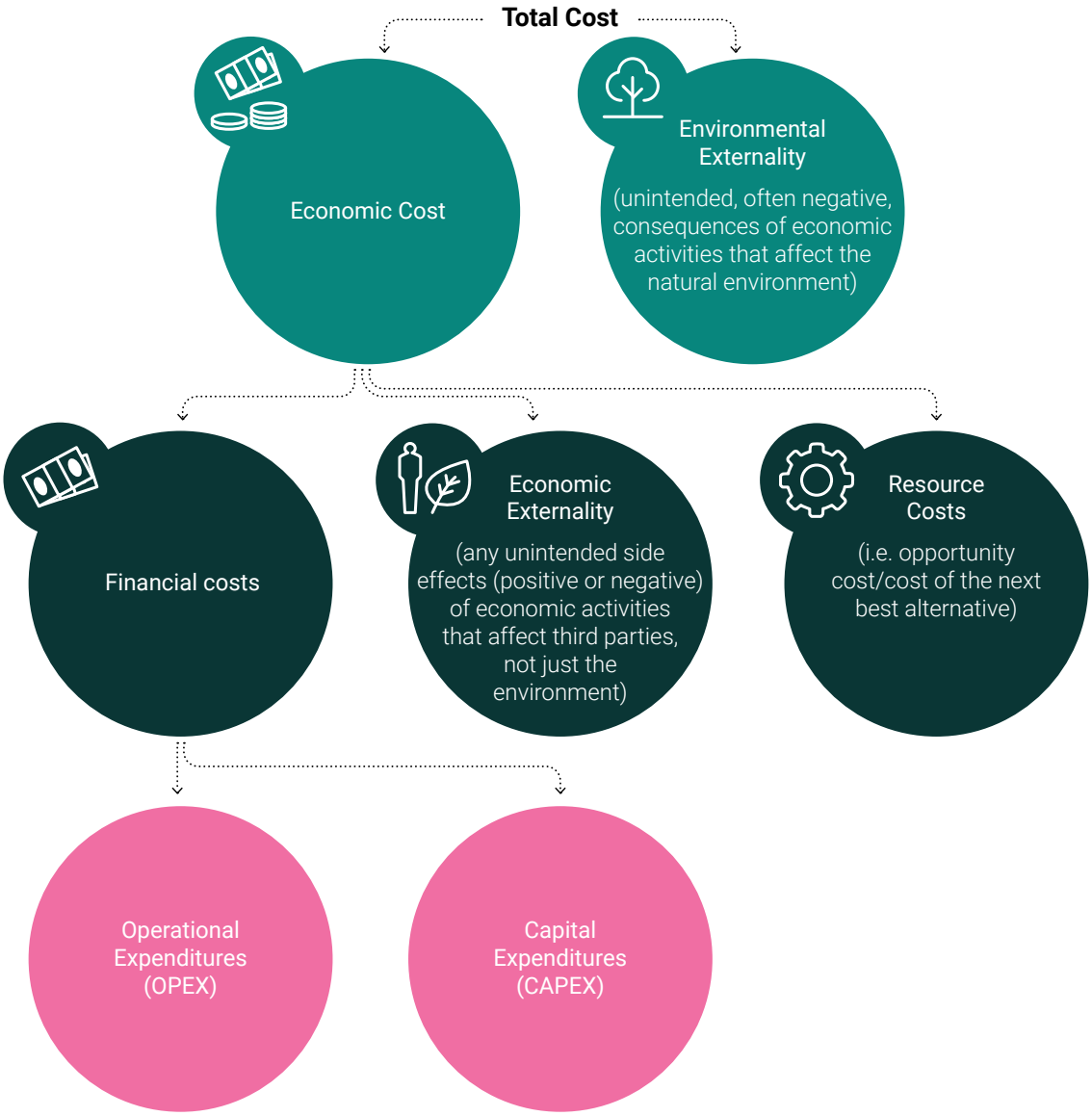
Deploy coordinated total cost recovery principles for sustainable resource management and allocation: Resource management and allocation through pricing should be driven by the concept of total costs and benefits of resource use, that is, the financial, environmental and resource costs (Barraqué 2020; Burritt and Christ 2021). This necessitates the identification and monetization of these costs (**Figure 14.7**). Moreover, it requires that all resource users and their respective costs and benefits be identified. While the concept of total cost recovery has long been discussed, its application remains fragmented and subject to data limitations. Technological developments and modern information technology tools including artificial intelligence, decision support software, geographical information systems mapping, remote sensing, large data management for environmental accounting and monetary valuation, and integrated models for risk assessment – should be put at the service of total cost recovery to facilitate application (Cox et al. 2023; Ddiba et al. 2023). Total cost recovery may raise social or redistributive issues (Farnault and Leflaive 2024). These issues can be addressed through stakeholder engagement, public awareness, and participatory approaches to resource management.

Implement integrated pricing that considers welfare, efficiency, and the polluter-pays principles: Total cost recovery links to welfare implications, allocative efficiency, financial sustainability of operators, and the ability to produce revenues to compensate for the environmental damages from resource use (Tsani, Koundouri and Akinsete 2020). Methodologically, total cost recovery necessitates data on marginal costs. Basic requirements must be met when choosing the instruments for achieving total cost recovery: ease and affordability of monetization; fair and full cost allocation; and dynamic and efficient incentives. Implementation should be based on the polluter-pays principle, with prices providing adequate and fully informed signals.

Coordinate policies and governance at regional and global levels for sustainable resource management through integrated pricing: An illustrative attempt to implement total cost recovery is the European Union's Water Framework Directive (WFD), Directive 2000/60/EC (European Union, 2000). The WFD is a pioneer systematic approach to water management that addresses simultaneous environmental, social, and economic stressors. The implementation of the WFD coincides with the implementation of the UN 2030 Agenda and EU commitment to meet the 17 SDGs (Akinsete et al. 2019). Article 9 of the WFD requires the total economic cost of water use to be considered. Total cost recovery comes with the advantage of incentive provision for water use and quality protection. On the downside, water pricing comes with opposing views on the objectives that water pricing and tariff design should meet. It is also often the case that water prices are not set in a transparent or understandable manner. This lack of transparency and high complexity often leads to misunderstanding of the real value of water or the aims that are to be met from the revenues collected from water pricing.

Beyond pricing and total water cost recovery, the WFD institutionalizes participatory processes in water-body management in the EU. Governance developments

Figure 14.7: Total cost elements



in the EU highlight existing challenges in the timely implementation of coordinated action across Member States, alignment with the SDGs and the ability to mobilize the required capital to support innovation in the water sector (Tsani, Koundouri and Akinsete 2020). Implementation and monetization of the polluter-pays principal ranges considerably across Member States. Different governance structures and levels apply even within the same country.

14.4.2 Action 2: Implementation of integrated fiscal and macroeconomic policies for just, timely and equitable transition

Addressing the global environmental crises and the transformation of the key systems, such as energy and food, requires moving beyond the fragmented policy systems that remain the norm today.

Implement and fine-tune the global loss and damage concept: Fiscal and macroeconomic policies should be updated and coordinated to serve loss and damage. The loss and damage concept has been discussed heavily in the recent past and it remains a highly politicized topic (Calliari, Serdeczny and Vanhala 2020; Pill 2022). The history of loss and damage and milestone developments, for example, the Warsaw International Mechanism for Loss and Damage, is well known (Roberts and Huq 2015; United Nations Framework Convention on Climate Change [UNFCCC] 2018). Developing nations with the lowest contribution to the climate crisis are the most heavily harmed by climate change, in terms of loss of GDP, cost of mitigation and adaptation, health,

environmental and social consequences, among other aspects (Buchanan and King 2019; IPCC 2022). It is a moral and economic obligation of developed countries to support developing nations for a just, equitable and timely sustainability transition at the global level (United Nations Trade and Development 2022; United Nations Trade and Development 2023). This necessitates delivery on bold financial commitments from developed countries and coordinated global implementation of environment-related fiscal tools such as the carbon tax and global environmental tax.

Coordinated fiscal and macroeconomic policies require transparency and a clear flow of information. Moving beyond GDP measures and conventional accounting is also required. These are particularly important for developing countries that are found at a turning point and require a new growth strategy based on green investment and labour-absorbing services (Rodrik and Stiglitz 2024).

Put debt at the service of environmental targets: The concept of debt-for-nature swaps (DNS) was first introduced in 1984 in response to the destruction of rainforests amid the growing debt of developing countries, particularly in Latin America (Rahim 2020). Debt-for-nature swaps reduce the debt obligation for a country in exchange for the debtor government's commitment to protect nature, thereby facilitating the restructuring of existing debt and supporting green recovery and development. Debt-for-nature swaps can also be used in cases where increased debt financing, as green loans or bonds, would raise debt to unsustainable levels. It is also a way to meet commitments under the Kunming-Montreal Global Biodiversity Framework, which aims to halt and reverse biodiversity loss by 2030, and to meet the SDGs (Yue and Nedopil 2021).

Early DNS examples included a tripartite swap with Bolivia in 1987, led by Conservation International, and a bilateral swap between the Netherlands and Costa Rica in 1989. Since then, more than 100 debt swap operations have taken place, including at least 50 trilateral swaps and approximately 90 bilateral swaps involving some fifteen countries (Chamon et al. 2022). Most swaps have taken place in Latin American countries such as El Salvador, Colombia, Jamaica, Peru, Chile, Costa Rica, and México; in African countries such as Egypt and the Republic of Seychelles; and in Europe's Poland.

Debt-for-nature swaps have helped reduce public debt and protect the marine environment in some Latin American and Caribbean countries in recent years, including Belize, Barbados and Ecuador. However, these operations have been small and have not provided a universal solution for countries facing difficulties related to debt sustainability and nature loss (Guajardo, Ugazio and Chensavasdijai 2023). Increasing the number and size of DNS can help countries strengthen fiscal and environmental sustainability at a time when financing is scarce.

In the Republic of Seychelles' 2015 DNS, the Seychelles government and The Nature Conservancy bought back US$21.6 million of public bilateral debt, mainly from Paris Club creditors, for US$20.2 million, a 6.5 per cent discount (Commonwealth Secretariat 2020). The Seychelles government used private philanthropic funds and loan capital raised by The Nature Conservancy's NatureVest conservation investment unit to purchase the debt through the Seychelles Climate Conservation and Adaptation Trust (Benzaken et al. 2024). In return, the government issued two promissory notes for the same US$21.6 million to repay the Nature Conservancy loan and endow the Seychelles Climate Conservation and Adaptation Trust as the new owner of the debt, which the government will repay over the longer term, providing cash relief on repayments (March et al. 2024). The government committed to protect 30 per cent of its waters, fifteen per cent of its high biodiversity areas, and to adopt a marine spatial plan to guide the updating of coastal zone management, fisheries and marine policies. In line with its commitment under the DNS, since 2015 Seychelles has moved from protecting 0.04 per cent to 30 per cent of its national waters.

Taking into consideration existing experience and to achieve better fiscal and environmental objectives, the following should be implemented:

- Develop a comprehensive bilateral debt swap programme;
- Reduce transaction costs and the time needed to reach agreements;
- Develop debt-for-nature swap agreements in line with the debtor country's conservation objectives;
- Establish agreements between creditors and stakeholders to build capacity and international coordination;

- Support commitment by debtor countries to project implementation and monitoring.

Wide and coordinated green budgeting: Governments and organizations must apply green budgeting widely, that is, integrate environmental and sustainable development targets into their budgeting process, as determined in the Paris Collaborative on Green Budgeting in 2017. This can be implemented through the identification and allocation of resources in favour of environmentally friendly and resilient alternatives. Green budgeting necessitates the prioritization of sustainable projects, full environmental cost integration into market prices, green procurements, and incentives, such as tax allowances and carbon pricing. The EU Green Deal and the US Inflation Reduction Act of 2022 can be referred to as examples of the implementation of green budgeting principles; however, more should be done to achieve a universal and effective design and implementation of these principles. These would need to embrace the increasingly multidimensional nature of green budgeting, requiring more delicate balancing than traditional budgeting where green attributes were historically not considered (The Energy and Resources Institute 2024).

14.4.3 Action 3: Key principles for economic model transformation to benefit people and the environment

Move beyond GDP metrics: To achieve a global balanced path towards sustainable living standards, economies should go beyond GDP growth targets and metrics. Traditional measures of economic growth such as GDP disregard natural resource depletion, biodiversity loss and environmental degradation. A panel of indicators is better suited to assess sustainability, with post-growth and degrowth approaches proposing policy targets and relevant indicators (Creutzig et al. 2022; Hickel et al. 2022; Olk, Schneider and Hickel 2023; Savin and van den Bergh 2022; Savini 2023; van den Bergh and Savin 2023; Vogel et al. 2024). Modern indicators should be based on objective physical parameters such as environmental vulnerability related to climate change (Tregarot et al. 2020) or more diverse development attributes like human development index/indicators that underpin the UN Human Development Reports (UNDP 2024). Modern economies and financial systems should not prioritize economic growth, disregarding the importance of valuing nature in economic planning and decision-making (Dasgupta 2021). Valuing nature does not necessarily come with lower GDP. Sustainability-driven innovation and investments or circular economy models, for instance, can improve efficiency and reduce consumption while promoting economic growth and environmental conservation. Indicators linked to nature-positive targets such as biodiversity restoration can be incorporated in the design and implementation of policies and financial instruments with no environmental or nature-positive effects. Indicators may expand to include ecosystem health, biodiversity, and natural capital values and changes. Frameworks such as the United Nations System of Environmental-Economic Accounting, the System of Environmental-Economic Accounting: Ecosystem Accounting, and the Taskforce on Nature-related Financial Disclosures can help track the contribution of natural capital to the economy.

Reduce inequality: Environmental damage is created disproportionately, with the wealthiest ten per cent accountable for 50 per cent of global consumption emissions (Khalfan et al. 2023). Progressive net wealth taxation schemes can reduce inequality by generating funds for the provision of extended and better-quality public services, as well as financing workers' reskilling required by the socioecological transformation (Tang, Duan and Yu 2023; Betts-Davies et al. 2024; Hou, Liu and Chai 2024;). However, while reducing inequality is essential, doing so may increase consumption among a large portion of the population as low-income households move towards fair and decent living standards, thus the net effects of reducing inequality on the environment may be either positive or negative (Oswald et al. 2021).

Ensure decent living standards for all: Despite population growth, decent living standards across the whole global population could be achieved at 40 per cent of current total energy consumption by 2050, through advanced technologies and demand-side changes to reduce consumption (Millward-Hopkins et al. 2020). Nature-based solutions also promote sustainable ecosystem management at lower long-term costs, while effectively addressing social and economic disparities (UNEP 2022; European Investment Bank 2023).

Increase public investment for the energy transition: The implementation of monetary policy instruments should rebalance financial flows from carbon-intensive assets towards low-carbon assets. This can be done by raising private banks' incentives to lend more for

green investment, as well as by shifting assets and collateral portfolio towards low-carbon assets, for example, mobilizing public finances to redirect or bring in additional private financial capital.

Set sufficiency as a core policy target: A balanced policy mix of incentives, such as subsidies, standards, labelling, and carbon pricing, and progressive taxation can steer production and consumption systems towards higher sustainability. These may send powerful market signals, helping to enable an orderly phasing out of destructive sectors, such as fossil fuels, and the transformation of production and consumption approaches, such as meat and dairy production, fast fashion, and advertising, to better align with circular economy principles.

14.4.4 Action 4: Identification and coordination of core actors at national, regional and global levels

Foster sustainable governance and multilevel cooperation: Developed countries should drive institutional capacity, transboundary cooperation and transparency in methods and approaches. Action should follow coordinated long-term strategic target-setting across countries and regions in a way that links to long-term sustainable development targets. Coordinated long-term strategies can ensure that short-term national deviations will not adversely affect long-term commitments and alignment with global initiatives. While novel ideas and public and private funding may be available, information asymmetries often hinder matching between innovators and funding sources, hampering the innovation process. Governance innovations and updates can improve transparency and upgrade accountability and tracking mechanisms, in turn benefiting financial mobilization.

Identify and coordinate core actors with primary target capital mobilization and coordinated policies for the sustainability transition: Core policy and economic agents operate at different scales and levels local, national, regional, and global, including Indigenous communities, non-governmental organizations, multinational corporations, international financial institutions, central banks, multilateral development banks, international coalitions, organizations and platforms. Related actions should aim to align regional governance with global sustainable development targets and coordinate the mobilization of capital.

Sovereign wealth funds (SWFs) are one group of institutional investors with global influence over the sustainability transition. SWFs are directly or indirectly government-owned and controlled investment funds (Kotter and Lel 2011; Tsani 2013; Aguilera, Capapé and Santitso 2015). SWFs have grown in number from 30 in 2000 to over 100 in 2023 (Sovereign Wealth Fund Institute 2023), and in 2023 had over US$12 trillion of assets under management. SWFs are perhaps the investor class for which it makes most sense to internalize the consequences of climate change, since their long-term investment horizon makes them directly vulnerable to its consequences (Tsani and Overland 2020).

On 6 July 2018, the President of France, Emmanuel Macron, and the Prime Minister of Norway, Erna Solberg, convened a round-table discussion with the One Planet SWF Group, comprising the Abu Dhabi Investment Authority, Kuwait Investment Authority, New Zealand Superannuation Fund, Norges Bank Investment Management of Norway, Public Investment Fund of the Kingdom of Saudi Arabia, and Qatar Investment Authority, with combined assets exceeding US$ three trillion. The meeting marked the launch of the One Planet Sovereign Wealth Fund Framework, aimed at promoting the integration of climate change considerations into the management of large, long-term and diversified asset pools (One Planet 2018). This includes the identification of climate-related risks and opportunities to improve investment decision-making and better inform SWFs' priorities as pivotal financial market actors.

The real-world experience of SWFs reveals several barriers that impede their engagement in green financing activities. These include conflict between long-term green investments and short-term liquidity requirements and between ownership and policy investment priorities and lack of coordination with the budgetary process. Climate policies are high priority in some countries, but not in all countries that operate a SWF.

14.5 Solution Pathway 3: Enhancing financial sector resilience and contribution to sustainability

The goal of this pathway is to strengthen the financial sector's contribution to sustainability efforts, without compromising its resilience to the risks

posed by climate change and environmental degradation. These must be inclusive solutions that also support gender equality and women's access to credit and other financial resources, as well as skills in financial and business management, education and training (Fan et al. 2021).

The global gap in finance needed to achieve the SDGs is estimated at US$3.9 trillion per year; yet, among low and middle-income countries, excluding China, there is a concerning downward trend in investment in renewable energy relative to advanced economies (OECD 2022). According to the Global Financial Markets Association (2020), to achieve the Paris Agreement's goals of limiting temperature rise to around 1.5°C, financing will need to exceed US$100–150 trillion cumulatively over the next three decades equivalent to an average global investment of over US$3–5 trillion per year to decarbonize ten sectors responsible for 75 per cent of global emissions. The Kunming-Montreal Global Biodiversity Framework calls for closing a US$700 billion per year biodiversity financing gap and aligning public and private financial flows to be sustainable over time, which is likely to be an underestimate given that it includes only direct effects. In the meantime, the private finance flows that have a direct harmful effect on nature are estimated at US$5 trillion (UNEP 2023).

Financial flows need to be redirected towards activities that ensure better environmental outcomes, limiting the harmful degradation of ecosystems, which threatens food production, a stable climate, clean water and air, and a place for recreation and inspiration (Mirzabaev and Wupepper 2023). The scale of the investment challenge exceeds the capacity of the public sector alone, and the broader financial sector has a pivotal role to play in supporting the transition to a sustainable and resilient future for all, while preserving the stability of the financial system.

Reorienting capital towards more sustainable investments requires a comprehensive shift to place sustainable finance at the core of the system. Traditionally, sustainable finance refers to the process of taking due account of environmental and social considerations in investment decision-making, addressing two urgent imperatives, improve the contribution of finance to sustainable and inclusive wealth by funding society's long-term needs and strengthen financial stability by incorporating sustainability matters into investment decision-making (High-Level Expert Group on Sustainable Finance 2018).

The following actions are recommended to scale up existing initiatives and address barriers to enable a shift in the financial system.

14.5.1 Action 1: Redesign and reorient investment flows towards green activities and projects

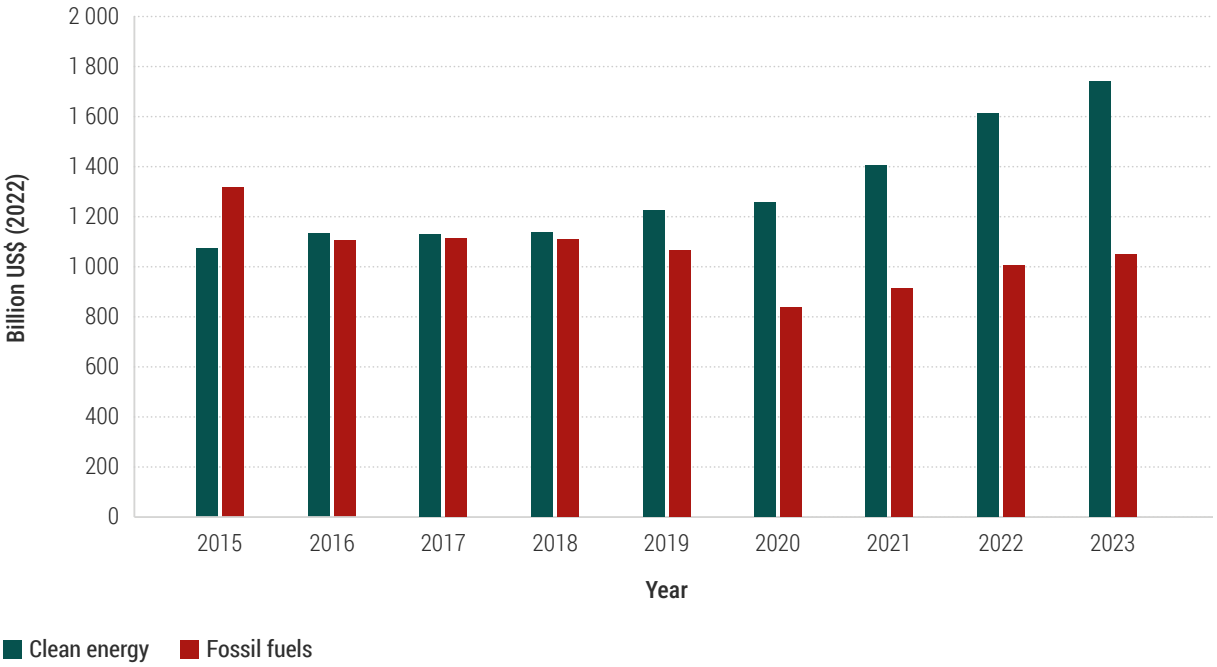
Capital markets are the primary source of external finance, channelling vast cash holdings towards investment opportunities. Allocating these resources towards green investments can provide environmental benefits while generating competitive financial returns. Financial institutions are integrating environmental sustainability into the investment decision-making process by placing green debt financing instruments on the market and building a market for green finance. Green finance includes, but is not limited to, climate finance, green loans, green investments and thematic bonds, each described in this section. Other forms of financing, such as debt-for-nature swaps, are described in SP2 and payment for ecosystem services in SP1.

Green loans intend to incentivize businesses that adopt green policies by introducing environmentally friendly services and products through clean energy investments and investments in NbS.

Clean energy investments are a cornerstone action for decarbonization. These typically include funds for research and development of clean energy technologies, construction of renewable energy infrastructure, or adoption of energy-efficient practices and technologies. Investment in renewable energy has increased significantly (**Figure 14.8**), with clean energy growing faster, at 24 per cent than investment in fossil fuels, at 15 per cent, between 2021 and 2023. Nonetheless, estimates point to the need to scale investment to a range of US$150-200 trillion by 2050, with US$5 to 8 trillion per year, while shifting US$1-2 trillion per year from fossil fuels to low-carbon technologies (International Renewable Energy Agency 2023; Allen and Overy and Climate Policy Initiative 2023; Forns Albuixech and Lyubomirova Lazarova 2024).

In 2022, investments in low-carbon energy technologies surpassed a record US$1 trillion, including

Figure 14.8: Global energy investment in clean energy and in fossil fuels



Source: International Energy Agency 2023

venture capital funding of around US$82 billion (World Economic Forum 2023). However, this was unequally distributed and concentrated in advanced economies and China, something that policymakers will need to address to ensure a secure and broad-based transition.

Around US$770 billion in clean energy investments go towards emerging markets and developing countries each year, albeit concentrated within a handful of large economies. China accounts for two-thirds of the total, and the top three countries, China, India and Brazil account for more than three-quarters (International Energy Agency 2023).

Clean energy investments often require larger up-front expenditures, changing the cost of financing and losing investors' interest, despite being offset by lower operating costs. For this reason, fiscal incentives through tax credits or subsidies can boost business investment in low-carbon technologies, especially if companies are confident about the influence of policies on their investment plans (Black et al. 2023).

Concessional finance is below-market-rate financing provided to developing countries by major financial institutions, such as development banks and multilateral funds, to accelerate development goals (World Bank 2023). To create the conditions for mobilizing as much private capital as possible, the use of concessional finance needs to be expanded, coordinated and carefully timed, particularly in low- and middle-income countries (Damania et al. 2023).

More than half of global GDP is estimated to be moderately or highly dependent on nature (PwC 2023), and therefore, investment flows must align with nature-positive economy goals, ensuring that financial instruments support biodiversity conservation and ecosystem restoration. Financial products, such as biodiversity bonds and ecosystem restoration funds, can help redirect capital towards nature-positive projects, strengthening the financial sector's role in achieving ecological resilience (**Box 14.1**).

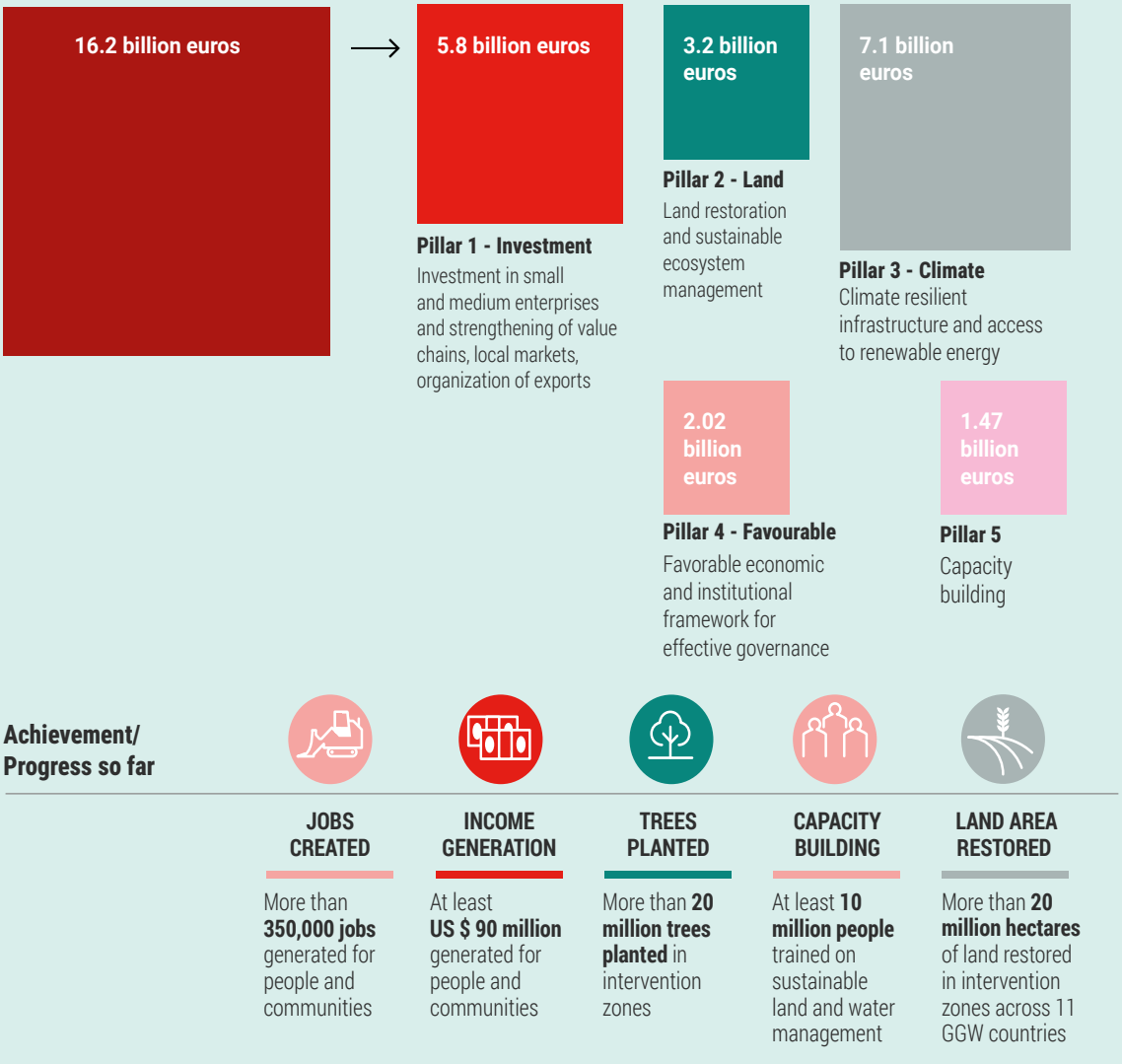
The amount currently being invested in restoring degraded ecosystems or preventing further degradation is far less than what is needed. (Mirzabaev and Wupepper 2023). UNEP (2021) estimates that investment in NbS needs to at least triple by 2030 and increase fourfold by 2050, if the world is to achieve the goal of net zero. This implies moving from the current annual investment of US$133.000 million to US$536.000 million per year by

Box 14.1: Nature-based solution (+ adaptation): Great Green Wall (GGW) Initiatives in the Sahara, Africa

The African Union endorsed the 'Great Green Wall for the Sahel and the Sahel Initiatives' in 2007. It brings the vision of combatting climate change and desertification, transforming the lives of millions of people by creating productive landscapes and addressing food insecurity and poverty in those regions (FAO 2014). The project spans 22 African nations, revitalizing thousands of communities by deploying more than US$ fourteen billion in support (UNCCD). The vegetation of the GGW offers numerous benefits: sequestration of carbon, improved water retention, improved soil productivity, shade provision and food for local animals (**Figure 14.9**)..

The Sahel is a hotspot for the increasing threats of climate change. Temperatures are expected to increase by three to six degrees by the end of the century, while precipitation becomes more unpredictable and intense. Precipitation and vegetation rates have increased, while improved water retention and transpiration of plants can accelerate this greening process (United Nations Office for Disaster Risk Reduction [UNDRR] 2023). Cost-benefit estimates indicate that while ten years of land restoration is required to generate market and ecosystem benefits, this project can be considered economically attractive and ecologically sustainable (Mirzabaev et al. 2022). Over 18 million hectares have been restored, with over 350,000 jobs created, as well as US$90 million in revenues generated by 2018.

Figure 14.9: Financial commitments – 5 Pillars, 1 Vision



2050. However,between 2022 and 2023, the increase in annual investment was modest at just eleven per cent (UNEP 2023).

Providing financing in an effective manner requires addressing a range of specific market failures and barriers, including information shortfalls due to a lack of data on the benefits and trade-offs, skills and expertise shortages, a lack of awareness among the general public, a failure in coordination across public agencies, high transaction costs, long time frames for financial returns, and higher risk profiles than other comparable investment options. Where the benefits of implementing NbS do not exceed the internalized costs, increasing private sector investment will require one or more of the following:

- A change in market structures, including regulatory interventions to provide direct incentives for private entities to either deploy NbS or to reduce the environmental impact of their economic activities;

- The development of private markets for public goods, such as extending carbon credit markets to cover biodiversity enhancement or pollution abatement, acknowledging the significant challenges in defining such certificates and credits and administering such markets;

- Co-financing, to blend public funds for public benefits with private funds for private benefits of investments in NbS (European Investment Bank et al. 2023).

Green bonds, alongside sustainability and blue bonds, allow entities such as firms, banks and governmental organizations, to borrow money from investors to finance green projects, assets or business activities. Sustainable debt issuances have grown rapidly in recent years. By early 2024, the Climate Bonds Initiative had recorded a cumulative volume of US$5.4 trillion of green, social, sustainability, and sustainability-linked debt in alignment with its screening methodologies. Aligned green, social, sustainability, and sustainability-linked bonds accounted for US$818.2 billion, an increase of eleven per cent compared to the same period in 2023, at US$738.3 billion (Climate Bond Initiative 2024). Despite this, the market remains small compared with traditional debt markets.

14.5.2 Action 2: Recognize transition finance efforts and align traditional investments with environmental objectives

The sustainability transition pathways of economic actors vary considerably. Transition finance provides support for the broader range of investments required for a whole-of-economy pathway towards sustainability, including assistance to reduce the negative consequences from a disorderly transition, such as transition risks related to the environment or limited access to inexpensive and dependable energy.

Capital markets are already responding to evolving investors' needs, political developments and regulatory changes to support transition financing by developing sustainability-linked debt instruments that operate in similar ways to green debt products, particularly:

- Sustainability-linked loans (SLL) place no limit on the use of proceeds but provide the potential to drive change through financial incentives, aiding borrowers in their sustainability goals by linking sustainability targets and performance indicators with interest repayment schedules. Due to the flexibility of SLL and potential for use across all sectors, they have quickly grown in popularity (UN 2023).

- Sustainability-linked bonds are defined by the International Capital Market Association as "any type of bond instrument for which the financial and/or structural characteristics can vary depending on whether the issuer achieves predefined [sustainability and environmental, social and governance] objectives" (International Capital Market Association 2021). This approach contrasts with the use-of-proceeds approach under SLLs.

- Reorientation and redesign of other traditional financial products: as an example, financial instruments such as insurance products can be restructured to cater for financial shocks in territories vulnerable to climate-induced disasters. Insurance can redistribute the burden of risk and provide fiscal stability as an alternative to bilateral loans that entrench debt. Mechanisms are already in place to

promote such products, for example the UNDP's Insurance and Risk Finance Facility that currently collaborates with 29 countries across Africa, the Middle East, Asia and the Pacific, Latin America and the Caribbean, to leverage insurance and risk-financing solutions to build financial resilience and safeguard sustainable development for vulnerable populations, communities and ecosystems. Within the EU, the ongoing Climate Resilience Dialogue between insurers, re-insurers, public authorities and other stakeholders facilitates an exchange on best practices and identifies ways to address the climate protection gap, either through recommendations or voluntary commitments.

Sustainable infrastructure project investing is especially important in the transition to a more sustainable economic model. According to the OECD, infrastructure contributes about 60 per cent of greenhouse gas emissions (OECD 2017). The world needs to ramp up investments in sustainable infrastructure to tackle large deficits in infrastructure services, especially in emerging markets and developing countries, in response to structural changes that are under way (including urbanization) and accelerating the replacement of ageing and polluting infrastructure. Altogether, around US$6.3 trillion of investment in infrastructure globally is needed every year between 2016 and 2030 to meet global development needs. A relatively modest additional US$600 billion will make these investments climate-compatible (World Bank, 2018).

Given the need for sustainable infrastructure investment, continued progress in developing appropriate frameworks to leverage private investment alongside public funds is key. A wide range of initiatives are under way to enhance the delivery of sustainable infrastructure, including the formulation of the G20 high-level principles on Quality Infrastructure, and to provide tools and methodologies to guide project design and execution (Watkins et al. 2019). Investor confidence is enhanced by strengthening the requirements for labelling financial products as either environmentally sustainable investments or transition finance. Other ways to enhance confidence also include increasing awareness of the environmental impact of financial products, creating visibility, addressing concerns about greenwashing, and establishing standards and requirements to monitor and assess the impact of nature-positive investments.

New approaches and tools should be developed to ensure positive outcomes related to proposed Actions one and two in this section. These include reducing fragmentation between and enhancing the compatibility and interoperability of approaches, allowing for a shared understanding of what environmental sustainability means. Many countries, regions and market actors have recognized the need to establish environmental-sustainability-related taxonomies to help classify financial products. Yet there is a proliferation of standards, principles and frameworks to assess the responsible nature of investments. More than 185 multi-stakeholder initiatives exist, involving 5,181 constituent members (UNEP Programme Inquiry 2015-2021; UNDP FC4S Network; Neto 2021), resulting in confusion and complexity. Global coordination of standards will help reduce adoption costs and overcome the difficult task of navigating various approaches, some of which have limited applicability across different jurisdictions.

The G20 Sustainable Finance Working Group has made a first step towards improving comparability and interoperability by defining high-level principles for countries and markets intending to develop their own approaches. Suggested steps include ensuring material-positive contributions to sustainability goals and focus on outcomes, avoiding negative effects on other sustainability goals, and being dynamic in adjustments reflecting changes in policies, technologies, and the state of the transition. Doing so would further require applying good governance and transparency, adopt science-based assessments for environmental goals setting and other sustainability issues, and address transition considerations (G20 2021).

Sustainability-linked loan principles are increasingly widely used by the capital markets. Developed by the Loan Market Association, the SLL principles set out a framework covering the development of a sustainability strategy, sustainability-related targets and metrics, reporting obligations and external review or verification, enabling financial market participants to have a common understanding of the characteristics of the financial product.

Green taxonomies can be developed through coordination among policymakers, financial market regulators, and other stakeholders. Typically, a government-driven approach is employed to

facilitate mandatory adoption. Examples of this include:

- The government-led taxonomy for China presents a detailed list of eligible economic activities and projects under various sectors and subsectors. Although not technology-neutral, it provides an explicit list of eligible technologies and sets key technical criteria in direct reference to national and international standards. The European Union similarly developed a common concept for classifying economic activities as environmentally sustainable or not.

- The Malaysian taxonomy was put in place by the country's central bank, while in Canada the development of a green and transition finance taxonomy is an external-to-government-led initiative.

- The Government of Colombia developed its Green Taxonomy (Taxonomía Verde de Colombia 2022), establishing how investments can contribute to climate change mitigation and adaptation, ecosystem and biodiversity conservation, water and land management, circular economy, and pollution prevention and control.

- The Government of México, through the Ministry of Finance and Public Credit (Taxonomía Sostenible de México 2023), has presented the Sustainable Taxonomy of México, oriented towards climate change mitigation and adaptation, with a focus on gender equality.

Taxonomies vary in scope: while some frameworks specifically define green investments such as the EU Taxonomy or set up principles for transition finance as in Japan, others embed the transition concept within broader green finance frameworks as Singapore does. As of December 2023, over 51 jurisdictions were developing green investment taxonomies (Marchewitz et al. 2024). Efforts are under way to consolidate different taxonomies to support interoperability. For example, the Common Framework Taxonomy in Latin America and the Caribbean provides guidance for taxonomies in the region, with a focus on climate change mitigation. It provides direction on the inclusion of activities, as well as guidance on the definition of metrics and thresholds for specific sectors of the taxonomy (UNEP 2023). The work to expand the initiative beyond climate change is ongoing, with a focus on conservation, restoration, sustainable use of biodiversity, and ecosystem services.

Sustainable finance products' labels and benchmarks need to be established. Standards and labels can protect integrity and create trust in the sustainable finance market, increasing investor engagement with these products. The most common practices involve clearly articulating the parameters for identifying sustainable investments or measuring the sustainability performance of assets, with the market for green bonds being a quintessential example. Early green bonds were self-labelled by the issuers as green, which was accepted by the market. As the market matured, formal standards and certification mechanisms were developed to validate the credibility of the market.

A market-led approach remains in use. The Climate Bonds Standards, developed based on the governing framework contained in Green Bond Principles, require issuers who intend to launch a green bond to establish a Green Bond Framework, which should align to the use of proceeds for environmentally sustainable activities. This includes putting in place a process for determining project eligibility, management of the proceeds in a transparent way that can be tracked and verified, and conducting regular reporting on the use of proceeds.

Drawing on current best practices, the EU has recently proposed a common framework of rules regarding a European green bond standard that would constitute a basis for high-integrity labelling of financial products. Labelling schemes can be particularly useful for retail investors who would value external verification of the sustainability credentials of their investment's activities. The lack of labelled financial products may prevent investors from directly channelling their funds into sustainable investments.

In addition to labels, benchmarks are indexes that play a central role in the price formation of financial instruments and other relevant assets in the financial system. Benchmarks are useful instruments, as they allow investors to track and measure performance and allocate assets accordingly. Traditional benchmarks reflect the status quo and their methodologies, as a result, reflect sustainability goals only to a limited degree. As such, they are not suitable for measuring the

Credit: williamperugini/Envato

performance of sustainable investments. In response, index providers have been developing sustainability-related benchmarks, including for example climate transition benchmarks, or benchmarks aligned with Paris Agreement targets, introduced under the EU Climate Transition Benchmarks Regulation (EU) 2019/2089 (European Comissions 2020) to capture sustainability goals. However, the lack of transparency regarding their methodologies has affected their reliability. More transparent and sounder methodologies for sustainable indexes are needed to reduce greenwashing risks.

14.5.3 Action 3: Manage sustainability risks at the system level

The financial system is increasingly exposed to climate change, pollution, accelerated degradation of ecosystems and loss of biodiversity, as well as the depletion of natural resources. Financial institutions must become better-equipped to withstand climate-related shocks, which requires coherent and relevant methodologies and tools, as well as capacity building to identify, measure and manage risks at the system level. This includes physical risks from climate change and the loss of biodiversity that can be systemic and hence invisible at the individual asset level. Transition risks may also arise from a disorderly or sudden transition. It is important to determine the nature and account for the degree of these risk exposures, and how they interact and evolve over time (European Commission 2021).

For a balance between ensuring financial stability and allowing the financial sector to pursue environmental sustainability efficiently, strategies to integrate sustainability factors in risk assessment and management in the financial sector need to accelerate. These would be holistic in nature, reflecting both financially material sustainability risks and sustainability impacts.

Sustainability risks need to be integrated into prudential frameworks. While governments should explicitly integrate sustainability criteria into the mandates of central banks, financial markets regulators and supervisors, the latter should ensure the integration of sustainability risks into the prudential framework. Specifically, supervisors should ensure that sustainability-related risks are adequately analysed and captured in their supervisory processes. This requires the development of coherent and relevant methodologies and scenarios to quantify sustainability risks and stress-test the resilience of the financial system.

Credit: akportfolio24 /Envato

Identifying and closing data gaps is key, as the lack of relevant sustainability data is common across jurisdictions. Financial sector experts and environmental experts need to collaborate to address these environmental data gaps. Comprehensive datasets should be built to assess the granular exposure of the financial sector to both physical and transition risk, including cross-border risks.

The Basel Framework, established by the Basel Committee on Banking Supervision, has ensured a globally recognized level playing field on financial regulations applicable to banks with active international operations. The Basel Framework can be adapted to respond to the urgency of the environmental crises and, where possible, the frameworks' Principles for the Effective Management and Supervision of Climate-related Financial Risks (BIS 2022) should be implemented by supervisors through adapted guidance and monitoring. This should consider the specific risk profile of each jurisdiction regarding the environmental effects, as well as the principle of proportionality. The Network of Central Banks and Supervisors for Greening the Financial System has rapidly established itself as a global network of more than 100 central banks and financial supervisors to help accelerate such efforts. Similarly, the International Association of Insurance Supervisors should consider how to integrate sustainability-related risks into insurance supervision.

A more holistic approach can be taken. The financial sector should focus on making all business and investment decisions more sustainable, and account for all positive and negative material effects, as well as risks and opportunities. The use of sustainability due diligence is the key approach for financial institutions to systematically consider and mitigate the influence of clients and investee companies and their supply chains on environmental and social issues. While financial due diligence is a well-established element of financial institutions, sustainability due diligence is based on voluntary schemes. Increasingly, financial institutions are voluntarily considering adverse effects on sustainability issues, referencing internationally recognized frameworks, technical guidelines and good practices (United Nations 2012; OECD 2023b) and incorporating sustainability due diligence in their decision-making.

Due diligence has not yet been sufficiently incorporated in the sustainability risk management procedures of

financial institutions. Information asymmetries, high search costs, and non-disclosure of value-chain relationships and sustainability effects in the supply chain are factors that hamper the ability of financial institutions to measure the adverse environmental and social impacts of their portfolio. These market imperfections can be addressed most efficiently by setting regulatory incentives for financial institutions to exercise corresponding due diligence. Since financial institutions need a level playing field, policymakers may consider legislative intervention to make sustainability due diligence mandatory.

14.5.4 Action 4: Build capacity and strengthen cooperation at the international level

Key actors in the financial sector need to build capacity to adopt financial stability risk assessment and regular stress-testing practices. Strengthening cooperation among all relevant actors regulating the capital market, such as governments, financial regulators, and supervisors, is key to converging approaches and providing the financial sector with usable tools and methodologies. Recognizing the need for global platforms to engage with key financial sector actors and harness the market intelligence of all partners to support the rapid scale-up of green investment and financing flows on a scale commensurate with the challenge, the OECD set up the Centre on Green Finance and Investment in 2016, and the G20 has established the Sustainable Finance Working Group.

14.5.5 Action 5: Foster transparency and long-termism

Investments in environmental objectives require a long-term orientation that is contrary to current market practices, which often emphasize high returns over short time frames. A pivotal challenge for sustainable finance is to reduce undue pressure for short-term performance in financial decision-making through increased adoption of credible, transparent and verifiable sustainability reporting frameworks.

Awareness, strategy, and management of sustainability aspects are no longer enough to meet demands for transparency and accountability. Stakeholders increasingly demand that the financial system align its sustainability interventions with leading performance standards. The evolving sustainability reporting landscape has increased granularity in data, enhanced the metrics with common and clear definitions for performance measurement and forecasting, and nurtures equal rigour in financial and non-financial reporting, and endorsement of environmental commitments by companies' management teams.

The disclosure of sustainability information has improved in recent years with a focus on comprehensiveness and reliability. However, there are still significant gaps and data inconsistencies to be addressed to achieve consistency and comparability of sustainability information across jurisdictions and to avoid fragmentation and the risk of greenwashing (Berg et al. 2022). There are several voluntary disclosure-related frameworks in place, with most of the jurisdictions translating their requirements into mandatory reporting, mainly in the case of climate-related aspects there is the Task Force on Climate-related Disclosure, but also in relation to biodiversity and NbS there is the Taskforce on Nature-related Financial Disclosures.

However, the spur for a more strategic approach to sustainability reporting comes from international policy initiatives that require progressively migrating from principle-based and best-effort basis approaches, to a more standardized, comprehensive, streamlined but granular, as well as forward-looking approach to reporting, based on high-resolution key performance indicators and where a good balance between quantitative and qualitative information is adopted. These can be achieved through the following.

Reflecting the double-perspective of materiality when addressing sustainability–related disclosure. Sustainability reporting hinges on the concept of materiality wherein sustainability factors are reported conditional on them having some material influence on the firm or the environment or both, as is the case in the double materiality perspective of sustainability performance. Existing voluntary reporting frameworks usually employ a single materiality perspective, either impact materiality or financial materiality. Financial system regulators, policymakers and standard setters should support the equal disclosure of sustainability-related consequences, both positive and negative, and risks and opportunities embedded into a comprehensive and coherent framework. The EU is an example case where mandatory disclosure from both perspectives has been introduced.

Credit: nikonlamp/Envato

Ensuring comparability of sustainability-related information. In response to the need for standardized sustainability data, the International Financial Reporting Standards Foundation has established the International Sustainability Standards Board to prepare understandable and enforceable sustainability standards. The Board has already released two exposure drafts that build on the industry-based disclosure requirements and are aligned with the Task Force on Climate-related Disclosure 's recommendations (International Financial Reporting Standards [IFRS] 2022). While largely voluntary, policymakers in certain jurisdictions, including Singapore, Japan and Canada, have begun to translate them into mandatory disclosure requirements. Global consistency and comparability of sustainability information across jurisdictions will reduce fragmentation and the risks of greenwashing (IFRS 2024).

Improving transparency of credit ratings and rating outlooks. Credit rating agencies play a crucial role in the financial system by evaluating the credit risk of both financial and non-financial issuers. Users of sustainability information disclosed by ratings agencies express concerns about the lack of transparency in how ratings incorporate sustainability factors into their methodologies. Therefore, policymakers and international boards such as the International Sustainability Standards Board may take action to improve transparency and regulation over the inclusion of relevant sustainability factors in credit ratings and credit outlooks, while promoting methodological consistency. Achieving this in practice may involve an important layer of coordination between conventional financial ratings providers, third-party environmental, social and governance and sustainability data providers and ratings agencies.

14.6 Solution Pathway 4: Fostering non-pricing approaches towards greening behaviours

In theory, pricing approaches, such as levying environmental taxes and implementing tradable permits, are the most efficient approaches for internalizing environmental externalities. In principle this means that they can realize policy goals, such as emissions reductions, at the lowest social cost. Pricing approaches have been widely used to address environmental pollution issues and allocate natural resources (Stavins 2003; Susswein 2003). However, pricing approaches have not always performed as expected. Evidence of the cost-effectiveness of pricing policies for lowering emissions and protecting natural resources is mixed (Henderson and Norris 2008). Important arguments are being made in favour of complementing pricing with non-

pricing approaches, including property rights responses, regulatory approaches and soft approaches.

Property rights responses include actions to institutionalize ownership of resources and introducing rules for governing behaviours of resource users. Carefully designed combinations of ownership and rules can achieve the desired allocation and use of resources (Starrett 2003). Regulatory approaches refer to the use of coercive power of the state to achieve public goals through influencing the conduct of individuals and firms by setting and enforcing rules (Howlett 2011). Soft approaches refer to less coercive and intrusive interventions, such as information-based approaches, engagement in research and development of green technologies, and fostering voluntary programmes.

Although they can be used in isolation, these approaches are generally seen as complementary to price-based market forces, for example, assigning property rights to individuals or mandating environmental labelling that may reflect different product prices. In considering which approaches to apply, the nature of the externality, the characteristics of the target populations, and the institutional capacity of the government for monitoring and enforcement are important considerations.

The following section outlines a series of actions aimed at encouraging non-pricing solutions towards greening or pro-environmental behaviours. It discusses how various actors, or combinations of actors, are responsible for the success of these approaches.

14.6.1 Action 1: Implement and enforce a coherent property rights system

Regardless of whether rights to the resources are assigned to individuals or collectives, clear delineation and identification of property rights are necessary for reaching agreement on how to allocate resources. Conflict arises only when enforceable property rights are uncertain or ambiguous (Buchanan 1975). Only after property rights are clear can the question of whether the resources should be privately owned or collectively owned be adequately addressed.

If a resource is partitionable and privately owned, it can be efficiently allocated through conventional markets. Under shared, or collective ownership, the collectives owning the resource property rights need to work together to agree access rights for individual collective members. Where resources have uncontrolled collective access rights, overconsumption of resources can occur. This can result in the tragedy-of-the-commons problem that requires government intervention.

When determining whether property rights should be individually or collectively owned, the following points should be considered. First is the issue of equity when market efficiency is taken as the sole value in decision-making. Second, many environmental resources are non-partitionable, making it difficult or impossible to enforce private property rights. Third, spatial fragmentation of resources may impair the effectiveness of using private property rights to address environmental issues (Heller 1998; Buchanan and Yoon 2000; Chasu, Liu and Mu 2023). In addition, there is a potential to introduce what is called a "resource curse" under improper allocation of property rights. This occurs when private resource ownership introduces unfair ownership costs, as in the case of conflicts and disputes over oil resources in the past.

Community-based management of natural resources based on collective property rights can be effective under certain conditions (Ostrom 1990; Agrawal, Erbaugh and Pradhan 2023). Examples include community forest management in the Himalaya region (Agrawal and Chhatre 2006) and community management of irrigation systems in Guangdong, China (Chai and Zeng 2018). Community-based management is a type of self-governance in which the community collectively decides rules regarding access and the use of resources. This can reduce administrative costs; however, the success of such arrangements depends on several factors, including the size of the community.

When managing environmental resources, there is no definitive answer regarding the correct approach to property rights assignment. The nature of the environmental problems, status quo of the rights to environmental resources, legal institutions, customs, and Indigenous Knowledge all matter.

14.6.2 Action 2: Set up technology or performance standards

Establishing standards is a commonly adopted regulatory approach. Standards serve as benchmarks for

compliance and specify sanctions for non-compliance. Two broad categories include technology standards and performance standards. Taking emissions control as the objective, a technology standard might mandate the use of specific technologies or production processes to lower emissions, while a performance standard typically limits the quantity of emissions per unit input or output. Technology standards can be useful when the cost of monitoring emissions is high and confirming adoption of a particular technology is comparatively easy. In contrast, performance standards can be useful when emissions monitoring costs are low and allow polluters flexibility to choose what technology to adopt to comply with the standards. These regulatory tools have been widely used in many countries (Schmitt and Schulze 2011; Greenstone and Hanna 2014; Tanaka 2015).

In designing and implementing technology or performance standards, regulatory agencies need to consult the affected sectors. Sector participants have better information on the availability and affordability of technologies, and the ultimate feasibility of different standards (Pan, Xu and Xue 2023).

Standards have proven effective in limiting pollutant emissions (Singhal 2018), provided that government agencies have the capacity and resources to enforce their use. However, technology standards, which often stipulate specific technologies or equipment that firms must adopt, may introduce costs without providing environmental benefits in some cases. There are also concerns that the use of government-mandated technologies could reduce incentives for firms to pursue innovation and potentially develop more effective technologies (Jaffe, Newell and Stavins 2003; Sterner and Coria 2013).

14.6.3 Action 3: Ban or limit the production and use of environmentally harmful products and services

Banning or limiting the use of environmentally harmful products, technologies or services is another regulatory tool frequently used by governments. For instance, signatory countries to the Montreal Protocol banned the production and use of listed ozone-depleting substances. China banned the use of high-polluting gasoline vehicles that fail to meet certain emission standards (Xiao et al. 2019). Other examples include France's ban on short-haul flights when rail transport is available, while various countries prohibit the open burning of refuse, or prohibit the production, use, import and export of certain toxic substances, as well as place bans on single-use plastic bags.

Bans or limits place firm controls on behaviours and are among the most effective approaches to addressing environmental issues in a timely fashion. For instance, banning the use of high-polluting household appliances such as stoves and replacing them with cleaner technologies can have immediate positive health effects (Seals and Krasner 2020; Gruenwald et al. 2023). However, this regulatory approach could be very costly if affordable substitutes are not readily available or if the required infrastructure is not in place. In many developing country settings, lack of electricity in rural areas may make it challenging to switch from dirty cooking fuels to cleaner options.

When deciding to ban or limit the production and use of environmentally harmful products, regulatory agencies must assess the social and economic effects of such decisions. Bans and limits can directly affect individuals' jobs or incomes, and businesses and individuals need enough time and flexibility to adjust. Where there are concerns that bans may interfere with individual choices and preferences, public awareness campaigns should be organized to explain the rationale. Government assistance for vulnerable businesses and individuals or households may be necessary.

Bans or limits can be designed to limit the cross-border exchange of environmentally harmful products. For example, the EU's Deforestation Regulation (European Commission 2023) prevents products associated with deforestation and forest degradation connected to certain commodities, such as cocoa, coffee, palm oil, rubber, soy, wood, and cattle, from entering the EU market, thereby discouraging environmental degradation in producer countries.

14.6.4 Action 4: Set up labelling programmes to influence consumers' choices

Environmental labelling programmes aim to influence people's choices in markets, to enhance awareness and diminish consumption of goods that are more environmentally harmful (Camilleri et al. 2019; Taufique et al. 2022). This approach involves the use of a simple and easy-to-understand signal, such as

a logo or seal; a quantitative declaration, such as energy consumption per unit of time; or a textual claim (OECD 2016), to inform individual and organizational choices. Environmental labelling schemes have been developed and managed by public agencies, private sector actors, and non-profit organizations. The label may reflect natural resource use, waste generation, biodiversity impacts, environmental pollution potential, climate impacts, energy consumption, and agricultural practice, individually or in combination. It can be mandatory or voluntary, and potentially externally certified. It should be non-misleading and non-discriminatory. A salient example is energy efficiency labelling on commonly used products that may consume large amounts of energy, such as refrigerators, air conditioners, or residential gas boilers.

Challenges with this approach are notable. First is the potential for greenwashing, where companies profit from sustainability-oriented consumers by making misleading and potentially false statements about the environmental benefits of their products (Shahrin et al. 2017). Second, this approach can require extensive education and awareness campaigns to overcome low consumer awareness, concern, interest and even trust in the implications of attached labels (Feucht and Zander 2017). Third, corporations, whose profits are greatest for products with the largest carbon footprints or adverse biodiversity effects, may be more resistant to labelling efforts. Fourth, empirical evaluations of labelling schemes' effectiveness do not provide a clear gauge on the effects of carbon, biodiversity and energy labelling on actual purchasing and consumption behaviours in different settings.

14.6.5 Action 5: Conduct information campaigns to promote environmental attitudes and behaviours

At any given time, individuals and firms face multiple, sometimes conflicting, interactions with environmental issues. They may be victims of environmental problems and wish to take protective measures. They may at the same time be contributors to environmental problems through their consumption patterns and need to adopt pro-environmental behaviours. They can serve as stewards in identifying and reporting environmental violations. They may express support or opposition regarding environmental policies. These can all be daily behaviours. The motivations and payoff structures for each of these types of behaviours are quite different, and thus, the level of difficulty in motivating pro-environmental behavioural change quickly becomes a very complex problem. In such conditions, information campaigns can be preferable to regulations in motivating desired behaviours and nudging social norms, as they are non-intrusive approaches and retain people's liberty of self-constraints on their behaviours. Studies suggest that social influence and shifting social norms in favour of environmental conservation can reduce emissions (Horne and Kennedy 2017) and motivate sustainable actions (Schneider and van der Linden 2023). One caveat is that there should be adequate, affordable and accessible substitute products available in the market.

Information campaigns for public goals are often initiated by government agencies as well as non-government organizations. For instance, many local governments use public information campaigns to raise awareness of the risk of polluted air to change people's responsive behaviours towards polluted air (Henry and Gordon 2003). In designing and transmitting messages, the psychological aspects of messages, local knowledge, the educational background of the target audiences, and the accessibility of the audiences to different information channels need to be fully considered to enhance the effectiveness of such measures. When conducting information campaigns, it is desirable to assess the pros and cons of sustained versus episodic campaigns. While the former may foster long-term change, the latter may be less costly.

14.6.6 Action 6: Engage in and support research and development of green technologies

Research and development in green technologies carries as much importance as promoting green behaviours among firms and individuals. While green financing from the private sector can help facilitate the deployment of green technologies, early-stage fundamental research for untested technologies benefits from government intervention. Moreover, there is an unequal distribution in technology use between developed and developing countries, where developed countries take the lion's share of the benefits of green technologies (United Nations 2023). For developing countries to benefit, they need to place substantial effort on building domestic capacities and installing supportive industrial and innovation conditions.

Assessing the effectiveness of non-pricing policies or actions is challenging, since their effectiveness is related to their specific design, as well as their enforcement. The simultaneous use of pricing and non-pricing instruments makes it difficult to disentangle the respective contributions each provides in reducing emissions. Nevertheless, some general conclusions can be reliably drawn.

If designed and implemented carefully, banning or limiting the production and use of environmentally harmful products will be effective in reducing environmental damage. Using standards to regulate individual and firm behaviours is expected to be effective. Maintaining vigilant oversight and attribution of property rights will help allocate resources efficiently. However, the effectiveness of information-based approaches such as environmental labelling and information campaigns is less certain, with many factors affecting people's behaviours. There have been synthesis findings showing that information campaigns significantly improved global conservation outcomes, complemented by evidence that non-price policies aimed specifically at renewable energy, fuel efficiency, electrification of passenger vehicles, and forestry have successfully been implemented in China, EU, India, Japan, and the United States (Green et al. 2019; Fekete et al. 2021). Drawing reference on the use of Nature-Positive Initiative metrics may be helpful for designing or assessing the effectiveness of non-pricing approaches to foster biodiversity-positive behaviours.

It is worth noting that studies have also shown that gender-related beliefs correlate with differences in pro-environmental behaviours, with green consumption choices and with other environmental intentions (Zelezny et al. 2000; Swim et al. 2020). Non-pricing approaches should therefore consider gender differences in behaviours and ensure that environmental programmes and interventions are tailored to be inclusive for all genders.

14.7 Combining solutions to achieve the goals

To reach and maintain transformative, inclusive and nature-positive change in economic and financial systems requires the implementation of combined solutions. Depending on a single solution pathway would be inefficient at best and ineffective at worst. Adapting over time and remaining open to switching between or reconfiguring the relative balance of importance of the various solution pathways will be crucial for ensuring effective change. Combining solutions to achieve economic transformation must include Indigenous People and local knowledge, as well as gender perspectives to ensure that all can benefit equally from sustainable development initiatives. Integrating these different considerations as early as possible can enhance the effectiveness and inclusivity of combined solutions.

Individual solution pathways will be strengthened by co-development of other supporting pathways. As such, possible synergies between the solution pathways are not only to be recognized but should be exploited. Moreover, simultaneous implementation of solution pathways is sought to adequately and promptly address facets of supply, demand, and system governance, to ensure that the development and implementation of actions and policies involve the relevant actors and stakeholders.

For instance, internalizing externalities (SP1) such as environmental damage from production works in tandem with green finance (SP3) tools such as environmental, social and governance rating, while also fulfilling a growing consumer demand for greener products (SP4), which is often achieved through well-structured macro-governance systems (SP2).

The key questions to consider are:

- Which pathways positively support the implementation of other pathways and how?
- Which pathways are incompatible with other pathways?
- Which pathways take longer to implement for sequencing considerations?
- Which pathways require social engineering or education campaigns?
- Which pathways may be contentious from a political perspective?
- Would implementing all pathways in parallel be the most effective strategy?

Table 14.1: Synergies and trade off which other systems.

Economic and financial solution	Energy Systems	Food Systems	Environmental Systems	Circularity
Fiscal tools Expanding externality pricing; Phasing out and repurposing existing subsidies and environmental taxes.	This solution will encourage the choice of cleaner alternatives such as renewable energy and energy efficiency, particularly for low- and middle-income countries that have difficulties in mobilizing the necessary financing (World Bank 2023).	This solution would improve fish stocks and achieve more sustainable agriculture (Damania et al. 2023).	This solution will be important in environmental systems to reduce the effects of water, soil and air pollution, greenhouse gas emissions and to avoid the loss of natural capital.	Revenues from the repurposing of subsidies can be used to promote the circular economy.
Making sustainability core in economic governance	This allows increased public and private investment for the energy transition.	Clear government signals will increase sustainable management of terrestrial and marine food production.	Sustainable economic governance helps combat biodiversity loss, climate change, pollution and land degradation.	Positive effect in accelerating and maintaining all aspects of economic circularity.
Enhancing financial sector resilience and contribution to sustainability: Promoting public and private investment in NbS, restoration of ecosystems, and climate change	This solution will modernize the energy mix, moving away from fossil fuels and increasing efficiency in energy distribution and use.	This solution could have a positive effect on agricultural land restoration and increase land production.	This solution could increase territorial and marine protected areas, avoid deforestation and wetland loss, and enhance the ecosystem services.	This solution will contribute to natural resources conservation, such as metal and biomass. It will also contribute to the strengthening of efforts to reach a nature-positive, regenerative form of economic circularity.
Non-pricing approaches	This will allow reduced energy consumption, more energy efficiency and the development of renewable energy.	The influence of these tools on the food system will make it possible to achieve sustainable agriculture, a reduction in land degradation and the production of healthier food.	The environmental benefits will be emission reduction, increased biodiversity, less pollution, and decreased land degradation.	Will foster social acceptance and behaviour change, helping to reduce material consumption and increase the recycling and reuse of materials already in economic circulation.

- While reviewing such questions it is also important to be mindful of overlapping questions or synergistic solutions that exist across different systems.

14.8 Synergies

Table 14.1 presents synergies among the four solution pathways for the transformation of economic and financial systems, and how they intersect with priorities and solutions in the energy, food and environment systems (Chapters 7, 16, 17 and 18) as well as circular systems of resource use (Chapter 15). These other systems are both components and users of economic and financial systems, and the full range of system-specific synergies is necessarily expanded within the respective systems chapters to ensure sector-specific nuances and insights are properly presented in context.

Solution Pathway 1 focuses on the actions necessary to accurately price externalities, including the elimination of environmentally harmful subsidies. Certain subsidies, such as fuel subsidies, when removed, will have direct and immediate effects on the energy system, likely helping to accelerate the adoption of electric vehicles into the mainstream, and the move to low-carbon electricity. Other systems will also benefit, particularly through the recycling of revenue from emissions pricing

schemes to nurture economic circularity and support nature-regenerative projects.

Solution Pathway 2 relates to multilevel and multilateral governance, macroeconomic and fiscal policy considerations. Synergies will arise from adopting integrative governance approaches to steward natural capital and resources with closer participation from Indigenous Peoples as well as local communities. Additionally, revised governance will help the uptake of circular resources systems, which will require expanded oversight relative to conventional linear consumption-based economies. Synergies among economic, environmental, and social systems must include Indigenous People and local communities, as well as gender considerations, to maximize the benefits of sustainable development for all members of society.

Solution Pathway 3 places an emphasis on financial sector tools and frameworks to unlock private financial capital for environmental sustainability projects. The most urgent changes will include frameworks for consistent, transparent and reliable valuation of NbS and biodiversity projects, where the current information gap is arguably the greatest. Benefits will accrue to all other systems, given the traversal role of project financing and requirements for the monitoring and oversight of investment activities across all parts of the economy.

Solution Pathway 4 concerns the role and use of non-price instruments to foster pro-sustainable norms, attitudes and behaviours. These will complement the other solution pathways and actions and can be applied across all sectors in varying configurations. Within the energy sector, for example, labelling is already widely applied and is likely to remain in place, sustained by technology support packages of different sorts. In food systems, information campaigns might be a strategy for promoting the adoption of alternative proteins. For environmental systems, there is a need for greater understanding of the dependence of natural resources in our economic systems and the adoption of value principles from Indigenous Peoples as well as local communities in stewarding and regenerating natural capital and promoting economic circularity.

Appendix 14.1:Additional detail on examples of payment for ecosystem services implementation in selected countries

Ecosystems service	Biodiversity conservation
Country applied	Indonesia
Reference	Kurbjeweit. B. (2022)
Funding	Mixed
Outcome	**Positive**. The payment for ecosystem services (PES) application allows for the conservation of forest and wildlife species in Nanga Lauk and the diversification of economic activities.The agreement with the companies guarantees income for the ecosystem services provided by the project for 25 years from 2019.
Country applied	México
Reference	Costedoat et al. (2015)
Funding	Government
Outcome	**Positive** México's PES programme for biodiversity conservation enabled greater protection of forest cover.
Country applied	United Kingdom of Great Britain and Northern Ireland
Reference	Alston, et al. (2013)
Funding	Government
Outcome	**Mixed**. The UK PES programme has seen a significant increase in the area covered. Most of the enrolled producers have relatively small farms. This is not the case for producers on larger, highly industrialized farms that receive more agricultural subsidies.
Country applied	Mauritania
Reference	Binet et al. (2013)
Funding	EU through fishing agreement
Outcome	**Positive**. The Banc d'Arguin National Park is using the European Fisheries Agreement as a PES to support the conservation of coastal biodiversity and to re-establish the link between fisheries and the management of marine protected areas. The results are positive, with sustainable long-term funding, adequate payments and livelihood benefits for local communities.

Ecosystems service	Biodiversity and agriculture
Country applied	Croatia
Reference	Capodaglio, and Callegari (2018)
Funding	No data
Outcome	**Positive**. Lonjsko Polje is an area with higher biodiversity. Land abandonment is high in these areas. PES is an incentive to avoid land abandonment and to maintain biodiversity.

Ecosystems service	Carbon sequestration and storage
Country applied	Kenya, Uganda, The United Republic of Tanzania
Reference	Osewe et al. (2023)
Funding	Mixed
Outcome	**Positive**. PES in these countries have increased the efficiency of ecosystem services (ES) conservation and benefited poor rural communities.
Country applied	Uganda
Reference	Jayachandran et al. (2016)
Funding	No governmental organization
Outcome	**Positive**. The PES programme in western Uganda offered cash payments to forest owners for conserving their forests. Tree cover decreased by only two to five per cent with PES, and by seven to ten per cent without PES. It had a positive effect on carbon sequestration.
Country applied	Mozambique
Reference	Alston et al. (2013)
Funding	User (international carbon payment)
Outcome	**Mixed**. The Carbon Livelihoods Project in Nhambita has made it possible to reduce agricultural activity and deforestation, adopt better production techniques and increase incomes. The disadvantage is that transaction costs are high.

Country applied	Serbia
Reference	Keca, and Marković, (2019)
Funding	Government
Outcome	**Mixed**. The Forestry Fund is a separate line item in the national budget that finances the increase of forest cover through afforestation. Afforestation is not necessarily a biodiversity-friendly activity. In some cases, valuable and biodiversity-rich forest areas have been reforested with species for intensive timber use.

Country applied	México
Reference	García Romero (2012); Reyes-Hernández (2023)
Funding	Government
Outcome	**Mixed**. This PES programme did not have a significant impact on preventing deforestation. The main problems were unclear selection criteria, failure to calculate opportunity costs for different ecosystems and failure to consider the risk of deforestation.

Country applied	China
Reference	Salzman et al. (2018); Chen, et al. (2020)
Funding	Government
Outcome	**Positive**. China has the Slope Land Conservation Programme to convert steep farmland into forests and grasslands and the Natural Forest Conservation Programme focusing on logging bans and afforestation. Assessments have found that all ecosystem services except biodiversity habitat have increased, with mostly positive socioeconomic benefits.

Country applied	Ecuador
Reference	Alston et al. (2013)
Funding	User
Outcome	**Positive**. The PROFAFOR project in Ecuador monitors individual plots of land to evaluate forest cover.

Ecosystems service	Landscape beauty
Country applied	Viet Nam
Reference	Nguyen et al. (2020)
Funding	Mixed
Outcome	**Positive**. Solutions have been successful in reducing forest cover.
Country applied	Cambodia
Reference	Milne and Chervier (2014)
Funding	Conservation organizations
Outcome	**Positive**. Cambodia has an extensive PES programme. One of these is community-based ecotourism in Preah Vihear to protect endangered bird species and their ecosystem. Bird watchers pay a fixed fee to a village committee, which collectively distributes the benefits to villagers. This encourages the creation of local natural resource management institutions.

Ecosystems service	Multiple services: carbon sequestration, hydrological services, biodiversity and scenic beauty.
Country applied	Costa Rica (Since 1987)
Reference	Alston et al. (2013)
Funding	Government
Outcome	**Mixed**. The programme has multiple objectives, making it difficult to assess the effectiveness of any one service. In terms of deforestation, there is no discernible difference in forest cover between participants and non-participants. Two studies show that land tenure has become more secure. The economic impact was found to be negative and the poor did not benefit.
Country applied	Romania
Reference	Capodaglio, and Callegari. (2018)
Funding	Public and Private
Outcome	**Negative**. The Oas-Gutai plateau area is rich in natural biodiversity and picturesque landscapes. The problem in the area is overgrazing and land abandonment. Payments have not been sufficient to fully cover costs and therefore have not solved the problems.

Ecosystems service	Aquifer quality and management
Country applied	Germany
Reference	Le Coent (2023)
Funding	User
Outcome	**Positive**. In response to increasing pollution of drinking water resources, the city of Munich developed a PES for farmers in the catchment area. Eighty per cent of the area was covered by the programme, which improved water quality at minimal cost to users.
Country applied	Croatia
Reference	Vuletić et al. (2019)
Funding	Government
Outcome	**Positive**. Subjects pay a percentage of their annual income for forest ecosystem services that affect water purification and the supply of drinking water from underground watercourses and water sources.

References

Adekunle, I.A. and Oseni, I.O. (2021). Fuel subsidies and carbon emission: evidence from asymmetric modelling. Environmental Science and Pollution Research 28(18), 22729-22741. https://doi.org/10.1007/s11356-021-12384-0

Agrawal, A. and Chhatre, A. (2006). Explaining success on the commons: Community forest governance in the Indian Himalaya. World Development 34(1), 149-166. https://doi.org/10.1016/j.worlddev.2005.07.013

Agrawal, A., Erbaugh, J. and Pradhan, N. (2023). The Commons. Annual Review of Environment and Resources 48. https://doi.org/10.1146/annurev-environ-112320-113509

Aguilar-Gómez, C.R., Arteaga-Reyes, T.T., Gomez-Demetrio, W., Ávila-Akerberg, V.D. and Perez-Campuzano, E. (2020). Differentiated payments for environmental services: A review of the literature. Ecosystem Services 44. https://doi.org/10.1016/j.ecoser.2020.101131

Aguilera, R., Capapé, J. and Santitso, J. (2015). Sovereign Wealth Funds: A Strategic Governance View. Academy of Management Perspectives 30. http://dx.doi.org/10.5465/amp.2013.0055

Akinsete, E., Apostolaki, S., Chatzistamoulou, N., Koundouri, P. and Tsani, S. (2019). The Link between Ecosystem Services and Human Wellbeing in the Implementation of the European Water Framework Directive: Assessing Four River Basins in Europe. Water 11(3), 508. https://doi.org/10.3390/w11030508

Allen & Overy and Climate Policy Initiative (2023). How big is the Net Zero financing gap? September 2023. https://www.aoshearman.com/en/insights/how-big-is-the-net-zero-financing-gap.

Alston, L., Andersson, K. and Smith, S. (2013). Payment for Environmental Services: Hypotheses and Evidence. Annual Review of Resource Economics 5. http://dx.doi.org/10.1146/annurev-resource-091912-151830

Amardeep, W., Waddell, S., March, A., Hart, B. and Failler, P. (2023). Assessment of the Scope, Scale and Impacts of Marine Pollution on Key Blue Economy Sectors in the Pacific Island Countries. Tourism Sector Report. 78. FCG New Zealand & APWC for the World Bank. https://www.cowater.com/en/project/assessment-of-the-scope-scale-and-impacts-of-marine-plastics-pollution-on-key-blue-economy-sectors-in-pacific-island-countries/

Angelsen, A., Martius, C., De Sy, V., Duchelle, A., Larson, A. and Pham, T. (2018). Transforming REDD+: Lessons and new directions. Bogor: Center for International Forestry Research. https://www.cifor.org/knowledge/publication/7045

Balasubramanian, M. and Sangha, K.K. (2021). Integrating Capabilities and Ecosystem Services Approaches to evaluate Indigenous connections with nature in a global biodiversity hotspot of Western Ghats, India. Global Ecology and Conservation 27, e01546. https://doi.org/10.1016/j.gecco.2021.e01546

Baranzini, A., van den Bergh, J.C.J.M., Carattini, S., Howarth, R.B., Padilla, E. and Roca, J. (2017). Carbon pricing in climate policy: seven reasons, complementary instruments, and political economy considerations. WIREs Climate Change 8(4), e462. https://doi.org/10.1002/wcc.462

Barraqué, B. (2020). Full cost recovery of water services and the 3 T's of OECD. Utilities Policy 62, 100981. https://doi.org/10.1016/j.jup.2019.100981

Bastien-Olvera, B. and Moore, F. (2022). Climate Impacts on Natural Capital: Consequences for the Social Cost of Carbon. Annual Review of Resource Economics 15, 515-532. https://doi.org/10.1146/annurev-resource-111820-020204

Baumol, W.J. and Oates, W.E. (1988). The Theory of Environmental Policy. 2 edition. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781139173513

Bennett, A. (2013). Personalising health benefits can cut costs. Occupational Health 65(12), 24-25. https://www.proquest.com/openview/1ab422d10f7561f3037615985fd03d2d/1?cbl=49149&pq-origsite=gscholar

Benzaken, D., Adam, J.P., Virdin, J. and Voyer, M. (2024). From concept to practice: Financing sustainable blue economy in lessons learnt from the Seychelles experience. Marine Policy 163, 106072. https://doi.org/10.1016/j.marpol.2024.106072

Berg, F., Koelbel, J.F., Pavlova, A. and Rigobon, R. (2022). ESG confusion and stock returns: Tackling the problem of noise. National Bureau of Economic Research. https://www.nber.org/system/files/working_papers/w30562/w30562.pdf

Berger, S. and Wyss, A.M. (2021). Measuring pro-environmental behavior using the carbon emission task. Journal of Environmental Psychology 75, 101613. https://doi.org/10.1016/j.jenvp.2021.101613

Betts-Davies, S., Barrett, J., Brockway, P. and Norman, J. (2024). Is all inequality reduction equal? Understanding motivations and mechanisms for socio-economic inequality reduction in economic narratives of climate change mitigation. Energy Research & Social Science 107, 103349. https://www.sciencedirect.com/science/article/pii/S2214629623004097

Bhardwaj, N.D. (2023). 4 Challenges in Healthcare in India. Administration in India. https://www.taylorfrancis.com/chapters/edit/10.4324/9781003433187-6/challenges-healthcare-india-nitin-dutt-bhardwaj

Bilal, A. and Känzig, D.R. (2024). The Macroeconomic Impact of Climate Change: Global vs. Local Temperature. National Bureau of Economic Research Working Paper Series 32540. https://doi.org/10.3386/w32450

Binet, T., Failler, P., Chavance, P. and Mayif, M. (2013). First international payment for marine ecosystem services: the case of the Banc d'Arguin National Park, Mauritania. Global Environmental Change 23(6), 1434-1443. https://doi.org/10.1016/j.gloenvcha.2013.09.015.

BIS (2022) Basel Committee issues principles for the effective management and supervision of climate-related financial risks. https://www.bis.org/press/p220615.htm#:~:text=Basel%20Committee%20issues%20principles%20for%20the%20effective%20management,and%20supervisors%27%20practices%20related%20to%20climate-related%20financial%20risks

Black, S., Liu, A.A., Parry, I.W.H. and Vernon, N. (2023). IMF Fossil Fuel Subsidies Data: 2023 Update. International Monetary Fund. https://www.imf.org/en/Publications/WP/Issues/2023/08/22/IMF-Fossil-Fuel-Subsidies-Data-2023-Update-537281

Bowen, A. and Fankhauser, S. (2017). Good practice in low-carbon policy. In Trends in Climate Change Legislation. Averchenkova, A., Fankhauser, S. and Nachmany, M. (eds.). Edward Elgar Publishing. Chapter 7. 123-140. https://ideas.repec.org/h/elg/eechap/17582_7.html

Broadstock, D.C., Fouquet, R. and Kim, J.W. (2025). Carbon pricing and stock performance: Are carbon prices already more influential than energy prices? Energy Policy 206, 114775. https://doi.org/10.1016/j.enpol.2025.114775.

Budina, N., Ebeke, C., Jaumotte, F., Medici, A. Panton, A., Tavares, M and Yao, B. (2023). Structural Reforms to Accelerate Growth, Ease Policy Trade-offs, and Support the Green Transition in Emerging Market and Developing Economies. Staff Discussion Note SDN/2023/007. Washington D.C.: International Monetary Fund https://www.elibrary.imf.org/view/journals/006/2023/007/article-A001-en.xml.

Buchanan, R. A., & King, P. E. (2019). Climate change and developing countries: A review of policy responses. Journal of Environmental Policy & Planning 21(1), 1-16. https://doi.org/10.1007/0-306-47980-X_9

Buchanan, J. and Yoon, Y.J. (2000). Symmetric Tragedies: Commons and Anticommons. Journal of Law and Economics 43(1), 1-13. https://EconPapers.repec.org/RePEc:ucp:jlawec:v:43:y:2000:i:1:p:1-13

Buchanan, J.M. (1975). The Limits of Liberty: between anarchy and Leviathan. University of Chicago Press. https://philpapers.org/rec/BUCTLO-4

Burritt, R.L. and Christ, K.L. (2021). Full cost accounting: A missing consideration in global tailings dam management. Journal of Cleaner Production 321, 129016. https://doi.org/10.1016/j.jclepro.2021.129016

Business and Sustainable Development Commission (2017). Better Business, Better World. https://sustainabledevelopment.un.org/content/documents/2399BetterBusinessBetterWorld.pdf

Calliari, E., Serdeczny, O. and Vanhala, L. (2020). Making sense of the politics in the climate change loss & damage debate. Global Environmental Change 64, 102133. https://doi.org/10.1016/j.gloenvcha.2020.102133

Camilleri, A.R., Larrick, R.P., Hossain, S. and Patino-Echeverri, D. (2019). Consumers underestimate the emissions associated with food but are aided by labels. Nature Climate Change 9(1), 53-58. https://doi.org/10.1038/s41558-018-0354-z

Capodaglio, A.G. and Callegari, A. (2018). Can payment for ecosystem services schemes be an alternative solution to achieve sustainable environmental development? A critical comparison of implementation between Europe and China. Resources 7(3), 40. https://doi.org/10.3390/resources7030040

Carattini, S., Carvalho, M. and Fankhauser, S. (2018). Overcoming public resistance to carbon taxes. WIREs Climate Change 9(5), e531. https://doi.org/10.1002/wcc.531

Chai, Y. and Zeng, Y. (2018). Social capital, institutional change, and adaptive governance of the 50-year-old Wang hilltop pond irrigation system in Guangdong, China. The Commons Journal 12(2), 191-216. https://doi.org/10.18352/ijc.851

Chamon, M., Klok, E., Thakoor, V. and Zettelmeyer, J. (2022). Debt-for-Climate Swaps: Analysis, Design, and Implementation. Working Paper No. 2022/162. International Monetary Fund. https://www.imf.org/en/Publications/WP/Issues/2022/08/11/Debt-for-Climate-Swaps-Analysis-Design-and-Implementation-522184

Chasu, L., Li, W. and Mu, Y. (2023). Why does rangeland integration by transfer fail to overcome the tragedy of anticommons? Ambio 52(10), 1676-1686. https://doi.org/10.1007/s13280-023-01883-8

Chen, H.L., Lewison, R.L., An, L. et al. (2020). Assessing the effects of payments for ecosystem services programs on forest structure and species biodiversity. Biodivers Conserv 29, 2123–2140. https://doi.org/10.1007/s10531-020-01953-3

Chen, M., Jiandong, W. and Saleem, H. (2022). The role of environmental taxes and stringent environmental policies in attaining the environmental quality: Evidence from OECD and non-OECD countries. Frontiers in Environmental Science 10. https://doi.org/10.3389/fenvs.2022.972354

Coase, R.H. (1960). The Problem of Social Cost. Journal of Law and Economics 3(1), 1-44. https://www.jstor.org/stable/724810

Coger, T., Dinshaw, A., Krishnan, N., Cook, M., Brown, A., Chu, E. et al. (2022). Tracking and Reporting Finance for Locally Led Adaptation to Climate Change. https://doi.org/10.46830/wriwp.20.00100

Copeland, B.R. and Taylor, M.S. (1995). Trade and the environment: a partial synthesis. American. Journal of Agricultural Economics 77(3), 765-771. https://doi.org/10.2307/1243249

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B. et al. (1997). The value of the world's ecosystem services and natural capital. Nature 387(6630), 253-260. https://doi.org/10.1038/387253a0

Costanza, R., De Groot, R., Sutton, P., Van der Ploeg, S., Anderson, S.J., Kubiszewski et al. (2014). Changes in the global value of ecosystem services. Global Environmental Change 26, 152-158. https://doi.org/10.1016/j.gloenvcha.2014.04.002

Costedoat, S., Corbera, E., Ezzine-de-Blas, D., Honey-Rosés, J., Baylis, K. and Castillo-Santiago, M. (2015). How Effective Are Biodiversity Conservation Payments in Mexico? HPLoS ONE 10(3), e0119881. https://doi.org/10.1371/journal.pone.0119881

Cox, B., Innis, S., Steen, J. and Kunz, N. (2023). The environmental and economic case for valuing water recovery and its relationship with tailings storage conservation. Minerals Engineering 201, 108157. https://doi.org/10.1016/j.mineng.2023.108157

Cranford, M. and Mourato, S. (2011). Community conservation and a two-stage approach to payments for ecosystem services. Ecological Economics 71, 89-98. https://doi.org/10.1016/j.ecolecon.2011.08.007

Creutzig, F., Niamir, L., Bai, X., Callaghan, M., Cullen, J., Díaz-José, J. et al. (2022). Demand-side solutions to climate change mitigation consistent with high levels of well-being. Nature Climate Change 12(1), 36-46. https://doi.org/10.1038/s41558-021-01219-y

Damania, R., Balseca, E., de Fontaubert, C., Gill, J., Kim, K., Rentschler, J. et al. (2023). Detox Development: Repurposing Environmentally Harmful Subsidies. International Bank for Reconstruction and Development. https://doi.org/10.1596/978-1-4648-1916-2

Dasgupta, P. (2021). The Economics of Biodiversity: The Dasgupta Review. Abridged Version. London: HM Treasury. https://assets.publishing.service.gov.uk/media/602e92b2e90e07660f807b47/The_Economics_of_Biodiversity_The_Dasgupta_Review_Full_Report.pdf

Ddiba, D., Andersson, K., Dickin, S., Ekener, E. and Finnveden, G. (2023). A review of how decision support tools address resource recovery in sanitation systems. Journal of Environmental Management 342, 118365. https://doi.org/10.1016/j.jenvman.2023.118365

Dechezleprêtre, A. and Sato, M. (2017). The impacts of environmental regulations on competitiveness. Review of Environmental Economics and Policy 11(2). https://doi.org/10.1093/reep/rex013

Drews, S. and van den Bergh, J.C.J.M. (2016). What explains public support for climate policies? A review of empirical and experimental studies. Climate Policy 16(7), 855-876. https://doi.org/10.1080/14693062.2015.1058240

T.D Economics (2015). The long and winding road towards Aboriginal economic prosperity. https://www.ccab.com/wp-content/uploads/2016/11/TD-AboriginalEconomicProsperity.pdf

European Commission (2020). Implementing and delegated acts - EU Climate Transition Benchmarks Regulation. https://finance.ec.europa.eu/regulation-and-supervision/financial-services-legislation/implementing-and-delegated-acts/eu-climate-transition-benchmarks-regulation_en

European Commission (2021). Strategy for Financing the Transition to a Sustainable Economy. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0390

European Commission (2023) Regulation on Deforestation-free Products Regulation on Deforestation-free products - European Commission Accessed August 13, 2025. https://environment.ec.europa.eu/topics/forests/deforestation/regulation-deforestation-free-products_en

European Commission (2025a). Carbon Border Adjustment Mechanism. https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en#cbam-transitional-phase-2023--2025

European Commission (2025b). Omnibus. https://commission.europa.eu/publications/omnibus-i_en

European Environmental Agency (2024). The costs to health and the environment from industrial air pollution in Europe. EEA. https://doi.org/10.2800/957087

European Investment Bank, Hudson, G., Hart, S. and Verbeek, A. (2023). Investing in nature-based solutions – State-of-play and way forward for public and private financial measures in Europe. https://data.europa.eu/doi/10.2867/031133

European Investment Bank (2023). Investing in nature-based solutions – State-of-play and way forward for public and private financial measures in Europe. Hudson, G., Hart, S. and Verbeek, A. (eds.) European Investment Bank. https://data.europa.eu/doi/10.2867/031133

European Union (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal L 327 , 22/12/2000 P. 0001 - 0073p. 1–73. ELI: http://data.europa.eu/eli/dir/2000/60/oj

Failler, P., Pan, H. and Akbari, N. (2022). Integrated Social-Economic-Ecological Modelling for Fisheries: The ECOST Model. Front. Mar. Sci. 8, 704371. https://doi.org/10.3389/fmars.2021.704371

Food and Agriculture Organization, International Fund for Agricultural Development and World Food Programme (2014). The State of Food Insecurity in the World 2014. Strengthening the enabling environment for food security and nutrition. Rome: Food and Agriculture Organization. https://openknowledge.fao.org/server/api/core/bitstreams/ad888f5b-a590-43d9-b066-9a852b95777e/content

Food and Agriculture Organization, United Nations Development Programme and United Nations Environment Programme (2021). A multi-billion-dollar opportunity – Repurposing agricultural support to transform food systems. Rome: FAO. https://doi.org/10.4060/cb6562en

Fan, S., Headey, D., Rue, C. and Thomas, T. (2021). Food Systems for Human and Planetary Health: Economic Perspectives and Challenges. Annual Review of Resource Economics 13, 131-156. https://doi.org/10.1146/annurev-resource-101520-081337

Farnault, A. and Leflaive, X. (2024). Cost recovery for water services under the Water Framework Directive. OECD Environment Working Papers. https://doi.org/10.1787/e2a363e3-en

Fekete, H., Kuramochi, T., Roelfsema, M., den Elzen, M., Forsell, N., Höhne, N. et al. (2021). A review of successful climate change mitigation policies in major emitting economies and the potential of global replication. Renewable and Sustainable Energy Reviews 137. https://doi.org/10.1016/j.rser.2020.110602

Feucht, Y. and Zander, K. (2017). Consumers' preferences for carbon labels and the underlying reasoning. A mixed methods approach in 6 European countries. Journal of Cleaner Production 178. http://dx.doi.org/10.1016/j.jclepro.2017.12.236

Forns Albuixech, A. and Lyubomirova Lazarova, K. (2024). Bridging the climate financing gap: seizing the opportunity. European Commission News Blog, 22 February 2024. Accessed 26 November 2025.

Freeman A.M. (1979). The benefits of environmental quality improvement. Baltimore: Johns Hopkins University Press. https://digitalrepository.unm.edu/cgi/viewcontent.cgi?article=2897&context=nrj

G20 Sustainable Finance Group (2021). 2021 Synthesis Report. https://g20sfwg.org/wp-content/uploads/2021/11/Synth_G20_Final.pdf

Gill, F.L., Viswanathan, K.K. and Karim, M.Z.A. (2018). The critical review of the pollution haven hypothesis. International Journal of Energy Economics and Policy 8(1), 167-174

Global Financial Markets Association (2020). Climate Finance Markets and Real Economy: Sizing the Global Need and Defining the Market Structure to Mobilize Capital. https://www.sifma.org/wp-content/uploads/2020/12/Climate-Finance-Markets-and-the-Real-Economy.pdf

Green, K.M., Crawford, B.A., Williamson, K.A. and DeWan, A.A. (2019). A meta-analysis of social marketing campaigns to improve global conservation outcomes. Social Marketing Quarterly 25(1), 69-87. https://psycnet.apa.org/doi/10.1177/1524500418824258

Greenstone, M. and Hanna, R. (2014). Environmental Regulations, Air and Water Pollution, and Infant Mortality in India. American Economic Review 104(10), 3038-3072. https://www.aeaweb.org/articles?id=10.1257/aer.104.10.3038

Grosjean, P.E. and Kontoleon, A. (2009). How Sustainable are Sustainable Development Programs? The Case of the Sloping Land Conversion Program in China. World Development 37(1), 268-285. https://doi.org/10.1016/j.worlddev.2008.05.003

Gruenwald, T., Seals, B.A., Knibbs, L.D. and Hosgood, H.D. (2023). Population Attributable Fraction of Gas Stoves and Childhood Asthma in the United States. International Journal of Environmental Research and Public Health 20(1), 75. https://doi.org/10.3390/ijerph20010075

Guajardo, J., Ugazio, G. and Chensavasdijai, V. (2023). Online Annex 5. Debt-for-Nature Swaps in Latin America and the Caribbean. International Monetary Fund. https://www.imf.org/-/media/Files/Publications/REO/WHD/2023/October/English/onlineannex-5-en.ashx

Hammar, H., Löfgren, A. and Sterner, T. (2004). Political economy obstacles to fuel taxation. The Energy Journal 25(3), 1-17. https://www.jstor.org/stable/41323039

Healy, S., Pietschmann, M., Schneider, L. and Karki, A. (2023). Assessing the transparency and integrity of benefit sharing arrangements related to voluntary carbon market projects. Berlin, Germany: Öko-Institut e.V. https://carbonmarketwatch.org/wp-content/uploads/2023/11/Assessing-transparency-and-integrity-of-benefit-sharing-arrangements-related-to-voluntary-carbon-market-projects.pdf

Heller, M.A. (1998). The Tragedy of the Anticommons: Property in the Transition from Marx to Markets. Harv. L. Rev. 111(3), 621-688. https://repository.law.umich.edu/articles/609/

Henderson, B. and Norris, K. (2008). Experiences with market-based instruments for environmental management. Australasian Journal of Environmental Management 15, 113-120. http://dx.doi.org/10.1080/14486563.2008.9725191

Hendriks, S., de Groot Ruiz, A., Herrero Acosta, M., Baumers, H., Galgani, P., Mason-D'Croz, D. et al. (2023). The True Cost of Food: A Preliminary Assessment. In: Science and Innovations for Food Systems Transformation. von Braun, J., Afsana, K., Fresco, L.O., Hassan, M.H.A. (eds) Cham.: Springer. https://doi.org/10.1007/978-3-031-15703-5_32

Henry, G.T. and Gordon, C.S. (2003). Driving Less for Better Air: Impacts of a Public Information Campaign. Journal of Policy Analysis and Management 22(1), 45-63. http://www.jstor.org/stable/3325845

Hickel, J., Kallis, G., Jackson, T., O'Neill, D.W., Schor, J.B., Steinberger, J.K. et al. (2022). Degrowth can work — Here's how science can help. Nature 612(7940), 400-403. https://doi.org/10.1038/d41586-022-04412-x

High-Level Expert Group on Sustainable Finance (2018). Financing a Sustainable European Economy. https://finance.ec.europa.eu/system/files/2018-01/180131-sustainable-finance-final-report_en.pdf

Horne, C. and Kennedy, E.H. (2017). The power of social norms for reducing and shifting electricity use. Energy Policy 107, 43-52. https://doi.org/10.1016/j.enpol.2017.04.029

Hou, A., Liu, A. and Chai, L. (2024). Does reducing income inequality promote the decoupling of economic growth from carbon footprint? World Development 173, 106423. https://doi.org/10.1016/j.worlddev.2023.106423

Howlett, M. (2011). Designing Public Policies: Principles and Instruments. 2nd ed. London: Routledge. https://doi.org/10.4324/9781315232003

Ihalanayake, R. (2013). Tourism Taxes and Negative Externalities In Tourism In Australia: A CGE Approach. Corporate Ownership & Control 10(4), 1-15. https://doi.org/10.22495/cocv10i4c1art4

Indigenous Carbon Industry Network (2024). Annual Report 2023-2024. Indigenous Carbon Industry Network. https://assets.nationbuilder.com/icin/pages/1574/attachments/original/1734601050/ICIN_AnnualReport2023-24.pdf?1734601050

IK & LK Dialogues. Indigenous Knowledge and Local Knowledge Dialogues. Global Environment Outlook 7. Mexico City: CopIt-arXives, 2025. https://copitarxives.fisica.unam.mx/SC0011EN/SC0011EN.php Indigenous Knowledge and Local Knowledge Dialogues - Copit Arxives (2025)

International Capital Market Association (2021). Sustainability-Linked Bond Principles: Related questions. https://www.icmagroup.org/assets/documents/Sustainable-finance/Sustainability-Linked-Bond-Principles-Related-questions-February-2021-170221v3.pdf

International Federation of Red Cross and Red Cross Societies (2018). World Disasters Report: Leaving no one behind. https://www.ifrc.org/sites/default/files/2021-09/B-WDR-2018-EN-LR.pdf

International Financial Reporting Standards (2022). Exposure Draft and comment letters: General Sustainability-related Disclosures. https://www.ifrs.org/content/dam/ifrs/project/general-sustainability-related-disclosures/exposure-draft-ifrs-s1-general-requirements-for-disclosure-of-sustainability-related-financial-information.pdf

International Financial Reporting Standards (2024). Progress towards adoption of ISSB Standards as jurisdictions consult. https://www.ifrs.org/news-and-events/news/2024/04/progress-towards-adoption-of-issb-standards-as-jurisdictions-consult

International Energy Agency (2023). Global energy investment in clean energy and in fossil fuels, 2015-2023. https://www.iea.org/data-and-statistics/charts/global-energy-investment-in-clean-energy-and-in-fossil-fuels-2015-2023

International Labour Organization (2020). World Employment and Social Outlook: Trends 2020. https://www.ilo.org/sites/default/files/wcmsp5/

groups/public/@dgreports/@dcomm/@publ/documents/publication/wcms_734455.pdf

International Renewable Energy Agency (2023). Renewable energy statistics 2023. https://www.irena.org/Publications/2023/Jul/Renewable-energy-statistics-2023

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2022). Summary for policymakers of the methodological assessment of the diverse values and valuation of nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://zenodo.org/doi/10.5281/zenodo.6522392

Intergovernmental Panel on Climate Change (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Geneva, Switzerland: Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar5/syr/

Intergovernmental Panel on Climate Change (2022). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/9781009325844

Intergovernmental Panel on Climate Change (2023). Synthesis Report of the IPCC Sixth Assessment Report. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf

Jaffe, A.B., Newell, R.G. and Stavins, R.N. (2003). Technological change and the Environment. In Handbook of Environmental Economics. Mäler, K.-G. and Vincent, J. (eds.). Chapter 11. Amsterdam: Elsevier Science. https://scholar.harvard.edu/files/stavins/files/technological_change_and_the_environment_handbook_chapter.pdf

Jayachandran, S. (2022). How Economic Development Influences the Environment. Annual Review of Economics 14, 229-252. https://www.annualreviews.org/doi/abs/10.1146/annurev-economics-082321-123803

Jayachandran, S., de Laat, J., Lambin, E.F. and Stanton, C. (2016). Cash for Carbon: A Randomized Controlled Trial of Payments for EcosystemServices to Reduce Deforestation. National Bureau of Economic Research, Inc. https://EconPapers.repec.org/RePEc:nbr:nberwo:22378

Kallis, G., Hickel, J., O'Neill, D.W., Jackson, T., Victor, P.A., Raworth, K., Schor, J.B., Steinberger, J.K., Ürge-Vorsatz, D., 2025. Post-growth: the science of wellbeing within planetary boundaries. The Lancet Planetary Health 9, e62–e78. https://doi.org/10.1016/S2542-5196(24)00310-3

Khalfan, A., Nilsson Lewis, A., Aguilar, C., Persson, J., Lawson, M., Dabi, N. et al. (2023). Climate Equality: A planet for the 99%. Oxfam International. https://doi.org/10.21201/2023.000001

Kotter, J. and Lel, U. (2011). Friends or foes? Target selection decisions of sovereign wealth funds and their consequences. Journal of Financial Economics 101(2), 360-381. https://doi.org/10.1016/j.jfineco.2011.03.007

Krishna, V.V., Drucker, G.A., Pascual, U., Raghu, P.T. and King, E.D. (2013). Estimating compensation payments for on-farm conservation of agricultural biodiversity in developing countries. Ecological Economics 87, 110-123. https://doi.org/10.1016/j.ecolecon.2012.12.013

Krugman, P. and Wells, R. (2013). Macroeconomics. New York, NY: Worth Publishers. https://www.academia.edu/32662086/Macroeconomics_in_Modules_3rd_Edition

Le Coent, P. (2023). Payment for environmental services related to aquifers: a review of specific issues and existing programmes. Review of Agricultural, Food and Environmental Studies 104(3), 273-310. https://doi.org/10.1007/s41130-023-00196-4

Leflaive, X. and Hjort, M. (2020). Addressing the social consequences of tariffs for water supply and sanitation. OECD Environment Working Papers 166. https://doi.org/10.1787/afede7d6-en

Lv, J., Li, Y., Huang, G. and Li, Y. (2022). Planning Economy-energy-environment Nexus System: A Case Study of Pearl River Delta, China. Proceedings of the 11th International Conference on Informatics, Environment, Energy and Applications. Xi'an, China. Association for Computing Machinery 75–81 https://doi.org/10.1145/3533254.3533269

March, A., Evans, T., Laing, S. and Raguain, J. (2024). Evaluating the World's First Sovereign Blue Bond: Lessons for Operationalising Blue Finance. Commodities 3(2), 151-167. https://doi.org/10.3390/commodities3020010

Marchewitz, C., Ballesteros, F., Schütze., F., and Arab, N. H. (2024). Sustainable Finance Taxonomies – Enabling the Transition towards Net Zero? A Transition Score for International Frameworks. Deutsches Institut für Wirtschaftsforschung 2083. https://www.diw.de/documents/publikationen/73/diw_01.c.902603.de/dp2083.pdf

Matthews, A. and Karousakis, K. (2022). Identifying and assessing subsidies and other incentives harmful to biodiversity: A comparative review of existing national-level assessments and insights for good practice. OECD Environment Working Papers 206. https://doi.org/10.1787/3e9118d3-en

Mert, M. and Bölük, G. (2016). Do foreign direct investment and renewable energy consumption affect the CO 2 emissions? New evidence from a panel ARDL approach to Kyoto Annex countries. Environmental Science and Pollution Research 23, 21669-21681. https://doi.org/10.1007/s11356-016-7413-7

Millward-Hopkins, J., Steinberger, J.K., Rao, N.D. and Oswald, Y. (2020). Providing decent living with minimum energy: A global scenario. Global Environmental Change 65, 102168. https://doi.org/10.1016/j.gloenvcha.2020.102168

Milne, S. and Chervier, C. (2014). A review of payments for environmental services (PES) experiences in Cambodia. https://www.researchgate.net/publication/285593302_A_review_of_payments_for_environmental_services_PES_experiences_in_Cambodia

Ministry of Finance and Public Credit (SHCP) (2023). Sustainable Taxonomy of Mexico. Mexico City, Mexico: Mexican Ministry of Finance and Public Credit. https://www.finanzassostenibles.hacienda.gob.mx/work/models/finanzassostenibles/recursos/documentos/TaxonomyEV_2024_V1.pdf

Mirzabaev, A., Sacande, M., Motlagh, F., Shyrokaya, A. and Martucci, A. (2022). Economic efficiency and targeting of the African Great Green Wall. Nature Sustainability 5(1), 17-25. https://doi.org/10.1038/s41893-021-00801-8

Mirzabaev, A. and Wuepper, D. (2023). Economics of Ecosystem Restoration. Annual Review of Resource Economics 15(1), 329-350. https://doi.org/10.1146/annurev-resource-101422-085414

Neto, M.A. (2021). Why ESG is failing sustainable development. UNDP SDG Finance Sector Hub. https://sdgfinance.undp.org/news-events/why-esg-failing-sustainable-development

Nguyen, Hieu & Thuy, Dang & Hoang Nguyen, Nam. (2020). Payment For Environmental Service: An Application in Tourism in Vietnam. Sustainable Environment Agricultural Science 4(1). http://dx.doi.org/10.22225/seas.4.1.1691.77-87

Nguyen-Thanh, N., Chin, K.-H. and Nguyen, V. (2022). Does the pollution halo hypothesis exist in this "better" world? The evidence from STIRPAT model. Environmental Science and Pollution Research 29(58), 87082-87096. https://doi.org/10.1007/s11356-022-21654-4

Ohlendorf, N., Jakob, M., Minx, J.C., Schröder, C. and Steckel, J.C. (2021). Distributional Impacts of Carbon Pricing: A Meta-Analysis. Environmental and Resource Economics 78(1), 1-42. https://doi.org/10.1007/s10640-020-00521-1

Olk, C., Schneider, C. and Hickel, J. (2023). How to pay for saving the world: Modern Monetary Theory for a degrowth transition. Ecological Economics 214, 107968. https://doi.org/10.1016/j.ecolecon.2023.107968

One Planet (2018). Integrating Climate Change Risks and Investing in the Smooth Transition to a Low Emissions Economy. https://oneplanetswfs.org

Organisation for Economic Co-operation and Development (2016). Environmental labelling and information schemes - Policy Perspectives. https://www.oecd.org/env/policy-persectives-environmental-labelling-and-information-schemes.pdf

Organisation for Economic Co-operation and Development (2017). Investing in Climate, Investing in Growth Investing in Climate, Investing in Growth. https://www.oecd.org/env/investing-in-climate-investing-in-growth-9789264273528-en.htm

Organisation for Economic Co-operation and Development (2021). Towards a more resource-efficient and circular economy. The role of the G20. https://www.researchgate.net/publication/357631601_Towards_a_more_resource-efficient_and_circular_economy_-_The_role_of_the_G20

Organisation for Economic Co-operation and Development (2022). Climate Finance Provided and Mobilised by Developed Countries in 2016-2020. https://doi.org/10.1787/286dae5d-en

Organisation for Economic Co-operation and Development (2022). Global Outlook on Financing for Sustainable Development 2023. https://doi.org/10.1787/fcbe6ce9-en

Organisation for Economic Co-operation and Development (2023a). Policy Instruments for the Environment (PINE) Database. https://www.oecd.org/environment/indicators-modelling-outlooks/policy-instruments-for-environment-database/

Organisation for Economic Co-operation and Development (2023b). OECD Guidelines for Multinational Enterprises on Responsible Business Conduct. https://doi.org/10.1787/81f92357-en

Organisation for Economic Co-operation and Development (2024). OECD Economic Outlook. Paris: Organisation for Economic Co-Operation and Development. https://doi.org/10.1787/69a0c310-en

Osewe, I., Hălălișan, A.-F., Talpă, N. and Popa, B. (2023). Critical Analysis of Payments for Ecosystem Services: Case Studies in Kenya, Uganda and Tanzania. Forests 14(6), 1209. https://doi.org/10.3390/f14061209

Ostrom, E. (1990). Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge, UK: Cambridge University Press. https://www.actu-environnement.com/media/pdf/ostrom_1990.pdf

Oswald, Y., Steinberger, J. K., Ivanova, D., & Millward-Hopkins, J. (2021). Global redistribution of income and household energy footprints: a computational thought experiment. Global Sustainability 4, e4. https://www.cambridge.org/core/services/aop-cambridge-core/content/view/34886E1B95AC092C9E0A86BE68C215A5/S2059479821000016a.pdf/global-redistribution-of-income-and-household-energy-footprints-a-computational-thought-experiment.pdf

Pan, F., Xu, J. and Xue, L. (2023). Beyond the campaign-style enforcement: A consensual approach to bridge the environmental policy implementation gap. Environmental Policy and Governance 33(4), 374-385. https://doi.org/10.1002/eet.2040,

Parry, I., Black, S. and Vernon, N. (2021). Still Not Getting Energy Prices Right: A Global and Country Update of Fossil Fuel Subsidies. Washington, DC: International Monetary Fund. https://www.imf.org/en/Publications/WP/Issues/2021/09/23/Still-Not-Getting-Energy-Prices-Right-A-Global-and-Country-Update-of-Fossil-Fuel-Subsidies-466004

Pawanka Fund (2021). Communities Adapt to Climate Change and Bridge Generational and Cultural Gaps. https://pawankafund.org/blog-news/communities-adapt-to-climate-change-and-bridge-generational-and-cultural-gaps

Pigou, A.C. (1920). The Economics of Welfare. https://oll.libertyfund.org/title/pigou-the-economics-of-welfare

Pill, M. (2022). Towards a funding mechanism for loss and damage from climate change impacts. Climate Risk Management 35, 100391. https://doi.org/10.1016/j.crm.2021.100391

PricewaterhouseCoopers (2023). Managing nature risks: From understanding to action. https://www.pwc.com/gx/en/strategy-and-business/content/sbpwc-2023-04-19-Managing-nature-risks-v2.pdf

Rahim, S. (2020). How Investors Are Coming up with the Green to Save the Ocean Blue. Washington Post. https://www.washingtonpost.com/climate-solutions/2020/10/28/climate-solutions-ocean-conservation/

Raworth, K (2017) Doughnut Economics. London: Random House

Rentschler, J. and Bazilian, M. (2016). Reforming fossil fuel subsidies: drivers, barriers and the state of progress. Climate Policy 17(7). https://doi.org/10.1080/14693062.2016.1169393

Rey, F. and Madiès, T. (2021). Addressing the concerns about carbon leakage in the implementation of carbon pricing policies: A focus on the issue of competitiveness. Journal of Industrial and Business Economics 48(1), 53-75. https://doi.org/10.1007/s40812-020-00157-8

Reyes-Hernández, H. (2023). Payment for environmental services: Forest conservation and poverty alleviation in a tropical region of Mexico. Land Use Policy 133(C). https://doi.org/10.1016/j.landusepol.2023.106847

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F. et al. (2023). Earth beyond six of nine planetary boundaries. Science Advances 9(37), eadh2458. https://doi.org/10.1126/sciadv.adh2458

Rights and Resources Initiative (2023). Annual Report 2023. https://rightsandresources.org/wp-content/uploads/RRI-Annual-Report-2023-WEB-EN.pdf

Roberts, E. and Huq, S. (2015). Coming full circle: the history of loss and damage under the UNFCCC. International Journal of Global Warming 8, 141-157. https://www.researchgate.net/publication/299483341_Coming_full_circle_the_history_of_loss_and_damage_under_the_UNFCCC

Rodrik, D. and Stiglitz, J.E. (2024). A New Growth Strategy for Developing Nations. https://drodrik.scholar.harvard.edu/publications/new-growth-strategy-developing-nations

Romero, G.H. (2012). Payments for Environmental Services: Can They Work? The Case of Mexico. Field Actions Science Reports. The journal of field actions. https://journals.openedition.org/factsreports/1711

Salzman, J., Bennett, G., Carroll, N., Goldstein, A. and Jenkins, M. (2018). The global status and trends of Payments for Ecosystem Services. Nature Sustainability 1. https://www.nature.com/articles/s41893-018-0033-0

Sangha, K.K. (2020). Global importance of indigenous and local communities' managed lands: building a case for stewardship schemes. Sustainability 12(19), 7839. https://doi.org/10.3390/SU12197839

Sangha, K.K., Evans, J., Edwards, A., Russell-Smith, J., Fisher, R., Yates, C. et al. (2021). Assessing the value of ecosystem services delivered by prescribed fire management in Australian tropical savannas. Ecosystem Services 51, 101343. https://doi.org/10.1016/j.ecoser.2021.101343

Sangha, K.K. and Russell-Smith, J. (2017). Towards an indigenous ecosystem services valuation framework: a north Australian example. Conservation and Society 15(3), 255-269. https://www.jstor.org/stable/26393294

Savin, I. and van den Bergh, J. (2022). Tired of climate targets? Shift focus of IPCC scenarios from emission and growth targets to policies. Annuals of the New York Academy of Sciences 1517(1), 5-10. https://doi.org/10.1111/nyas.14900

Savini, F. (2023). Futures of the social metabolism: Degrowth, circular economy and the value of waste. Futures 150, 103180. https://doi.org/10.1016/j.futures.2023.103180

Schmalensee, R. and Stavins, R.N. (2017). Lessons Learned from Three Decades of Experience with Cap and Trade. Review of Environmental Economics and Policy 11(1), 59-79. https://doi.org/10.1093/reep/rew017

Schmitt, S. and Schulze, K. (2011). Choosing Environmental Policy Instruments: An Assessment of the 'Environmental Dimension' of EU Energy Policy. European Integration Online Papers 15(9). http://dx.doi.org/10.1695/2011009

Schneider, C.R. and van der Linden, S. (2023). Social norms as a powerful lever for motivating pro-climate actions. One Earth 6(4), 346-351. https://doi.org/10.1016/j.oneear.2023.03.014

Seals, B. and Krasner, A. (2020). Health Effects from Gas Stove Pollution. Rocky Mountain Institute, Physicians for Social Responsibility, Mothers Out Front, and Sierra Club. https://rmi.org/insight/gas-stoves-pollution-health

Secretariat, C. (2020). Case Study: Innovative Financing – Debt for Conservation Swap, Seychelles' Conservation and Climate Adaptation Trust and the Blue Bonds Plan. Seychelles (on-going). https://thecommonwealth.org/case-study/case-study-innovative-financing-debt-conservation-swap-seychelles-conservation-and

Seroa da Motta, R. and Ortiz, R.A. (2018). Costs and Perceptions Conditioning Willingness to Accept Payments for Ecosystem Services in a Brazilian Case. Ecological Economics 147, 333-342. https://doi.org/10.1016/j.ecolecon.2018.01.032

Shahbaz, M., Nasreen, S., Abbas, F. and Anis, O. (2015). Does foreign direct investment impede environmental quality in high-, middle-, and low-income countries? Energy Economics 51, 275-287. https://doi.org/10.1016/j.eneco.2015.06.014

Shahrin, R., Quoquab, F., Jamil, R., Mahadi, N., Mohammad, J., Salam, Z. et al. (2017). Green "Eco-Label" or "Greenwashing"? Building Awareness

About Environmental Claims of Marketers. Advanced Science Letters 23, 3205-3208. https://dx.doi.org/10.1166/asl.2017.7713

Singhal, P. (2018). Environmental Regulations: Lessons from the Command-and-Control Approach. DIW Roundup: Politik im Fokus 124. https://www.diw.de/de/diw_01.c.597527.de/publikationen/roundup/2018_0124/environmental_regulations__lessons_from_the_command-and-control_approach.html

Sovacool, B., Kim, J. and Yang, M. (2021). The hidden costs of energy and mobility: A global meta-analysis and research synthesis of electricity and transport externalities. Energy Research & Social Science 72, 101885. https://doi.org/10.1016/j.erss.2020.101885

Sovereign Wealth Fund Institute (2023). Fund Rankings. https://www.swfinstitute.org/fund-rankings

Starrett, D.A. (2003). Property rights, public goods and the environment. In Handbook of Environmental Economics. Mäler, K.G. and Vincent, J.R. (eds.). Chapter 3, 97-125. https://EconPapers.repec.org/RePEc:eee:envchp:1-03

Stavins, R. (2003). Experience with market-based environmental policy instruments. In Handbook of Environmental Economics. Mäler, K.G. and Vincent, J.R. (eds.). Chapter 9, 355-435. https://EconPapers.repec.org/RePEc:eee:envchp:1-09

Sterner, T. and Coria, J. (2013). Policy Instruments for Environmental and Natural Resource Management. Policy Instruments for Environmental and Natural Resource Management. 2nd ed. 1-638. http://dx.doi.org/10.4324/9781315780894

Sterner, T. and Robinson, E.J.Z. (2018). Chapter 6 - Selection and design of environmental policy instruments. In Handbook of Environmental Economics. Dasgupta, P., Pattanayak, S.K. and Smith, V.K. (eds.). Elsevier. 231-284. https://www.sciencedirect.com/science/article/pii/S157400991830007X

Stiglitz, J., Fitoussi, J. and Durand, M. (2018). Beyond GDP: Measuring what counts for economic and social performance. Paris: OECD Publishing https://doi.org/10.1787/9789264307292-en.

Stiglitz, J.E., Stern, N., Duan, M., Edenhofer, O., Giraud, G., Heal, G.M. et al. (2017). Report of the high-level commission on carbon prices. https://static1.squarespace.com/static/54ff9c5ce4b0a53decccfb4c/t/59244eed17bffc0ac256cf16/1495551740633/CarbonPricing_Final_May29.pdf

Susswein, P. (2003). The Use of Market Based Economic Instruments for Sustainable Environmental Management in Africa: A Case Study of the SADC Region. 297-325. http://dx.doi.org/10.1007/978-94-017-0135-8_14

Climate Bond Initiative (2024). Sustainable Debt Market Summary Q3 2024. https://www.climatebonds.net/files/reports/cbi_mr_q3_2024_01c.pdf

Swim, J. K., Gillis, A. J., and Hamaty, K. J. (2020). Gender bending and gender conformity: the social consequences of engaging in feminine and masculine pro-environmental behaviors. Sex Roles 82, 363–385. https://doi.org/10.1007/s11199-019-01061-9

Tanaka, S. (2015). Environmental regulations on air pollution in China and their impact on infant mortality. Journal of Health Economics 42, 90-103. https://doi.org/10.1016/j.jhealeco.2015.02.004

Tang, Y., Duan, H. and Yu, S. (2023). Mitigating climate change to alleviate economic inequality under the Paris Agreement. iScience 26(1). https://doi.org/10.1016/j.isci.2022.105734

Taufique, K.M.R., Nielsen, K.S., Dietz, T., Shwom, R., Stern, P.C. and Vandenbergh, M.P. (2022). Revisiting the promise of carbon labelling. Nature Climate Change 12(2), 132-140. https://doi.org/10.1038/s41558-021-01271-8

Taxonomía Sostenible de México (2023) Primera edición. https://www.gob.mx/shcp/documentos/taxonomia-sostenible-de-mexico

Taxonomía Verde de Colombia (2022) https://www.taxonomiaverde.gov.co/

The Energy and Resources Institute. (2024). TERI's Solutions for Sustainable Development New Delhi. https://teriin.org/files/50_Solutions_TERI_Inside_2023_Final.pdf

Tisserand, J.-C., Hopfensitz, A., Blondel, S., Loheac, Y., Mantilla, C., Mateu, G. et al. (2022). Management of common pool resources in a nation-wide experiment. Ecological Economics 201, 107566. https://doi.org/10.1016/j.ecolecon.2022.107566

Tregarot, E., Touron-Gardic, G., Cornet, C. and Failler, P. (2020). Valuation of coastal ecosystem services in the Large Marine Ecosystems of Africa. Environmental Development 36, 100584. https://doi.org/10.1016/j.envdev.2020.100584

Tsani, S. (2013). Natural resources, governance and institutional quality: The role of resource funds. Resources Policy 38(2), 181-195. https://doi.org/10.1016/j.resourpol.2012.11.001

Tsani, S., Koundouri, P. and Akinsete, E. (2020). Resource management and sustainable development: A review of the European water policies in accordance with the United Nations' Sustainable Development Goals. Environmental Science & Policy 114, 570-579. http://dx.doi.org/10.1016/j.envsci.2020.09.008

Tsani, S. and Overland, I. (2020). Sovereign Wealth Funds and Public Financing for Climate Action. In Climate Action. Leal Filho, W., Azul, A.M., Brandli, L., Özuyar, P.G. and Wall, T. (eds.). 1-10. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-71063-1_130-1

United Nations (2012). System of Environmental-Economic Accounting 2012—Central Framework. https://seea.un.org/content/seea-central-framework

United Nations (2021). System of Environmental-Economic Accounting Ecosystem Accounting. https://seea.un.org/content/methodology

United Nations (2023). Our Common Agenda. Policy Brief 4. Valuing What Counts: Framework to Progress Beyond Gross Domestic Product. https://digitallibrary.un.org/record/4011889?ln=es&v=pdf

United Nations Development Programme (2024). UNDP Annual Report 2024. New York (NY): United Nations Development Programme. https://annualreport.undp.org/assets/Annual-Report-2024.pdf

United Nations Environment Programme (2022): UNEP/EA.5/Res.5 https://wedocs.unep.org/bitstream/handle/20.500.11822/39864/NATURE-BASED%20SOLUTIONS%20FOR%20SUPPORTING%20SUSTAINABLE%20DEVELOPMENT.%20English.pdf?sequence=1&isAllowed=y

United Nations Environment Programme (2023). State of Finance for Nature. https://www.unep.org/resources/state-finance-nature-2023

United Nations Environment Programme and International Resource Panel. (2024). Global Resources Outlook. https://www.unep.org/resources/Global-Resource-Outlook-2024

United Nations Environment Programme (2023). Global Framework on Chemicals – For a Planet Free of Harm from Chemicals and Waste. https://www.unep.org/resources/global-framework-chemicals-planet-free-harm-chemicals-and-waste

United Nations Environment Programme (2024). Global Resources Outlook 2024: Bend the Trend – Pathways to a liveable planet as resource use spikes. https://wedocs.unep.org/20.500.11822/44901

United Nations Framework Convention on Climate Change (n.d.). What is REDD+? https://unfccc.int/topics/land-use/workstreams/redd/what-is-redd#:~:text='REDD'%20stands%20for%20'Reducing,enhancement%20of%20forest%20carbon%20stocks

United Nations Framework Convention on Climate Change (2018). Approaches to address Loss and Damage associated with Climate Change impacts in developing countries. UNFCC. https://unfccc.int/topics/adaptation-and-resilience/workstreams/approaches-to-address-loss-and-damage-associated-with-climate-change-impacts-in-developing-countries

United Nations Office for Disaster Risk Reduction (2023). GAR Special Report: Measuring Resilience for the Sustainable Development Goals. Geneva United Nations Office for Disaster Risk Reduction. https://www.undrr.org/media/88718

United Nations Trade and Development (2022). The Least Developed Countries Report 2022. https://unctad.org/system/files/official-document/ldc2022overview_en.pdf

United Nations Trade and Development (2023). Technology and Innovation Report 2023: Opening Green Windows: Technological opportunities for a low-carbon world. UNCTAD/TIR/2022 and Corr.1. https://digitallibrary.un.org/record/4007851

Vaishnav, P. (2023). Implications of Green Technologies for Environmental Justice. Annual Review of Environment and Resources 48, 505-530. https://doi.org/10.1146/annurev-environ-120920-101002

Van Asselt, H. and Brewer, T. (2010). Addressing competitiveness and leakage concerns in climate policy: An analysis of border adjustment measures in the US and the EU. Energy Policy 28(1), 42-51. https://doi.org/10.1016/j.enpol.2009.08.061

Van den Bergh, J. and Savin, I. (2023). The role of interest in the unsustainability of growth: analytical findings using an accounting model. Sustainability: Science, Practice and Policy 19(1), 2262830. https://doi.org/10.1080/15487733.2023.2262830

Vogel, J., Guerin, G., O'Neill, D.W. and Steinberger, J.K. (2024). Safeguarding livelihoods against reductions in economic output. Ecological Economics 215, 107977. https://doi.org/10.1016/j.ecolecon.2023.107977

Vuletić, D., Krajter Ostoić, S., Keča, L., Avdibegović, M., Potočki, K., Posavec, S. et al. (2020). Water-related payment schemes for forest ecosystem services in selected Southeast European (SEE) countries. Forests 11(6), 654. https://doi.org/10.3390/f11060654

Watkins, G.C., Contreras Casado, C., Silvia Zungia, M.C., Bhattacharya, A., Jeongm, M. and Amin, A.-L. (2019). Attributes and Framework for Sustainable Infrastructure. Inter - American Development Bank. http://dx.doi.org/10.18235/0001723

Wang, Q. and Wang, L. (2020). Renewable energy consumption and economic growth in OECD countries: A nonlinear panel data analysis. Energy 207(118200). https://doi.org/10.1016/j.energy.2020.118200

Wildlife Protection Act (1972). Wildlife Protection Act https://www.indiacode.nic.in/bitstream/123456789/1726/1/a1972-53.pdf

Wildlife Protection Society of India (n.d.). Periyar Tiger Reserve. https://www.wpsi-india.org/tiger/periyar.php

Woerner, A., Imai, T., Pace, D.D. and Schmidt, K.M. (2024). How to increase public support for carbon pricing with revenue recycling. Nature Sustainability 1-9. https://www.nature.com/articles/s41893-024-01466-9.pdf

Wolf, J., Johnston, R.B., Ambelu, A., Arnold, B.F., Bain, R., Brauer, M. et al. (2023). Burden of disease attributable to unsafe drinking water, sanitation, and hygiene in domestic settings: a global analysis for selected adverse health outcomes. Lancet 401(10393), 2060-2071. https://doi.org/10.1016/S0140-6736(23)00458-0

World Bank (2018) Tracking SDG7: the energy progress report 2018 (English). Washington, D.C. : World Bank Group http://documents.worldbank.org/curated/en/495461525783464109

World Bank (2021). The Changing Wealth of Nations 2021: Managing Assets for the Future. https://elibrary.worldbank.org/doi/abs/10.1596/978-1-4648-1590-4

World Bank (2022). The Global Health Cost of PM2.5 Air Pollution: A Case for Action Beyond 2021. International Bank for Reconstruction and Development / The World Bank: Washington. https://hdl.handle.net/10986/36501

World Bank (2023). State and Trends of Carbon Pricing. http://hdl.handle.net/10986/39796

World Economic Forum (2023). Fostering Effective Energy Transition. https://www3.weforum.org/docs/WEF_Fostering_Effective_Energy_Transition_2023.pdf

World Health Organization (2023). Burden of disease attributable to unsafe drinking-water, sanitation and hygiene. World Health Organization: Geneva. https://doi.org/10.1016/s0140-6736(23)00458-0

Wunder, S., Börner, J., Ezzine-de-Blas, D., Feder, S. and Pagiola, S. (2020). Payments for environmental services: past performance and pending potentials. Annual Review of Resource Economics 12, 209-234. https://doi.org/10.1146/annurev-resource-100518-094206

Xiao, C., Chang, M., Guo, P., Chen, Q. and Tian, X., 2019. Comparison of the cost-effectiveness of eliminating high-polluting old vehicles and imposing driving restrictions to reduce vehicle emissions in Beijing. Transportation Research Part D: Transport and Environment, 67, pp.291-302. https://doi.org/10.1016/j.trd.2018.10.006

Yue, M. and Nedopil, C. (2021). Debt-For-Nature Swaps: A Triple-Win Solution for Debt Sustainability and Biodiversity Finance in the Belt and Road Initiative (BRI)? http://dx.doi.org/10.13140/RG.2.2.29143.19368

Zelezny, L., Chua, P., and Aldrich, C. (2000). Elaborating on gender differences in environmentalism-statistical data included. Journal of Social Issues 56, 443–445. https://doi.org/10.1111/0022-4537.00177.

15 Solution Pathways for Transformation Towards Circularity

Coordinating Lead Authors: Patrick Schröder (Chatham House), Apoorva Arya (Circular Innovation Lab)

Lead authors: Bonmwa Fwangkwal (African Circular Economy Alliance Secretariat, AfDB), Kamal Kumar Rai (ITT-Nepal, Indigenous Knowledge and Peoples Network, Society for Wetland Biodiversity Conservation, Nepal Indigenous Forum for Biodiversity), Ken Webster (Cranfield University, Cambridge Institute for Sustainability Leadership), Maria Cristina Tirado (University of California, SHE Foundation), Olena Maslyukivska (National University of Kyiv-Mohyla Academy, University of Vaasa), Sigrid Kusch-Brandt (Ulm University of Applied Sciences, University of Southampton), Xianlai Zeng (Tsinghua University)

Contributing authors: Arthur Silva (Federal University of Rio de Janeiro)

Fellows: Arthur Silva (Federal University of Rio de Janeiro), Botho Bahumi Motlhanka (Global Green Growth Institute)

Credit: perutskyy/Envato

Chapter summary

Credit: siwabudv/Envato

A global shift to a circular economy is a leading solution to the interconnected environmental crises of climate change, biodiversity loss and land degradation, and pollution and waste *(well established)*. Maintaining stocks of materials and a circular flow of resources in the economy will also contribute positively to socioeconomic development while safeguarding nature and people {15.1.3}.

The GEO-7 target-seeking scenarios show that by 2060, a circular economy can achieve a global material demand peak below 120 billion tons per year, compared to a business-a-usual scenario of extraction rates exceeding 160 billion tons per by 2060 *(established but incomplete)*. By combining technological innovations and behavioural changes that increase material circularity, the world can reduce global primary material demand {15.2}.

Global plastic pollution is worsening and 8000 Mt of plastic waste pollute the planet while production is projected to increase from 475 Mt in 2022 to 1200 Mt by 2060 *(well established)*. Plastic pollution is the cause disease and death and are responsible for health-related economic losses exceeding US$1·5 trillion annually. (well established) {15.1.1}.

In contrast, a circular economy approach can help to address these issues an 80 per cent reduction of plastic waste by 2040 can potentially generate net savings and avoided external costs of US$1.2 trillion per year, US$18 trillion cumulatively over the next 15 years *(well established)*. A circular economy approach addressing the global municipal waste crisis could generate a projected annual full net gains of US$108.5 billion by 2050 through waste avoidance, circular practices and full waste management. Downstream solutions such as recycling and waste management alone are not sufficient to tackle plastic pollution. In addition, a combination of upstream solutions and regulatory measures to reduce unsustainable production and curb plastic demand through eco-design, reuse models, remanufacturing

and product repair is the most cost-effective pathway to eliminate plastic pollution {15.2.1, 15.2.5}

Beyond eliminating waste and pollution, the circular economy can create new economic opportunities *(established but incomplete)*. Multiple studies and economic modelling across regions demonstrate that the circular economy can drive job creation and economic development across key industries such as manufacturing, construction, transport, food and services by fostering resource efficiency, innovation and new business models in both developed and developing countries {15.2.1}.

Between 30 and 58 per cent of the demand for critical energy transition minerals, such as lithium, cobalt, nickel, manganese, rare earth elements, platinum and copper, could be met through secondary supply and circular economy practices by 2050 *(established but incomplete)*. The circularity of critical energy transition minerals will be essential in reducing the to: the growing demand for primary minerals and declining the need for primary mining {15.1.6}.

Electronic waste recycling offers significant economic opportunities for the recovery of critical materials. An estimated 62 million tons of electronic waste was generated globally in 2022, with a global market potential of US$65.8 billion by 2026 *(well established)*. In addition to increasing recycling rates of the various minerals and metals used in digital technologies and renewable energy systems, circular economy practices such as lifetime extension, refurbishment and recovery, as well as material substitution, will be essential {15.2.1; 15.4}.

As of 2024, a total of 75 national circular economy road maps have been launched, from 4 road maps that existed in 2016, and more are under development. *(established, but incomplete)*. These road maps include a collective commitment from governments to introduce just under 3,000 circular economy policies spanning 17 sectors, making this one of the fastest-growing environmental policy categories worldwide over the next decade. However, these road maps are currently insufficient to drive transformational change at the scale and pace needed to reduce pressures and impacts on natural systems {15.2, 15.3.1}.

Circular economy solutions are critical to achieving climate change mitigation targets in high-impact economic sectors *(well established)*. Businesses and value chains with high environmental footprints, including for hard-to-abate sectors such as steel, cement, chemicals and batteries, depend on the successful implementation of circular economy strategies {15.1.6}.

Circular regenerative practices in agricultural and food systems can contribute to reducing waste and pollution, preserving and restoring soil health *(well established)*, as well as protecting biodiversity and achieving nature-positive outcomes *(established but incomplete)*. Such practices include nutrient cycling, regenerative agricultural practices, and Indigenous practices in agriculture and food systems {15.2.2, 15.2.5, 15.2.6}.

Circular practices are instrumental in preventing negative effects of the bioeconomy *(established but incomplete)*. Shifting from non-renewable resources to biobased materials can reduce environmental pressures associated with the extraction and use of materials, but safeguards are needed to ensure that substitutes have lower adverse impacts throughout their life cycle. Integrating nature-positive solutions into these models can ensure that economic activities actively regenerate and enhance natural ecosystems {15.2.6}.

Rights-based approaches are needed to ensure equitable, socially just, sustainable outcomes for the circular economy and for the protection of biodiversity *(established)*. It requires free, prior and informed consent, accountability measures, and full and effective participation of Indigenous Peoples to safeguard their rights on lands, waters and territories and to sustain their biocultural, customary practices, Indigenous Knowledge and Local Knowledge systems {15.2.2, 15.2.5}.

The following five solution pathways are proposed:

1. **Designing out waste from production and consumption by designing in circularity**

   Circular product design, transparency, and traceability of products, components and materials are prerequisites for eliminating toxicants and recovering materials, rendering

more benefits for people with the same or lower amounts of materials *(well established)*. Mandatory requirements for product information systems to increase the transparency of chemical and material compositions and internationally harmonized circular product design and material processing standards are required {15.1.3, 15.2.1}.

2. **Creating fair and effective markets for circular goods and services across industries and global value chains**

Improving the transparency about materials and prices of circular goods and services is a key requirement to enabling traceability and achieving material circularity across value chains *(well established)*. Digital technologies such as product passports and blockchain protocols will play a crucial role in market transformation for circularity {15.2.1, 15.2.2}.

Including informal sector stakeholders, such as those working in waste management, repair and upcycling, is essential to ensuring a just transition to a circular economy (well established). This can be achieved through capacity-building, formal recognition and upholding the right to unionize, national labour law reforms and due diligence requirements, while ensuring socially just transitions and decent work, especially for women and Indigenous Peoples {15.2.2}.

Small and medium-sized enterprises will require capacity-building support and access to finance and technology (well established). This backing is vital to scale circular business models, create local employment opportunities, meet the requirements on traceability and reporting, and become integrated into international markets {15.2.1, 15.2.3, 15.2.4}.

Taxation reforms are needed, such as shifting taxes from recycled materials, secondary resources and labour to non-renewable resources and waste. This approach will capture the true value of natural resources and the costs of extraction, thereby reducing market failures and negative externalities *(established but incomplete)*. Measures to compensate low-income groups and to prevent rising energy and material costs must accompany these changes to ensure social equity {15.2.1}.

3. **Reform of the financial system to shift investments from linear extractive economic activities to circular and regenerative business models**

Building capacity within financial regulators, national institutions and across the finance sector to understand and evaluate the value proposition of circular and nature-positive business models is required *(well established)*. Enhanced capacity will enable financial institutions to develop and offer new financial products and revise risk-assessment tools to improve access to finance for circular businesses {15.2.3}.

Making financial information relating to the circularity of finance and investment portfolios publicly available will require the adoption of new metrics and disclosure of non-financial, nature-related reporting by companies and investors *(established but incomplete)*. This access can be achieved by international adoption and harmonization of sustainable finance taxonomies, green bonds and other methods by national financial regulators, central banks and the financial sector {15.2.3}.

4. **Enabling a transparent and fair global trade system for circular goods and services**

The global illegal waste trade is a multi-billion-dollar industry, with profits estimated between US$10 billion and US$12 billion annually *(well established)*. Expanding the existing mechanisms and international initiatives of law enforcement agencies to address the illegal waste trade and waste dumping practices, notably from developed to developing countries {15.2.4}.

Embedding circularity provisions in bilateral and regional trade agreements that provide preferential treatments and remove barriers to trade in circular goods and services is a key mechanism. Reducing tariffs on technologies essential for circular economy activities, such as advanced recycling, material recovery and pollution control, would be a critical step *(established but incomplete)* {15.2.4}.

Credit: ©UNEP

5. **Translating circularity aspirations into actionable societal goals**

To make circular lifestyles convenient and practical, it is essential to implement enabling infrastructures and incentivize pro-circular behaviour *(established but incomplete)*. Easy-to-use schemes for product take-back, repair, reuse and renting will mainstream circular economy practices into society and promote new norms based on sufficiency. Standards for second-hand products and regulations protecting consumer rights will be needed to ensure societal acceptance, safety and the quality of circular goods and services *(well established)* {15.2.5}.

Implementing regulatory measures to phase out linear models while incentivizing circular choices will accelerate changes in consumption patterns *(well established)*. User charges for single-use products and items are a successful policy example of reducing wasteful practices and enabling the uptake of circular alternatives {15.2.5}.

The circular economy strongly intersects with the other solution pathways that are critical to addressing the global environmental crises *(established but incomplete)*. It aligns closely with the energy transition, particularly through the needed recovery and reuse of critical energy transition minerals. In the food system, circular practices help reduce food loss and waste while also supporting regenerative agricultural approaches. The circular bioeconomy is directly linked to environmental systems and is essential for the sustainable use of biological resources. Integrating circularity in the financial and economic systems involves tax reforms and efforts to align investment and finance with circular business models {15.4}.

15.1 Introduction

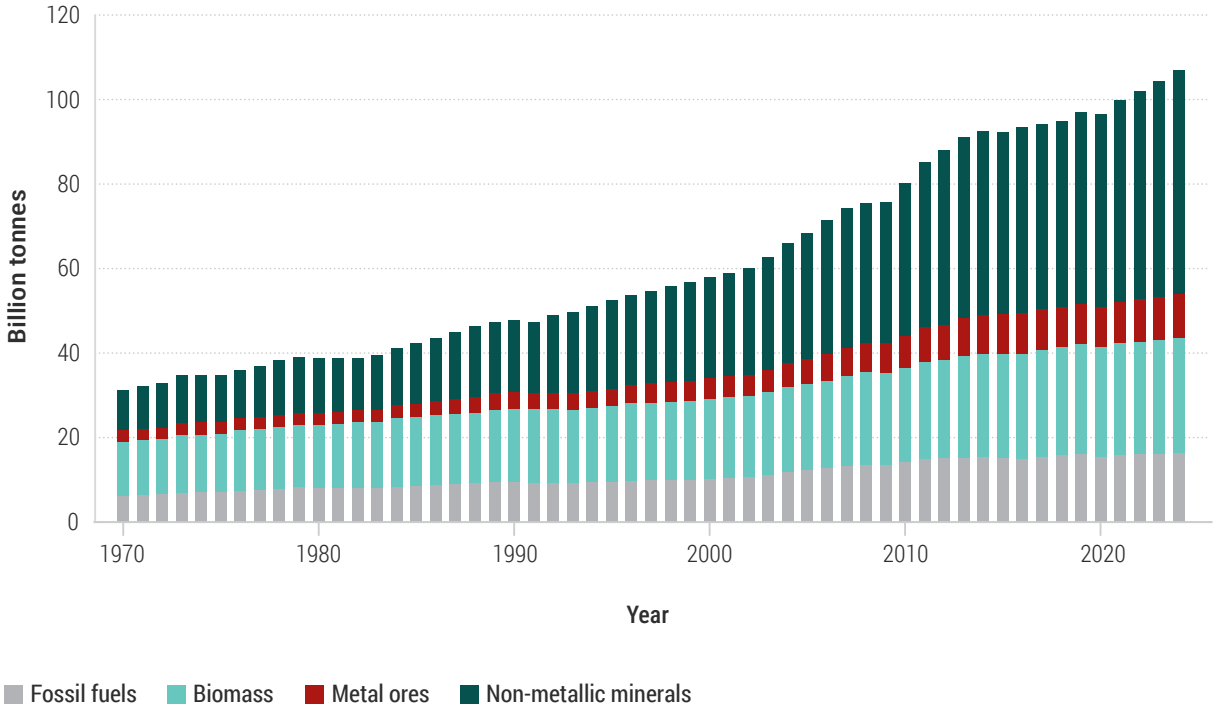
The circular economy is a systems approach to preserving resources that applies across all sectors – from the built environment and energy infrastructures to significant assets like ships and airplanes, as well as consumer products such as electronics and textiles. Integrating both technical and biological cycles not only minimizes waste and maximizes material value but also supports nature-positive outcomes through regeneration and sustainable resource management. It is an alternative to the current linear economic model of "take-make-dispose" that comes at the expense of nature and human health. This linear flow of materials – from extraction to disposal – drives demand for natural resources, increases emissions and significantly contributes to climate change and biodiversity loss. Since the 1970s, materials extraction has more than tripled, reaching 106.6 billion tons in 2024, following an annual average growth rate of 2.3 per cent **(Figure 15.1).**

According to the International Resource Panel's Global Resource Outlook, the extraction and processing of resources – fossil fuels, metals, non-metallic minerals and biomass – account for over 55 per cent of greenhouse gas (GHG) emissions and 40 per cent of health effects from particulate matter (United Nations Environment Programme [UNEP] 2024a). More than 90 per cent of terrestrial biodiversity loss is linked to resource extraction, with adverse effects on water and land use (UNEP 2019a; Jaureguiberry et al. 2022).

Collectively, the food, construction, energy, and textile sectors account for approximately 90 per cent of the pressure on biodiversity worldwide (European Environment Agency [EEA] 2023). There is a critical need to address the linear pressures driving biodiversity loss, as current conservation and regeneration efforts alone cannot solve this crisis (Intergovernmental Platform for Biodiversity and Ecosystem Services [IPBES] 2019). While the planet's environmental systems and regenerative capacity are severely under pressure, worldwide demand for resources is projected to more than double between 2011 and 2060 (Organisation for Economic Cooperation and Development [OECD] 2019).

Credit: ABBPhoto/Envato

Figure 15.1: Global material extraction of four main material categories from 1970 to 2024



Source: UNEP IRP Global Material Flows Database

15.1.1 Linear economic flows cause excessive waste and pollution

Current production and consumption systems, with their linear patterns of material flows, create waste with volumes so high that the capacity to manage it safely has been lost. Reliably quantifying global waste is complicated by limited data availability for many waste types and differing reporting standards (Maalouf and Mavropoulos 2022a). In developing countries, particularly in rural areas, waste often remains uncollected (Kaza et al., 2018; UNEP, 2018a), and waste generation may be significantly underestimated. A broad grouping of urban wastes – municipal solid waste (MSW), commercial and industrial wastes, and construction and demolition wastes – was estimated at 7 billion to 10 billion tons per year (UNEP and International Solid Waste Association [ISWA] 2015). Total annual solid waste, estimated at 19.8 billion tons in 2017, is projected to reach 46 billion tons by 2050 (Maalouf and Mavropoulos 2022b), with MSW alone expected to rise by 81 per cent (2.1 billion to 3.8 billion) from 2023 to 2050 (Chen et al. 2020; UNEP 2024a). There are inconsistent estimates on whether waste generation growth will then continue and if a "waste peak" might be reached in the second half of this century (Hoornweg, Bhada-Tata and Kennedy 2013) or not (Chen et al. 2020).

Mismanaged waste is a significant contributor to GHG emissions and air pollution. About 15 per cent of global anthropogenic methane emissions come from decomposing organic material in landfill sites (Höglund-Isaksson et al. 2020). In 2023, open burning of MSW was responsible for 70 per cent of GHG emissions within the global MSW management sector (Gómez-Sanabria et al. 2022; Zaw et al. 2024; Wiedinmyer; UNEP 2024c;). The release of unintentional persistent organic pollutants harms ecosystems, leading to biodiversity loss (UNEP 2024c). The uncontrolled burning of plastics releases dangerous pollutants linked to a range of health issues, from cardiovascular and respiratory problems to neurological disorders (Pathak et al. 2023).

While global solid waste streams multiply, the world still lacks equitable waste management systems (ISWA 2021; UNEP 2024c). In 2020, the net costs and externalities of MSW management were US$361 billion and are expected to increase to US$640 billion by 2050 under business as usual without additional waste reduction and increased recycling rates (UNEP 2024c).

Mismanaged waste and pollution created by the linear economic system also have a human cost (UNEP 2024c). Pollution risk factors have risen by over 66

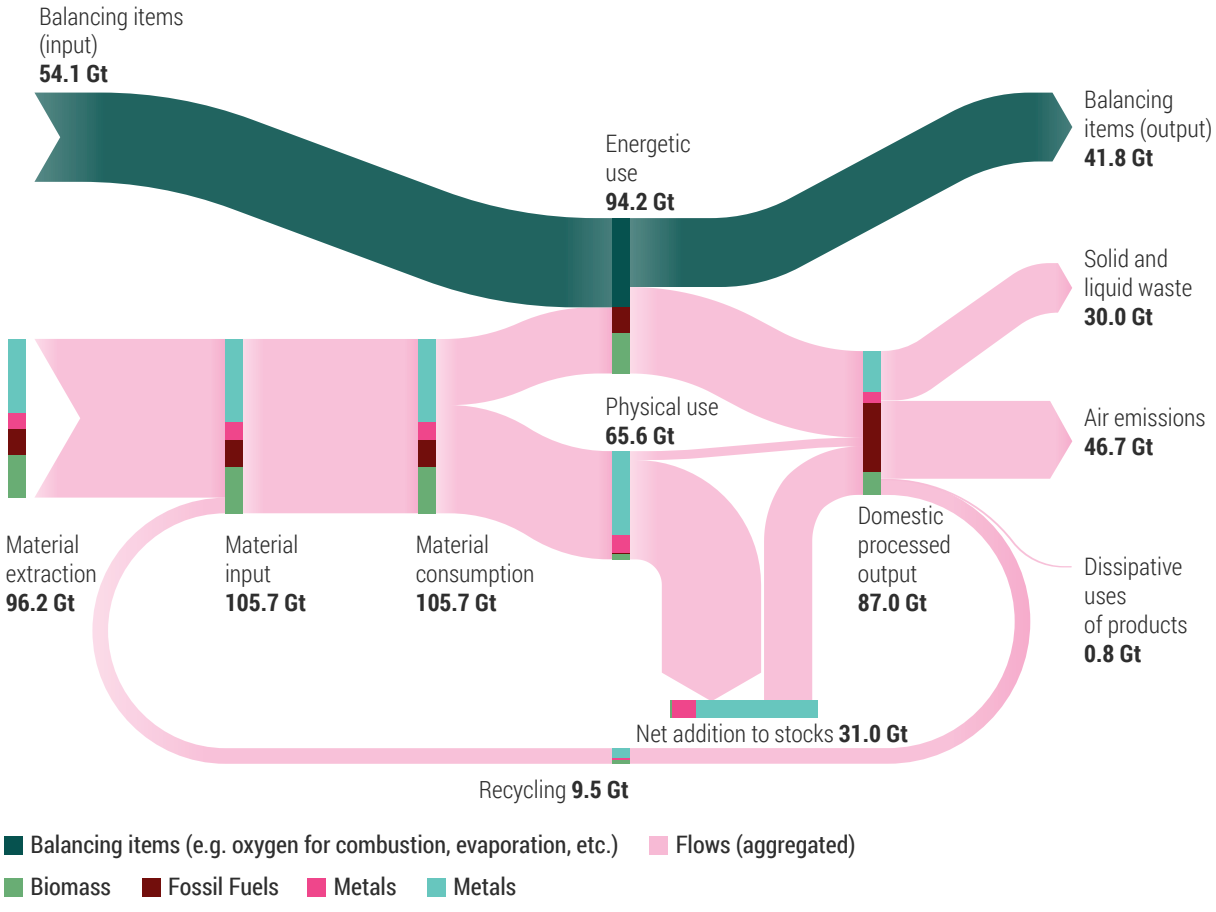
per cent since 2000 and in 2019 pollution contributed to approximately nine million premature deaths worldwide (Fuller et al. 2022). Annually, mismanaged waste disproportionately impacts low- and middle-income countries, contributing to an estimated 400,000 to one million deaths due to diseases like diarrhoea, malaria and cancer (Williams et al. 2019).

Especially global plastic pollution is worsening. An estimated 8000 Mt of plastic waste pollute the planet while production is projected to increase from 475 Mt in 2022 to 1200 Mt by 2060. Plastics cause disease and death and are responsible for health-related economic losses exceeding US$1.5 trillion annually (Landrigan et al. 2025) On a global level, a circular economy approach to address the global municipal waste crisis could generate a projected annual full net gain of US$108.5 billion by 2050 through waste avoidance, sustainable business practices, and fully circular waste management (UNEP 2024c).

15.1.2 Goals of the transformation from a linear to a circular economy

The Global Resources Outlook quantified that in 2019, secondary resources from recycling and material recovery contributed 9 per cent to the 105.7 billion tons of materials taken in by the global economy, while most material intake was extracted or harvested primary resources **(Figure 15.2)**. Of the 60 per cent used as structural and technical materials, half was incorporated into durable assets such as buildings, transportation and communication infrastructure, equipment and consumer products. This use was accompanied by significant quantities of solid and liquid waste, amounting to 30 billion tons, and gaseous emissions. Mainly non-metallic minerals and metals contributed to a net addition of 31 billion tons to material stocks as accumulated durable assets (UNEP 2024a). This trend shows a growing resource

Figure 15.2: Global material flows, waste and emissions



Note: The balancing items amount to 54.1 billion tonnes on the input side and 41.8 billion tonnes on the output side. These figures include factors such as oxygen used in combustion and evaporation. Such components are necessary to ensure that the system's inputs and outputs are properly balanced.

Source: Global Material Flows Database (UNEP 2023a)

demand and a significant future anthropogenic resource potential.

Achieving a circular economy is not a goal in itself but a means to address the global environmental crises and attain environmental sustainability, economic prosperity, equitable distribution of resources, human well-being and other essential objectives of the Sustainable Development Goals (Schroeder, Anggraeni and Weber 2019; Ferraz and Pyka 2023).

Based on the assessment of the literature in Chapters 2–6, the following four high-level goals are defined for the circular economy transformation:

Goal 1: Achieve absolute reductions in extraction and consumption of natural resources within recognized planetary boundaries and attain near-zero waste and pollution across the life cycle, from materials extraction to end of life. This goal involves redesigning products, processes and business models to address legacy waste issues and eliminate the generation of waste, wastewater and pollution, thereby contributing to a cleaner and healthier environment through an inclusive approach.

Goal 2: Ensure net-positive contributions to biodiversity, ecosystem health and soils through materials recovery, nutrient cycling, restoration and regeneration practices, recognizing and respecting the vital roles of Indigenous Knowledge and Local Knowledge, and the practices and innovations of Indigenous Peoples, their customary and biocultural systems, and their rights over lands, waters and territories.

Goal 3: Achieve climate stabilization through industrial decarbonization and near-zero life-cycle emissions from materials extraction, processing, use and end of life. This goal encompasses improving energy efficiency and transitioning to renewable energy sources across all sectors. Reduce the effects of climate change on vulnerable populations and communities, including Indigenous Peoples, and support climate adaptation and resilience through the application of circular economy principles, innovations and technologies (Wang et al. 2022).

Goal 4: Promote equitable socioeconomic development and sustainable lifestyles by creating safe and decent jobs, preventing adverse health effects and costs to society from mismanaged waste and pollution, while building resilient supply chains and ensuring that the transformation to a circular economy benefits all members of society and contributes to global efforts to eradicate poverty and promote social inclusion.

The solution pathways proposed in Section 15.2 follow the 7-step evaluation methodology described in Chapter 13. To achieve the four goals just described, combinations of levers and solutions are presented in the five solution pathways in Section 15.2. The actions proposed in the pathways match the three phases of the X-curve: activation, acceleration, and completion of the transformation (Chapter 13). The proposed actions explicitly include measures to phase out or remove elements of the linear economic system. Each solution pathway evaluates and prioritizes solutions according to immediate actions and longer-term strategies. Key actors and their interactions on international, national and local levels are identified to realize the potential of the circular economy.

15.1.3 Potential of the circular economy to address the global environmental crises

The circular economy concept emulates the cyclical processes in nature by aiming to preserve material value (Stahel 2019; Patwa et al. 2021). The circular economy, as a life-cycle approach, significantly reduces both unsustainable consumption of primary natural resources and waste and pollution. It is, in many ways, a heuristic for transforming the linear economy into one that is "… regenerative and restorative by intention and design…" (Ellen MacArthur Foundation 2015).

There are variations in meaning associated with restoration and regeneration in the circular economy literature. Restorative practices emphasize a continuous loop of use, reuse and repair, while regenerative practices involve cycles that sustain ecosystem functionality and enhance the self-renewal capacity of biological systems (Morseletto 2020). The circular economy model employs systems thinking, where effective strategies for sustainable resource usage consider how the entire system functions and how its elements interact with one another. This model acknowledges that the economic process also engages with values and culture, immaterial and financial assets, and institutional frameworks (Morseletto 2020; Balanay and Halog 2021; Iacovidou, Hahladakis and Purnell 2021). Integrating regenerative principles into systems thinking promotes ecological restoration and biodiversity enhancement, ensuring that economic activities contribute to the self-renewing capacity of ecosystems. This approach aligns with global

Credit: antonpetrus/Envato

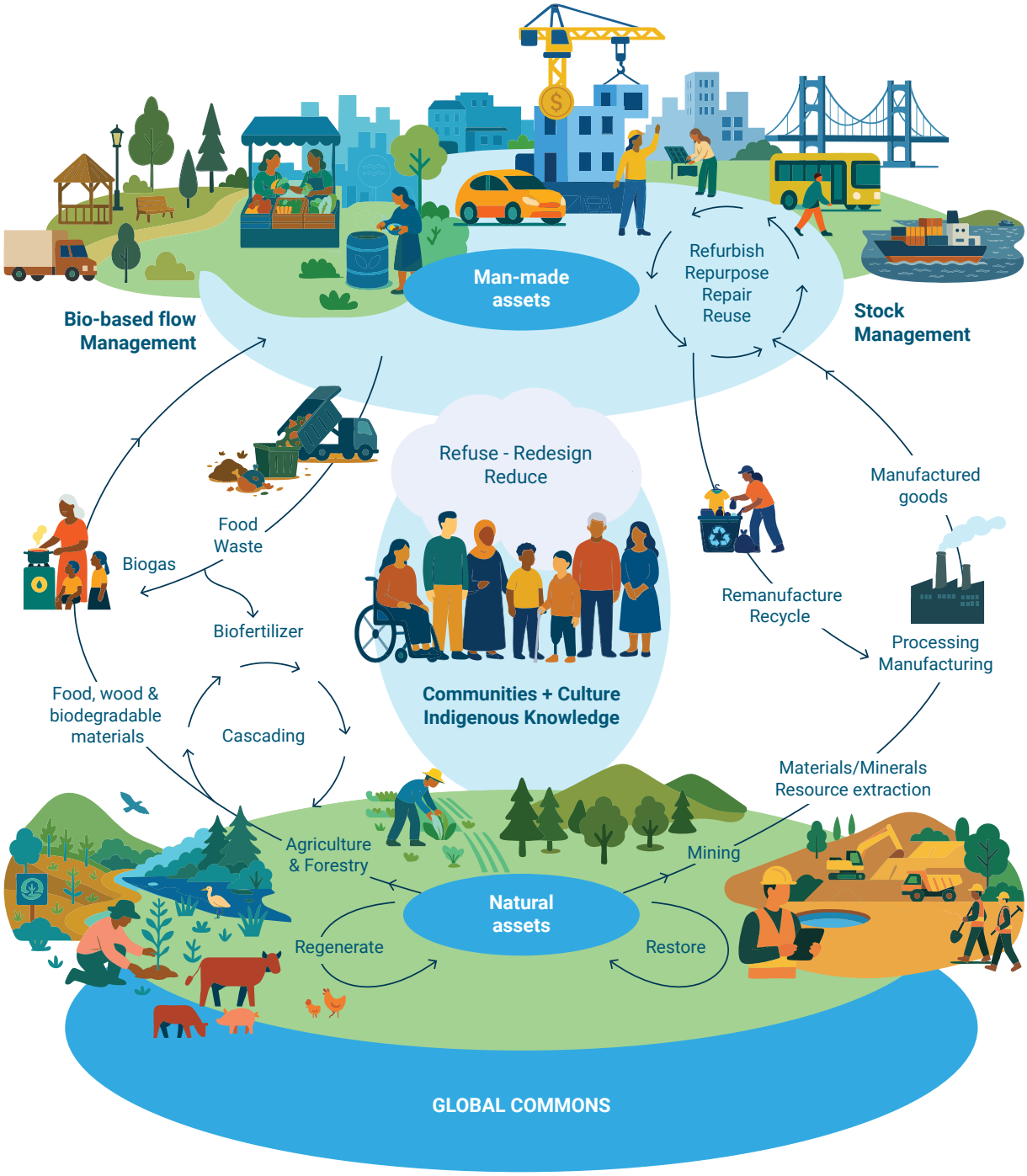
frameworks such as the Kunming-Montreal Global Biodiversity Framework and the Nature Positive Initiative, an international civil society-led framework (Nature Positive Initiative 2025) that stress the importance of a measurable recovery of nature by 2030 and thriving ecosystems by 2050. Circularity is an integral part of the worldview practised by Indigenous Peoples around the world, with value systems, innovations and practical ancestral pathways of living within natural cycles, as well as customary and biocultural initiatives (Rai 2023).

At its simplest level, the circular economy primarily applies to products, components and materials and is commonly associated with "closing the loop" through energy and material efficiency. A more sophisticated approach aims at transforming systems such as mobility, the built environment, and food and energy systems through strategies and principles that slow, close, and narrow resource loops (Bocken et al. 2016). These strategies contribute to a circular economy by prolonging product use (slowing), enhancing recycling and reuse (closing), and reducing resource input per unit of service (narrowing) (Stahel and Clift 2016). It is, therefore, possible to achieve near-zero waste systems in which resource inputs and waste generation are reduced to the lowest practical level, ideally diverting at least 90 per cent of all discarded materials from landfill and incineration through redesign, reuse, recycling and recovery.

Circularity can maintain and create value at many levels – from improving a single product's life cycle to reconnecting human activities with natural systems. A circular economy sustains both man-made assets and natural capital by applying the 9R principles at various levels and scales, ensuring the regeneration, repair, reuse, and recycling of resources. By integrating these principles into production and consumption systems, it fosters resilient communities and healthy ecosystems. Central to this approach is the well-being of people, as the circular economy provides equitable provisioning systems that support social and economic needs. (**Figure 15.3**).

The circular economy encourages a shift in focus from simply generating income and using up resources to maintaining and regenerating the natural and social systems – also considered as capital – that support human lives. Instead of turning natural and social capital into financial profit, the circular approach prioritizes preserving and improving these essential resources. Some experts view the circular economy as a new perspective on how economies function, drawing inspiration from complex, self-regulating systems found in nature (Von Bertalanffy, 1968), particularly living systems and their principles (Capra and Jakobsen, 2017). This means creating an economy where waste becomes a resource and materials flow in loops rather than being extracted and used up. These insights from complex adaptive systems are also becoming increasingly relevant for industrial supply chain networks (Braz and Marotti de Mello 2022), circular manufacturing systems (Roci et al. 2022), and the organizational management of circular business models (De Angelis 2022).

Figure 15.3: **Connecting natural and man-made assets through regenerative and circular flows**



15.1.4 From concept to policy design and implementation

A global policy stocktake conducted by the United Nations Industrial Development Organization and Chatham House identified a total of 75 national circular economy road maps launched by governments worldwide – up from only four in 2016. These road maps include a collective commitment from governments to introduce nearly 3,000 circular economy policies spanning 17 sectors, making it one of the fastest-growing environmental policy categories worldwide over the next decade (Barrie et al. 2024). Common definitions, metrics and frameworks are essential for effective circular policy design and road map implementation because they enable alignment across stakeholders, ensure comparability of progress, and provide a clear basis for setting targets, measuring results and coordinating actions at local, national and international levels.

While there are numerous definitions of the circular economy in the scientific literature (Kirchherr et al. 2023),

the United Nations Economic Commission for Europe (UNECE) along with the OECD developed a set of common guidelines within a framework of concepts, terms and definitions. The headline definition of the circular economy combines the common elements of existing definitions: "maintaining the value of materials in the economy for as long as possible while ensuring a positive outcome to society, and preserving natural capital (natural resources, environmental quality) and human health." (UNECE 2024). The ISO 59000 family of standards, specifically designed to foster a shift towards a circular economy, is particularly relevant for policy implementation and for the private sector reconfiguring business models. It defines the circular economy as an "economic system that uses a systemic approach to maintain a circular flow of resources (concerning both stocks and flows), by recovering, retaining or adding to their value, while contributing to sustainable development" (International Organization for Standardization [ISO] 2024).

The 9R model has emerged as a commonly used framework in policymaking. The model consists of nine practices or strategies that help to maximize the value of materials and reduce waste throughout their life cycle (Potting et al. 2017). It provides a structured hierarchy of circular strategies for policymakers that helps prioritize actions, design effective interventions and assess the circularity potential of policies and practices. The framework continues to evolve, with new R-strategies such as regenerate, rethink, and recover being proposed, which reflect the increasing sophistication of the circular economy and its expanding scope.

15.1.5 From resource extraction to maintenance of material stocks – International Resource Panel and GEO-7 modelling and scenario results

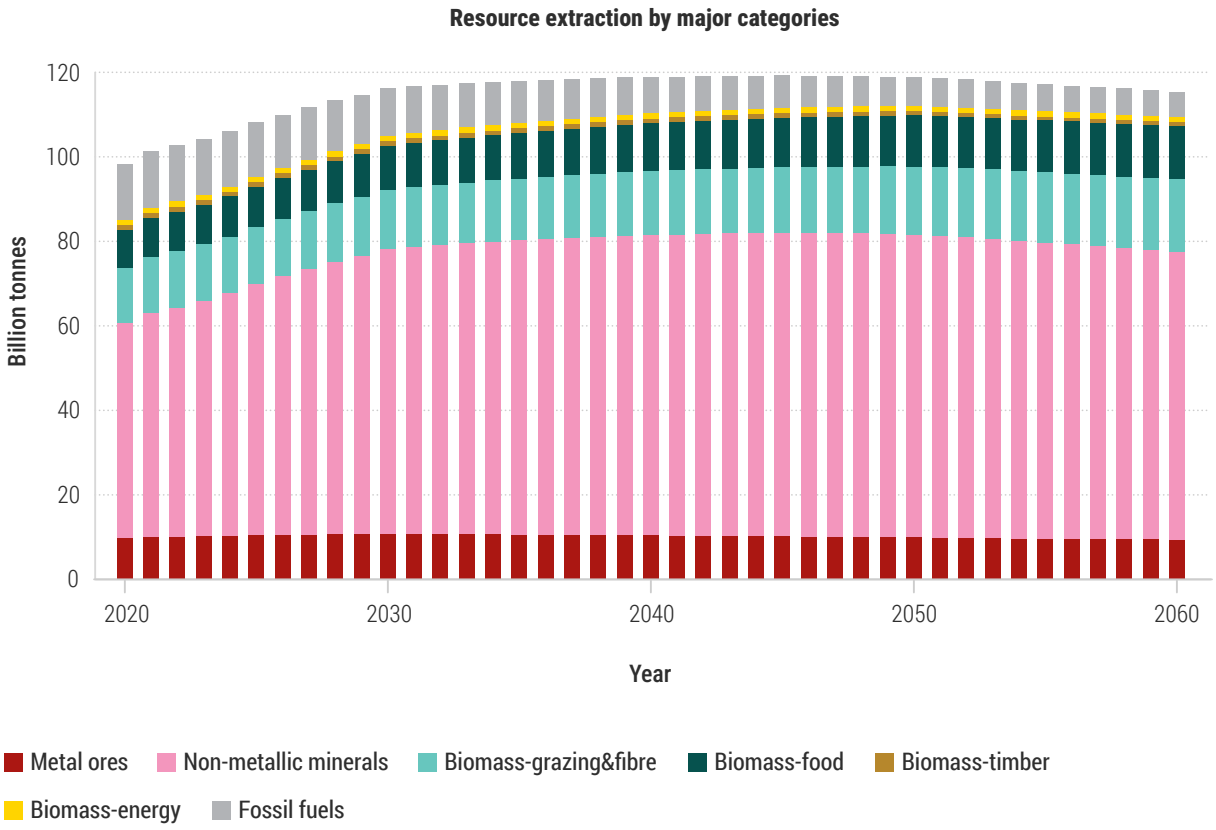
Economic growth drives not only resource depletion and waste generation but also net additions to stocks of materials (Robinson 2022). Significant quantities of minerals and aggregates and lesser amounts of steel, aluminium and plastics enter stock in the form of infrastructure and the built environment and are locked away for upward of 30 years (Plank et al. 2022). An increased focus on long-term management of materials is needed in national economies around the world. Stock saturation for materials such as steel and concrete is anticipated for 2035 in some countries (Wiedenhofer et al. 2021). Reducing expected future demand increases from material stock will require circular approaches, including more intensive utilization of existing stocks, longer service lifetimes, refurbishment, and more efficient and circular building design (Bragança et al. 2025).

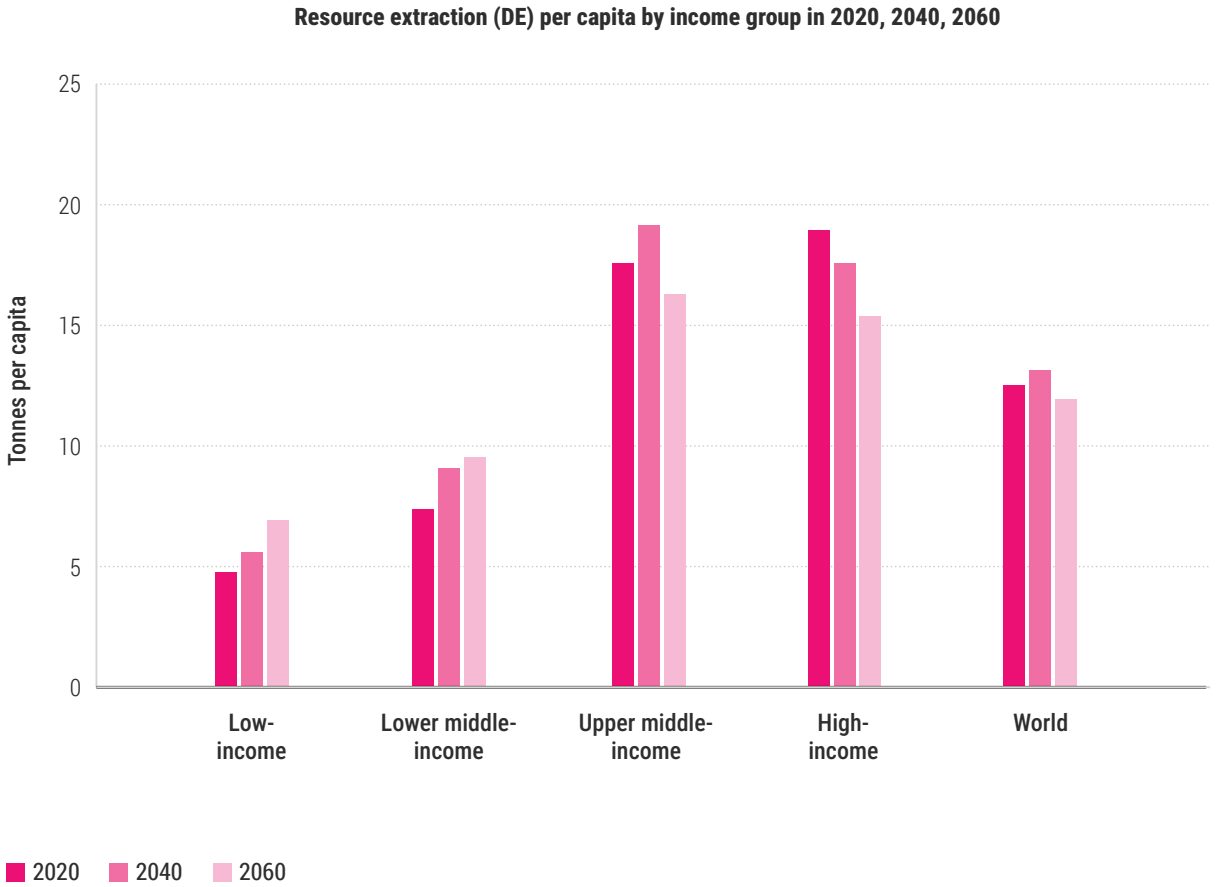
According to modelling by GEO-7 contributors and the International Resource Panel, global material demand can be cut by 26 per cent by transitioning to a circular economy. Key resource categories, including minerals, metals, fossil fuels and biomass, are estimated to peak below 120 billion tons per year by mid-century, compared to a historical trend scenario where global resource extraction would exceed 160 billion tons per year before stabilizing (UNEP, 2024a). The achieved reduction in material demand translates into savings at the global level, down to 13 tons per capita by 2050, from 16 tons per capita under current trends (Chapter 10, Section 10.3.3). This circularity scenario primarily considers optimized recycling rates, especially for non-metallic minerals and metals. Further essential reductions in resource extraction can be achieved by adopting circular practices, such as reuse, repair, remanufacturing and refurbishment, to preserve material stocks and facilitate the adoption of sustainable lifestyles. Achieving this objective also requires embedding circular design principles and transforming systems in key areas, such as mobility, energy and the built environment, to reduce material demand and extend the life of products and infrastructure.

Several key interventions are necessary to achieve global economic circularity for these major resource categories. One crucial step would be the establishment of a global target for resource use alongside clearly defined global and national resource-use pathways. For example, Germany has set an absolute material footprint reduction target, aiming for per capita material consumption of six to eight tons by 2050, as outlined in its 2024 national circular economy road map (Breschi 2024). Similarly, in the ongoing United Nations process of the Intergovernmental Negotiating Committee on Plastic Pollution, setting a global production target for primary plastics will help drive coordinated action on resource efficiency and plastic waste minimization (Pottinger et al. 2024).

Robust monitoring frameworks and data are also essential in tracking global progress. The European Union's circular economy indicator framework can serve as a valuable reference for developing clear, standardized indicators at both national and international levels. Institutionalizing resource use within sustainability agendas and environmental agreements – both globally and nationally – would also ensure long-term policy commitment. To support this, the establishment of an international resource agency could play a pivotal role in coordinating national

Figure 15.4: Resource extraction globally by major categories and per capita by income group





policy actions, facilitating data and information exchange on resource utilization, building capacity for monitoring progress and ensuring alignment between national and international targets on resource efficiency, waste reduction and material circularity (UNEP 2024c; Barrie et al. 2024).

15.1.6 A spotlight on the circular economy potentials for key sectors and value chains with high environmental and resource footprints

In the transformation to a circular economy, key industrial sectors and global value chains with high environmental and resource footprints merit specific attention, both in terms of their material input and economic opportunities. In the United States of America alone, moving to a circular economy in three industries – the built environment, electric vehicles and battery manufacturing – could cut raw material inputs and unlock US$883 billion to US$1.5 trillion in new revenue and economic value, which corresponds to 4-7 per cent of US gross domestic product (GDP) (Ellen MacArthur Foundation 2024). For the African continent, key sectors of the food system – plastics and packaging, the built environment, electronics, and fashion and textiles – could create new employment opportunities, eliminate waste and emissions, and reduce resource use under a circular economy (Alliance, 2021). For the Asia and the Pacific region, the circular economy could boost GDP by US$340 billion – a 1.1 per cent net growth – and reduce net emissions by 7.2 per cent compared to business as usual (PricewaterhouseCoopers [PWC] 2024).

In hard-to-abate industry sectors such as steel, cement and chemicals, circular strategies including material reuse, remanufacturing, design for longevity, and product-as-a-service models will be essential for tackling Scope 3 emissions, which reflect totals through a value chain. However, current accounting tools, such as the GHG Protocol, lack sufficient guidance on how to capture the emissions benefits of circular practices for Scope 3 accounting (Greenhouse Gas Protocol, 2013). Updating these methodologies to reflect circular strategies will enable more accurate carbon accounting and incentivize system-wide decarbonization.

The circular economy is also relevant for global industries like shipping, where ship-breaking presents major environmental and labour rights challenges but also opportunities for responsible material recovery and reuse, for example, secondary steel. Circular economy principles can extend ship lifespans by improving dismantling processes and maximizing resource efficiency (Rahman and Kim 2020). At the same time, circularity is gaining attention in emerging global issues such as space debris. The European Space Agency has proposed developing a circular space economy by 2050, aiming to design spacecraft, satellites and missions with reuse, repair and end-of-life recovery in mind – highlighting the growing importance of circular principles applied to activities in Earth and lunar orbits (Turner 2024).

The following paragraphs offer a brief overview of key challenges and the potential for circular-economy solutions in selected priority sectors highlighted in national circular economy road maps and targeted by government strategies (Barrie et al. 2024).

Built environment and construction:
While the construction sector's particularly high material consumption is responsible for 40 per cent of GHG emissions, construction activities convert resources into beneficial structures for long-term use; (International Resource Panel 2020; UNEP 2022; International Finance Corporations 2023). At the same time, construction and demolition waste often dominates solid waste generation, contributing about 10 billion tons per year globally (Wu et al. 2019). This mixture of inert, non-inert non-hazardous, and hazardous waste varies greatly in composition between regions (Menegaki and Damigos 2018). Circular economy practices in some European Union Member States already achieve recycling construction and demolition waste rates of more than 90 per cent, while globally one third are sent to landfills (Chen et al. 2022). In the building sector, circular-economy actions such as retrofitting, refurbishment and recycling can reduce a building's materials-related total GHG emissions by up to 61 per cent (Ramboll, Fraunhofer and Institute 2020). Recycling concrete and cement from demolition rubble is an emerging technological solution that can help "build cities from cities" with reduced material footprints (Gebremariam et al. 2020; Dunant et al. 2024). Recycling cement paste from concrete can potentially reduce emissions from cement production by 15 per cent, equivalent to 0.8 per cent of 2020's global anthropogenic GHG emissions (Driver et al. 2024). Beyond recycling, circular solutions such as floor space reduction and lightweight building design can reduce cumulative GHG emissions by up to 44 per cent for the period 2020–2050 (Pauliuk et al. 2024).

Policies such as setting mandatory demolition recycling rates or new construction minimums for recycled materials at 90 and 15 per cent, respectively, have proven successful in several European countries (Interreg Europe 2024).

Furthermore, the built environment can go beyond minimizing harm and adopt regenerative, nature-positive practices (World Business Council for Sustainable Development 2023). Regenerative design can create buildings that enhance natural ecosystems through appropriate tools and technologies. This shift can mark an evolution from green buildings to regenerative and circular buildings, which actively contributes to environmental regeneration (Stracqualursi and Andreucci 2023). Switching from carbon-intensive materials to sustainably harvested renewable materials such as timber and bamboo and utilizing Indigenous Knowledge and traditional materials can support resilient local supply chains, job creation, preservation of local culture, and enhancement of regenerative local natural systems (Churkina, Organschi and Reyer 2020).

Plastics:

These are ubiquitous in modern societies, with 98 per cent made of synthetic, fossil-fuel-derived polymers (Schirmeister and Mülhaupt 2022). According to the OECD's Global Plastics Outlook, current plastic waste leakage into the environment amounts to 22 million tons per year and is expected to double to 44 million tons by 2060 if no policy action is taken (OECD 2022a). A circular economy has the potential to reduce up to 80 per cent of plastic pollution, thereby saving external costs estimated at around $18 trillion by 2040. In the absence of policy action, the externalized costs to the environment and society are projected to be significantly higher. (UNEP 2023a; Landrigan et al. 2025). The growing plastic pollution crisis endangers food security, human health, and marine ecosystems in Indigenous communities across the Arctic (WWF 2024), while in the Asia and the Pacific region, it contaminates waters, food sources such as fish and shellfish, poses serious health risks and disrupts cultural practices – further threatening Indigenous Peoples' traditional way of life.

In 2015, plastics accounted for 4.5 per cent or 1.7 billion tons of CO_2-equivalent (CO_2e) of global GHG emissions and could grow to 6.5 billion tons CO_2e by 2050 under the current trajectory (Zheng and Suh 2019; Stegmann et al. 2022). Circularity can help address these issues as it can directly reduce GHG emissions from plastics. For example, black carbon from the open burning of plastics and other waste could be eliminated by 2050 through circular waste management approaches (Reyna-Bensusan et al. 2019; Gómez-Sanabria et al. 2022).

Plastic recycling rates are increasing globally yet are still very low. The share of end-of-life plastics that was recycled in India, China, and Europe in 2019 was 12–13 per cent, in Sub-Saharan Africa 5.7 per cent, while the US managed to reach only a 4.5 per cent recycling rate (OECD 2022b). The single-use feature of a large proportion of plastics is the most problematic aspect, together with the propensity of plastics to break down into micro- and nanoplastics. These tiny plastic bits have become ubiquitous in the environment and even human bodies, and their ability to adsorb, as well as release, hazardous chemicals is an added danger. To enable a safe and non-toxic circular plastic economy, there is a need for improved transparency and harmonized measures in addressing chemicals of concern in plastic products. Plastics and polymers that hinder circularity, such as flexible plastics, thermosets and polyvinyl chloride, are especially problematic and need to be phased out (Tan, Jia and Ramakrishna 2023; Lisiecki et al. 2023).

There are economic barriers to circularity, such as primary plastics being persistently cheaper than recycled ones, and social practices that favour the convenience of single-use versus multiple-use products (UNEP 2023b). A combination of addressing upstream production, curbing plastics demand and designing for circularity, as well as downstream solutions such as recycling and waste management, will be the most cost-effective pathway to eliminate plastic pollution by 2040 (OECD 2024b). The cross-contamination of recycled materials with chemicals must also be addressed (Aurisano, Weber and Fantke 2021; UNEP 2023c). More than 4,200 chemicals used or found in plastics are of environmental or human health concern due to toxic, persistent, bioaccumulative or mobile characteristics. Furthermore, two-thirds of the over 16,000 plastic-related chemicals lack hazard assessments, and only 1 per cent of those assessed are considered non-hazardous (Wagner et al. 2024). Addressing these chemicals of concern is key to creating a circular plastics economy. The adoption of the Global Framework on Chemicals is a step towards supporting developing countries in the safe and sustainable management of chemicals and waste. The framework builds on the Strategic Approach to International Chemicals Management and guides governments and stakeholders in jointly addressing the life cycle of chemicals, including products and waste.

Textiles:

The fashion and textiles industry has significant environmental repercussions throughout its global value-chain operations, from waste generation to

resource consumption and carbon footprint. Textiles' global value chain accounts for an estimated 2–8 per cent of GHG emissions, consumes an estimated 215 trillion litres of water and contributes 9 per cent of annual microplastic pollution to the oceans (UNEP 2023d). The Global Chemicals Outlook identified the textile sector as a significant contributor of chemicals of concern and persistent organic pollutants; circular solutions would involve reducing the use of harmful chemicals and promoting more environmentally sound alternatives (UNEP 2019).

Less than 1 per cent of the material used to produce clothing is recycled into new clothing, and most is either incinerated or sent to landfills (Ellen MacArthur Foundation 2017). Between 2000 and 2015, clothing production doubled, while the number of times that an item is used before it is discarded decreased by an estimated 36 per cent, leading to an estimated equivalent of a garbage truck full of clothing being thrown away every second (Ellen MacArthur Foundation 2017). Shifting consumption patterns, scaling circular business models and improving clothing utility and durability, improving production practices, addressing low garment quality, , and investing in renewable energy infrastructure can move the sector towards circularity (UNEP 2023a). Second-hand clothing markets and the recycling of fabrics and fibres are among the circular economy solutions for the textile and garment sector (Baloyi et al., 2023).

Electronics, digital technologies and data centres: Information and communication technology industries are experiencing rapid growth that will accelerate in the coming decades. Approximately 62 million tons of e-waste was generated globally in 2022, growing five times faster than documented e-waste recycling (United Nations Institute for Training and Research 2024). The accelerating development of artificial intelligence and data centres contributes additional e-waste, potentially reaching a total accumulation of between 1.2 million and 5.0 million tons during 2020–2030 (Wang et al. 2024).

E-waste data has increased annually since systematic records began in 2014. China and the United States of America are the largest generators of e-waste, and nearly 10 per cent, or 5.1 million tons, of global e-waste crossed country borders in 2019. Around 35 per cent of the transboundary movement was shipped in a controlled manner, while nearly two-thirds or 3.3 million tons, was uncontrolled or shipped illegally (United Nations Institute for Training and Research 2022). At the global level, only 22.3 per cent was recycled in a formal manner, and the majority was stored or disposed of informally (Zeng and Li 2021; United Nations Institute for Training and Research 2024). At the same time, e-waste recycling offers significant economic opportunities, with the global market potential expected to reach US$65.8 billion by 2026 (Seif, Salem and Allam 2024).

New digital technologies like artificial intelligence and machine learning can enable material circularity and circular business models for material tracking and resource optimization in the circular economy, but will also result in additional e-waste generation and resource demands. Dozens of material types, including rare earth metals and other critical energy transition materials, are found in the servers, storage and networking equipment of data centres. Embedding circularity principles in their design and operation will help reduce resource demands in future (Hoosain et al. 2023).

Critical energy transition minerals:
The adoption of clean energy technologies implies an increasing demand for critical energy transition minerals such as aluminium, copper, cobalt, lithium, nickel, and rare earth elements such as neodymium and coltan. Demand is projected to almost triple by 2030 and grow to over 3.5 times the current levels by 2050, reaching nearly 40 million tons (International Energy Agency [IEA] 2024). Mining in many regions will escalate, with adverse effects on biodiversity and Indigenous Peoples' rights, as well as increased water pollution and land degradation (UNECE 2023a). Of the 5,097 existing energy transition mineral projects globally, an estimated 54 per cent are located on or near Indigenous Peoples' lands, waters and territories and will require free, prior and informed consent (Owen et al. 2023), full and effective participation, and fair and equitable benefit-sharing with Indigenous Peoples (Owen et al. 2023). Circular solutions such as lifetime extension, sharing models, materials recovery and recycling can help to reduce overall demand for primary mined materials, as well as alleviate political tensions about securing access (Geng, Sarkis and Bleischwitz 2023). Models show that new technological solutions and circular economy approaches, such as lifetime extension through repair and refurbishment of renewable energy equipment, and the recycling of materials, can reduce the demand for the mining of critical energy transition minerals by up to 58 per cent from 2022 to 2050 (Simas, Aponte and Wiebe 2022). For materials like cobalt, which currently has a global recycling rate of only about 5 per cent, if recycling rates were to increase to 90 per cent by 2050, this could cover

20 per cent of global demand by 2040 and 30 per cent by 2050 (Systemiq 2022; University of Cambridge Institute for Sustainability Leadership and The Wuppertal Institute 2023). Advanced metal and mineral recycling processes for low-carbon energy and storage technologies already exist but need to be scaled up (Zante et al. 2024). New technological, economic and logistical approaches are needed, especially for hard-to-recycle materials such as rare earth metals, which currently have recycling rates as low as 1 per cent (Wayman 2023).

A comprehensive strategy that integrates investment, innovation, recycling, rigorous sustainability standards, and well-designed safety nets must be developed (IEA 2023). The urban mining of scrap and e-waste can deliver enhanced resource sustainability and improved environmental protection while developing a circular economy for critical minerals essential for the energy transition. Since urban mines increasingly serve as a key material source for a circular economy, it is essential to include their prospecting into national data-collection activities in all countries. Furthermore, identifying, accounting for and assuming the cost of externalities in the extraction of energy transition minerals will help make urban mining and circularity more financially viable.

Ultimately, producer countries must retain and value their local resources. The Nairobi Declaration and Call to Action, signed by African leaders in 2023, advocates for the advancement of green industrialization across the continent. By leveraging Africa's significant renewable energy potential, the establishment of energy-intensive processing industries would require fewer resources and raw materials than in other regions (African Union 2023).

15.2 Potential solutions to achieve transformative change – immediate policy actions and strategic long-term planning

To achieve the shift to a circular economy, policymakers need to engage in strategic long-term planning over the next two to three decades. This section highlights possible actions that can be implemented immediately, as well as longer-term planning and policy implementation. The solutions summarized in **Figure 15.5** and **Figure 15.6** are not a one-to-one match between a pathway and the high-level goals defined in Section 15.1.2 for the circular economy transformation. Pathways will contribute to multiple goals through a combination of actions and solutions. The five levers described in Chapter 12 - economics and finance, individual and collective action, knowledge and innovation, governance, capabilities– are an integral part of the solutions, reflecting the systemic approach of the circular economy. Each pathway presents a collection of actions, their sequencing, and the appropriate actors for their implementation.

15.2.1 Solution pathway 1: Designing out waste/designing in circularity into the full life cycle of products

Circular design is often associated with the creation of products, components and materials, but it also encompasses business models and systems design (Moreno et al. 2016; Charter 2019). Systems thinking prioritizes connections and processes, not isolated parts. A circular economy is not only about material or energy recovery but improves the entire economic model. It is based on adopting a life-cycle perspective as well as factoring in the interaction between any process and the environment and the economy in which it is embedded (Ghisellini, Cialani and Ulgiati 2016). A truly cyclical system designs out waste. The value embedded in materials is preserved through their use in high-value applications (Korhonen, Honkasalo and Seppälä 2018), while any emissions are productively taken up by another process.

A systemic approach that designs circularity into the product's entire life cycle slows resource flows through durability and life extension – repair, refurbishment, remanufacturing – while closing resource cycles by transforming waste materials into value (Geissdoerfer et al. 2018; McDonough and Braungart 2002). Life-cycle analysis is an essential tool in assessing the effects of products, but small and medium-sized enterprise suppliers in developing countries often lack the resources for such studies. Circularity-oriented product design, circular business models, and supporting governance throughout the entire value chain, while also considering potential trade-offs and rebound effects, are prerequisites for integrating circularity into the system (Zink and Geyer 2017). For example, shifting business models from "scale and sale" to alternatives that focus on increased product utilization or access on demand is facilitated by mandating extended producer ownership or liability (Stahel 2019).

The following set of actions will be required to implement this solution pathway.

Figure 15.5: Summary of the proposed five solution pathways and actions for transformative change towards a circular economy from now until 2050

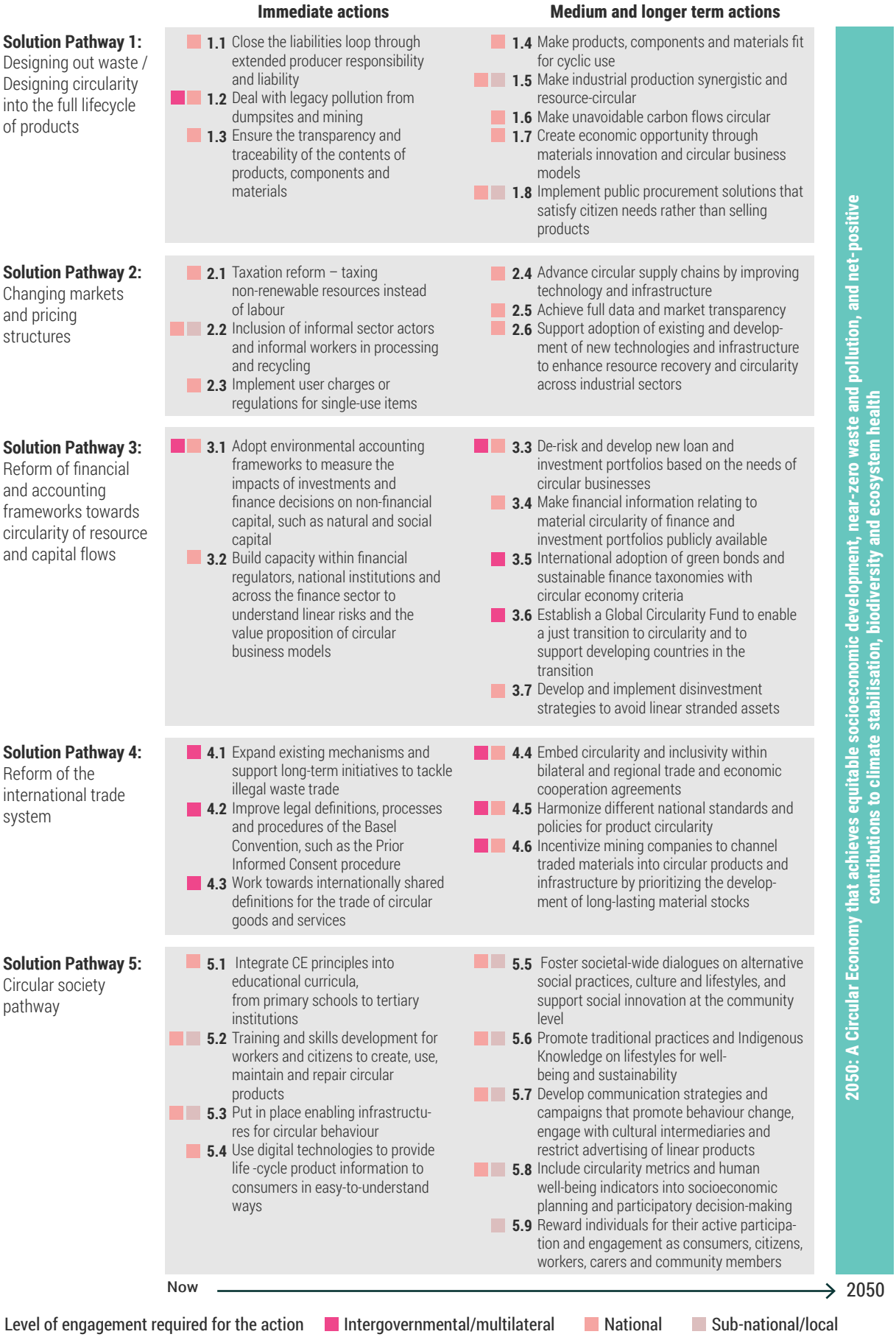


Figure 15.6: Closing the loop: Transforming systems through circularity

Creating fair and effective markets for circular goods and services

Objective: Establish transparent and efficient markets for circular goods and services, ensuring equitable participation and scaling of circular business models.

Use digital technologies like blockchain for traceability and transparency in value chains.

Reform taxation to incentivize circular economy practices and discourage non-renewable resorce use

Support SMEs and informal waste sector integration through capacity building and access to finance.

Ensure socially just transitions, especially for vulnerable groups, through legal protection and financial support.

Enabling transparent and fair global trade systems

Objective: Establish trade systems that facilitate the movement of circular goods and prevent illegal waste dumping, fostering global circular economy development.

Repurpose subsidies from extractive sectors to resource recovery and circular business models.

Develop technical guidelines and digital customs processes to improve interoperability across countries.

Expand international agreements and law enforcement to tackle illegal waste trade and promote legal, efficient transboundary movement of secondary resources.

Embed circularity provisions in trade agreements to encourage preferential treatment for circular goods.

Action 1: Close the liabilities loop through extended producer responsibility and liability

Extended producer responsibility (EPR) policies are a key approach to providing much-needed funding for municipal waste recycling while also facilitating material recovery and increasing recycling rates. More than 63 governments have implemented EPR policies, covering seven main industries, including packaging, textiles, electronics and electrical equipment, over the last 20 years (OECD 2001; Kunz, Mayers and Van Wassenhove 2018; Mallick et al. 2024; Brown et al. 2024). EPR schemes are the first step for governments to involve the private sector in covering end-of-life costs, enabling recycling and preventing pollution (Pouikli 2020). In India, the EPR Policy was first introduced and implemented in 2011 through the "E-Waste (Management and Handling) Rules" that made it mandatory for producers to manage their electronic waste (Ministry of Environment 2011). In 2016, the policy was expanded to include plastic waste management by local bodies, Gram Panchayats (village level self-government), waste generators, retailers, and street vendors.

To enhance EPR systems and promote eco-design, eco-modulated fees adjust the financial contributions that producers make to producer responsibility organizations based on the environmental performance of their products (Arya and Bhutani 2023). This incentive rewards circular design choices with lower fees, while products with lower recyclability and higher environmental damage incur higher charges (Lifset et al. 2023). Governments and existing producer responsibility organizations play a key role in elevating EPR towards transformative extended producer liability regulations. Action 1 is closely linked with other actions that follow, including Action 3, digital product passports and fitness for circularity, and Solution pathway 2's Action 3, data and market transparency.

Building on EPR policies, new concepts such as extended producer ownership or total product liability further shift responsibility to the manufacturers, brands and retailers (Domenech and Ekins 2019; Stahel 2019). This becomes the foundation of a comprehensive circular economy in practice: encouraging the management of material stocks and their quality, as well as utilizing whole value chain transparency. Applying the polluter-pays principle, an additional sum is added to a product's price to reflect potential recovery costs for materials that appear as waste. EPR and liability promotes business model and material innovation and provides a gateway to constructively allocating full cost pricing (Kunz, Mayers and Van Wassenhove 2018; Domenech and Ekins 2019; De Sadeleer 2020; Pouikli 2020).

Action 2: Deal with legacy pollution from dumpsites and mining

The linear economic model has created a dire legacy of waste and pollution, with chemically hazardous sites jeopardizing public health and safety. The world's 50 largest dumpsites affect the daily lives of 64 million people (ISWA 2016; He, Wu and Zhang 2016). Open dumping of waste contributes to chemical pollution, especially in developing countries in Sub-Saharan Africa, Latin America, and Oceania, mainly due to a lack of collection services (UNEP 2024c). Legacy pollutants leaching out of contaminated sites are a leading cause of failing water quality targets in aquatic ecosystems (Choo et al. 2020). With municipal solid waste generation rates set to increase in developing countries, systems for the collection and disposal of uncontrolled waste must be strengthened and modernized (Adiansyah et al. 2015; UNEP 2024c).

Addressing the issue of data availability and the lack of standardization in measurement and reporting from dumpsites remains critical (OECD 2024a). Technologies such as remote sensing can detect dumpsites and collect information for the analysis of landfill evolution and potential damages (Hannan et al. 2015; Khan et al. 2022; Papale et al. 2023). At an industrial level, one solution is landfill mining, where valuable raw materials and energy are extracted from existing dumpsites. This approach mitigates landfill emissions and increases landfill capacity (Wagner and Raymond 2015; He, Wu and Zhang 2016; Hogland, Marques and Nimmermark 2004; Ojha et al. 2024). Approaches for remediating heavy-metal-contaminated sites include treatments such as soil washing and in situ immobilization (Zhai et al., 2018), a process whereby contaminants are separated from the soil matrix, and thermal desorption, which utilizes heat to vaporize and capture organic pollutants.

In the mining industry, the handling and storing of toxic tailings at extraction sites is inadequate (Global Tailings Review 2020). Current methods include disposal into rivers and oceans, retention in wetlands, backfilling into mined-out areas, dry stacking, and storage behind dams (Lottermoser 2010; Watson et al. 2010; Adiansyah et al. 2015). The re-mining of tailings has emerged as an approach to recover valuable minerals from mine waste, reducing the volume of stored tailings. Remediation strategies include containment barriers to prevent further spread, chemical additives to neutralize acidic drainage, and transferring contaminated materials to designated

Credit: duallogic/Envato

storage areas after cleaning (Engels et al., 2004; Kossoff et al., 2014; Park et al., 2019). Government regulation is key: China has established environmental investigations and risk assessments to prevent pollution from mining tailings (Government of China, 2022), while Brazil has developed guidelines for their proper disposal (Kossoff et al., 2014; Government of Brazil, 2022;). However, greater government action is required to address and remediate legacy pollution at mining sites globally (World Bank 2023).

Action 3: Ensure the transparency and traceability of the contents of products, components and materials

A materials and product passport is effective in recording the content of products, components and materials from supplier to buyer or user through to the end of the first life cycle, enabling recovery and reuse (Göswein et al. 2022). Product designs that use fewer materials facilitate this. Digital product passports (DPPs) are already being mandated, such as the European Union's Battery Regulation for lithium-ion batteries used in electric vehicles, which is due to take effect in 2026 (European Commission, 2023a). China introduced the Interim Provisions on Traceability Management of Power Battery Recycling in New Energy Vehicles in 2018 and is currently developing a battery passport (IEA 2025). International cooperation will be needed to establish common standards for battery DPPs (World Economic Forum 2023). The European Union's Ecodesign for Sustainable Products Regulation, which aims to improve transparency along product value chains by offering detailed information on each product's origin, materials, environmental footprint and disposal guidance, will likewise require international coordination (European Commission 2023a; European Commission 2024).

DPPs should declare details about the product's lifetime and residual longevity, including any previous defects and repairs. Ensuring transparency and traceability of materials will be key to enabling circular supply chain management and preventing greenwashing and unsubstantiated environmental claims (Zhang and Seuring 2024; Choudhury, Islam and Sujauddin 2024). Building on existing initiatives, an international multi-stakeholder initiative co-convened by UNEP and the International Telecommunications Union would be well-positioned to define an internationally agreed framework and protocol on what information DPPs should contain. Developing countries will require targeted support in building capacity for the adoption and use of DPPs, particularly for small businesses and those in the informal sector.

Action 4: Make products, components and materials fit for cyclic use

With stock management and lifetime extension in mind, design for durability, repair, remanufacture, refurbishment, and even design for disassembly and reassembly are the hallmarks of circular product design (Abuzied et al. 2020). These design approaches offer new business opportunities, especially in providing the use and access to products instead of ownership, including through product-as-a-service models (Olivetti and Cullen 2018; Fernandes et al. 2020). Ending practices that undermine circularity must be prioritized, such as spare parts restrictions, suspension of services for updating software, or lock-ins that force customers to stay within a specific brand's system (Poppe et al. 2021). Standardized product design and product lifespan requirements can act as strategies against planned obsolescence (Prakash et al. 2020).

The ability to recover high-quality materials from end-of-life products is essential for circularity, especially where extensive material stocks have accumulated. This also speaks not only to materials and product passports but also to design for disassembly (Talens Peiró, Ardente, and Mathieux, 2017). Multi-stakeholder processes convened by international standardization bodies, such as ISO and the European Committee for Standardization, together with business associations, independent scientists and engineers, will need to further develop circular design guidelines at the sectoral and product levels. National and subnational regulatory agencies need to ensure compliance with such standards for trade within and across their jurisdictions (Maiurova et al. 2022).

Action 5: Make industrial production synergistic and resource-circular

Cross-sectoral cooperation through industrial symbiosis, industrial hubs for circularity or similar schemes to facilitate effective resource usage and create synergies between industrial actors, public entities and regional communities are needed (Mendez Alva, De Boever and Van Eetvelde 2021). The sharing of energy, materials, services, infrastructure, and information is central to such schemes, and participants co-create mutually beneficial solutions (Chertow and Ashton 2009). Some common interlinkages are the uptake of by-product materials considered waste by another entity, the pooling of resources, and shared energy supplies (Chertow 2000; Neves et al. 2020; Lybæk, Christensen and Thomsen 2021). Public and private initiatives have both successfully driven industrial symbiosis implementation (Domenech et al. 2019). A variety of policies, financial incentives, and knowledge transfer mechanisms can encourage the private sector to take the lead or get engaged (Mortensen and Kørnøv 2019; Lybæk, Christensen and Thomsen 2021). Standardized data facilitated through digital knowledge centres, AI-based tools and industrial ecology methods, such as material flow accounting, can support allocating resources across different value chains and anticipate resource needs more accurately. Digital applications such as blockchain technology aid small and medium-sized enterprises in embedding transparency and efficiency into their operations (Saavedra et al. 2018; Iranmanesh et al. 2023; Jawad and Balázs 2024). However, artificial intelligence and other digital solutions have their own environmental impacts that are still difficult to quantify (Kaack et al. 2022).

Action 6: Make unavoidable carbon flows circular

The pursuit of carbon circularity complements mitigation efforts, but it is not a substitute for the imperative of phasing out fossil fuels. Industrial sectors, such as the chemical industry, are heavily reliant on carbon derived from fossil fuel. There is a need for non-fossil-based carbon flows, which can be achieved by biomass-based solutions, along with recovery and valorization of unavoidable carbon flows. The cement industry alone is responsible for about 7 per cent of global CO_2 emissions, and a significant share is unavoidable (Mohamad et al. 2022; Monteiro and Roussanaly 2022; Supriya et al. 2023). CO_2 from point sources, such as cement or biomethane production, has the potential to be converted into hydrocarbons for the chemical industry, polymer feedstock, fuels, or food-grade CO_2 (Pan et al., 2020; Mohamad et al., 2022; Monteiro and Roussanaly, 2022; Ministerium of Transport Baden-Württemberg, 2022; Supriya et al., 2023). An example of an existing business activity is CO_2 recovery from biogas upgrading into biomethane, with valorization in the food and beverage industry or technical schemes that rely on CO_2 (Esposito et al. 2019). Solutions that chemically transform CO_2 into products based on carbon structures may be more prone to environmental burden shifting as they are energy intensive, and most of them rely on hydrogen.

Action 7: Create economic opportunity through materials innovation and circular business models

Novel materials, particularly those suitable as replacements for short-cycle, low-value, but hard-to-manage polymers or existing construction materials with high CO_2 emissions, are

still underexploited, despite a disruptive potential (Bucknall 2020; Sizirici et al. 2021; Labaran, Mathur and Farouq 2021). Mechanisms to promote such materials at the local, regional and international level are needed. Businesses and investors with long-term vision and patient capital can provide the needed investments to shift material science innovations from the lab to the market. Alongside circular supplies and resource recovery are digitally enabled models of selling products as services, product life extension and varieties of the sharing economy (Ferasso et al. 2020; Geissdoerfer et al. 2020). Such business models, much like materials innovation, become increasingly attractive if real cost pricing progressively disadvantages linear models of scale and sale, and if firms can leverage industry consolidation and use the opportunities afforded if transparency around materials and liability for materials recovery is increasingly allocated to manufacturers (Action 1).

Action 8: Implement public procurement solutions that satisfy citizen needs rather than selling products

Identifying and satisfying the needs of customers rather than selling product ownership disrupts the logic of the linear throughput economy. Such practices are usually linked to business models around access – for example, through performance agreements, pay-per-use, rental, lease and subscription – and are suitable for products that are used but not used up (Ogunmakinde, Sher and Egbelakin 2021; Gsell et al. 2024; Golinska-Dawson, Zysnarska and Pender 2024). However, continued product ownership across the full value chain remains key; access or service models per se are not sufficient for a circular economy on their own. Lowering costs and increasing profitability involves building in product durability, easing maintenance, supporting upgrades, and facilitating recovery, especially for products, components and materials of high value, and industries with high business concentration. In these highly concentrated industries, technological complexity and intellectual property often play a key role in limiting competition, which also creates challenges in managing economic rent-seeking (Webster 2021).

Government spending on public procurement amounts to 10–15 per cent of gross domestic product on average (World Bank 2021). Hence, government agencies and public authorities can leverage public procurement to shift from purchasing products to procuring services – such as leasing office equipment, using pay-per-use lighting systems and adopting shared or rented vehicle fleets – thereby promoting resource efficiency and circular economy principles. Under the green procurement policy in Denmark, the Partnership for Green Public Procurement, a collaborative initiative between Danish regions, municipalities, and the Ministry of Environment and Food, has integrated circularity into their procurement policies through criteria ranging from recyclability to product lifespan, and total cost of ownership (OECD 2024b). Donations of used computer equipment from the public sector to communities can help reduce digital exclusion (Good Things Foundation, 2023). Circular procurement guidelines have been published by UNEP (UNEP 2018b) in reorientating spending towards low-energy transport choices in including repair, reuse and refurbish, rather than buying new. Reworking procurement criteria for local authorities and associated anchor institutions enables local providers to use public procurement as a way to support local economic development. This approach prioritizes community wealth building by redirecting local government spending and resources via participatory decision-making to benefit the local economy (Community Wealth Building 2021).

15.2.2 Solution pathway 2: Changing markets and pricing structures

This pathway aims to create markets for circular goods and services by addressing market signals and pricing structures so products, components and materials are maintained at their highest value for as long as possible. Reusing products and components and recycling materials that retain their integrity and value makes them cheaper over their life cycle than primary materials. This is, however, currently not reflected in markets and prices. For example, in January 2024, recycled polyethylene terephthalate was priced at US$1,000 per ton, while primary plastic was around US$800–900 per ton (Hicks 2024). Recycled cotton textile fibres are roughly double the price of conventional cotton (Marini 2024).

This disparity is compounded by subsidies, both direct and indirect, in exploiting fossil fuels, mineral resources and other forms of natural capital, further distorting costs and prices. The estimated environmental cost associated with certain subsidies far exceeds their monetary value. According to the International Monetary Fund, when factoring in the adverse external effects stemming from fossil fuel subsidies, the combined cost amounts to approximately US$5.2 trillion per year (Coady et al. 2019). At the same time, in most countries labour is overtaxed compared to capital gains, for example, as it is the factor bearing most taxation, alongside consumption (OECD 2018).

A mature circular economy is based on stock or capital maintenance rather than revenue and throughput. Shifting taxation to pollution and waste and to non-renewable resource use shows positive outcomes in key indicators like employment, energy use and economic growth, even where the proposals are broadly revenue neutral. A comprehensive study for the European Union context broadly indicates the feasibility and potential (Groothuis 2022) of shifting €526 billion from labour to resource use by 2025.

Another example is the Mining Royalty bill in Chile, which came into effect in 2024, imposing a 1 per cent tax on lithium and copper mining. The revenue generated will be distributed across the country through three dedicated funds aimed at supporting municipalities and low-income communities. These funds are designed to help mitigate the negative environmental and social impacts of mining activities, including pollution and the disposal of mine tailings. By placing a cost on resource extraction, the royalty serves as an economic disincentive for over-exploitation and helps internalize the environmental costs associated with mining (IEA 2023).

As alternatives to resource taxation, several market-based instruments can effectively reduce material consumption and waste generation. One option is to implement a cap on the total amount of virgin materials allowed to enter the economy, combined with a system of tradable permits allocated to producers or importers. Such measures would create a controlled supply and a market incentive to use fewer raw materials. Another approach involves introducing material efficiency credits, where companies are rewarded for reducing material use or improving product circularity.

There is no guarantee that jobs created in a circular economy will be inherently just and well-paid. For a successful and inclusive circular economy transition, considerations of justice and social equity are as important as they are in the contexts of low-carbon transitions and digitalization of the economy. Without considering social justice, the transition to a circular economy will face challenges in establishing itself as a new economic model and will lack public acceptance and support as a sustainable alternative (Schröder 2020). Tax shifting away from labour and support-related statutory elements around minimum wage or living wage can be expected to maintain or boost spending power, other things being equal. The low-income response might be in circulating fees taken from resource rents as one form of compensatory lift to citizens' income (Miller and Hansen 2019). A reduction in income tax and social security contributions would ease the burden on households, while income support and social safety nets would help low-income groups. Such adjustments will be the cornerstone for a socially just transition.

Action 1: Taxation reform – taxing non-renewable resources instead of labour

Taxing non-renewable resources instead of renewable resources, such as human labour, is an important policy lever to advance resource efficiency and circularity (Groothuis 2014; Vence and López Pérez 2021). The current taxation system favours new product manufacturing activities that are increasingly highly automated and generally materials and energy intensive while penalizing circular economic activities that are generally more labour-intensive, such as repair and service models (Vence and López Pérez 2021). Taxing the value of common resources, such as materials and non-renewable energy sources, and access to waste sinks including the atmosphere, would promote low-carbon and low-resource solutions and a shift towards a circular regional economy, as opposed to the linear global economy. Additionally, a taxation shift could result in substantial improvements in material and energy efficiency, regional job creation, and national greenhouse gas emission reductions (Milios 2021).

The lack of progress appears to be a combination of the political difficulty of making any changes to a country's tax system and its distributional consequences (Pisani-Ferry 2021). For instance, taxes on carbon could be redistributed through a universal basic dividend, addressing all low-income groups and easing concerns about opposition or social unrest (Webster 2022). Set at an appropriate level, this dividend would go beyond merely compensating for necessary price rises. For instance, as part of the Baker-Shultz Carbon Dividends Plan, an annual carbon dividend of US$2,000 for a family of four has been proposed for US citizens (Climate Leadership Council, 2024). Tax reform could be fairly structured to account for different income levels by applying lower tax rates to lower-income groups and higher rates to those with higher incomes.

At the same time, destabilizing non-circular practices relies on levying taxes on landfills and incineration. This is the most common economic instrument in many countries, with 22 European Union Member States implementing these taxes (European Economic Area

Credit: recstockfootage/Envato

2023). National taxation departments, treasuries, and Ministries of Finance will need to anchor these changes in their annual budgets as new government revenue streams. In the short term, viable options include VAT exemption on repair, refurbishment and removal of tax benefits for linear economic activities while phasing in incremental taxes on primary extraction of non-renewable resources.

Action 2: Inclusion of informal sector actors and informal workers in processing and recycling

Making secondary raw material markets work requires the inclusion of the informal sector, which plays a key role in collecting, sorting, processing and recycling of many material and waste streams. The integration of informal actors, particularly waste pickers, is crucial for addressing precarious working conditions and social inequality, as well as for developing circular modes of production and supply chains that can compete in global markets (Dewick et al., 2022). Within many developing economies, waste pickers are key stakeholders who must be actively included, as the informal sector plays a crucial role in circular value chains, encompassing activities such as collection, trade, repair, reuse, recovery and recycling of goods (Sun, Schnoor, and Zeng, 2022).

Of major concern are the circularity-oriented practices that increase risks to human and environmental health. Such practices are often associated with informal sectors and are prevalent in all regions worldwide, particularly in economically less-developed countries. Many informal waste collectors in less-developed countries are women, which increases their exposure to waste hazards (Cottom, Cook, and Velis, 2024).

Generally, these activities offer economic and entrepreneurial opportunities for individuals engaged in the informal sector. However, workers often face precarious working conditions, health risks, inadequate legal protection, and insufficient economic benefits (Buch et al. 2021). A circular economy where materials recovery and recycling are achieved by exploiting the informal sector is not acceptable. Without adequate infrastructure, it is difficult to envision a circular economy that supports decent work, well-being and human needs. Infrastructure that allows for added value and returns to local businesses and enterprises would be a substantial and significant addition (Preston City Council, 2019).

The first step in facilitating a covenant relationship with municipalities and the informal sector is the formation

of cooperatives or other legally or partially recognized structures (Gupta 2012). This multi-faceted process requires several policy, economic and institutional measures (Aparcana 2017), including a regulatory framework that incentivizes and safeguards informal workers. Measures could include providing ease of registration, reducing bureaucratic hurdles, offering safety nets in the form of insurance, as well as financial and technological support (Gupta 2012; Aparcana 2017). An example of hybrid waste management emerged in Buenos Aires, where dry-waste scavenging is formalized into cooperatives, and value added equipment and infrastructure are provided, while wet organic waste is managed by large-scale contractors (Knowledge Hub 2020). Training and capacity-building initiatives are crucial and must outline the duties and accountabilities of waste generators at all levels of the waste management system (Adiansyah et al. 2015) and society (Mor and Ravindra 2023). For example, in Bamako, community-based private enterprises acted as intermediaries between the local associations and the municipality, engaging in outreach to households and organizing training sessions for the government, economic interest groups, health committees, and informal workers (World Bank 2023).

Action 3: Implement user charges or regulations for single-use items

In a circular economy, implementing user charges, deposit-return schemes, or bans on single-use products such as plastic packaging and containers serves as a deterrent to wasteful consumption, promotes innovation in product design and supply chains (Syberg et al., 2021), and counteracts environmental littering (European Commission, 2018). Charges also internalize external costs on society, such as those associated with pollution, waste and natural resource depletion, and can fund investments in the circular economy. This approach requires effective legal measures at the country level, including the introduction of alternatives for banned or disfavoured items.

Action 4: Advance circular supply chains by improving technology and infrastructure

Investment in technological solutions is essential for facilitating the tracking, recovery and management of materials across various supply chains, including electronics, textiles, automotive, and construction materials for the built environment (Garrido-Hidalgo et al. 2020Ni, Chan and Tan 2023). Implementing digital technologies, such as big data and Internet of Things devices, can optimize the tracking of secondary materials (Krstić et al. 2022) by gathering real-time information and mapping collection points with the highest waste generation (Centobelli et al. 2022; Mallick et al. 2023). A logistics technology system, combined with an optimized and interconnected transport infrastructure (Garrido-Hidalgo et al. 2020; Kaewunruen et al. 2023) is crucial for the adoption of reverse logistics. This system would include both information and physical infrastructure, such as collection and processing points, to ensure efficient resource recovery and waste management. Enabling effective partnerships among distributors, suppliers and logistics companies is crucial for establishing robust networks.

Action 5: Achieve full data and market transparency

A major barrier to markets for circularity is the inadequate transparency and traceability of product value chains. This hinders the effective tracking and reporting of material flows, as well as providing comprehensive information on products and their impacts (Serna-Guerrero et al. 2022). The establishment of traceability mechanisms within the circular economy will enable the amalgamation of supply chain information-sharing and visibility, thereby granting stakeholders access to accurate, trustworthy, timely and operationally valuable information. Traceability ensures the accuracy of sustainability claims and facilitates the retracing of steps, verifying processes, history and location of products, aiding in recovery and recycling at the end of life.

The circularity transformation will need to leverage innovative technologies such as artificial intelligence, data-collection platforms, digital passports, the Internet of Things (Hakanen and Rajala 2018) and blockchain solutions to augment the traceability and transparency of product value chains (Centobelli et al. 2022). The integration of digital advances encourages systemic transformation by improving the economic and environmental sustainability of products throughout their entire supply chains. These digital tools can aid in the reduction and recovery of waste and optimization of production, processing and logistics, as well as the enhancement of overall visibility. Examples include the circular value chain traceability protocol for garments and footwear, developed by the United Nations Commission for Europe (UNECE 2023b). This traceability can be further strengthened through mandatory DPPs that track the entire product value chain (Walden, Steinbrecher and

Marinkovic 2021). DPP adoption is particularly relevant in sectors such as electronics and textiles, where there is a lack of transparency, supply chain collaboration, and comprehensive information on composition, producers and origin. At the same time, increased transparency about the resource and energy demands of digital tools employed for traceability is important in ensuring that any adverse environmental consequences do not outweigh the benefits of circularity (European Commission 2023b).

Action 6: Support adoption of existing and development of new technologies and infrastructure to enhance resource recovery and circularity across industrial sectors

Many technologies that can increase circularity and even closed-loop systems already exist, but they are not commonly adopted to the scale needed. Barriers to their transfer and adoption include a lack of awareness among industry stakeholders, a lack of technical capability among the workforce, and limited government support (Ren et al., 2023).

High-volume material streams, such as e-waste, need to be managed through repair, remanufacturing and recycling at the end of their life to enable full circularity. Dismantling, crushing and screening are commonly applied to separate components and enable the recycling of, for example, metals and plastics, typically followed by pyrometallurgical processing in developed countries and hydrometallurgical processing in developing countries to recover different metals (Li et al. 2015). Minority components, such as rare earth elements, largely remain unrecovered due to their challenging economic viability (Andersson et al. 2019). New technologies and infrastructure for large-scale recycling, specifically for metals and critical raw materials, require research and development as well as investment.

In the textile and garments industry, new technologies are emerging to reduce textile waste, recycle textile fibres, phase out toxic substances, and reduce workers' and consumers' exposure to harmful materials such as per- and polyfluoroalkyl substances, but they still need to be brought to market (Reike, Hekkert and Negro 2023; Bour et al. 2023).

Wastewater technologies can facilitate the recovery of secondary resources, which applies to both industrial and municipal water. Biological and physio-chemical treatment methods are widely used to decontaminate wastewater before discharge into the environment. Microorganisms, such as bacteria, fungi (Abinandan and Shanthakumar, 2015), and microalgae (Kalra, Gaur and Goel, 2021), are effective biological agents. In contrast, industrial effluents often require alternative or additional physicochemical processes, including membrane filtration or electrochemical treatment. Advanced filtration systems and reverse osmosis improve the quality of treated water, while emerging technologies, such as membrane bioreactors, enhance contaminant removal and optimize energy recovery processes (Zhang, Wang, and Li, 2020). State-of-the-art solutions include combining wastewater treatment with nutrient recovery, such as phosphorus and nitrogen, for agricultural use (Zhu, Cakmak and Cetecioglu 2023). The anaerobic digestion of resultant sludges can cover some of the high energy demands of wastewater treatment plants (Khawer et al. 2022). Additional circularity schemes, such as the production of polymers or other value added bioproducts from wastewater constituents, need to be advanced towards market competitiveness (Capodaglio 2023).

More widespread adoption of such practices and technologies across different regions would stimulate transnational governmental initiatives for technology transfer and investment in recycling infrastructure. Industrial research and development engagement, as well as regulatory frameworks and financial incentives, will be crucial (15.2.3).

15.2.3 Solution pathway 3: Reform financial and accounting frameworks towards circularity of resource and capital flows

The transformation to a circular economy at scale requires making financing circularity the new normal in mainstream financial instruments and government spending. According to the UNEP Finance Initiative (UNEP-FI), "financing for circularity covers any type of financial service where money is exclusively used to finance, re-finance, invest in or insure in part or in full, new and/or existing companies or projects that advance the circularity of our economies" (UNEP 2020a). There are interlinkages among circular economy finance, responsible banking and finance for climate and biodiversity, where circular economy finance can act as an enabler (United Nations Development Programme 2024).

Despite the recent emergence of new models and frameworks for circular economy finance, both public

UNEP's Textile Initiative supports Small and Medium-sized Enterprises in minimizing the environmental footprint of their textile products
Credit: ©UNEP

and private circular spending remains small-scale in comparison with climate finance and spending in the linear economy, with insufficient funding for circular business models, large-scale recycling infrastructure and technology innovation to drive a global transition at scale. Although financial data availability remains very limited, initial estimates show that only about 4 per cent of global total government spending of US$13 trillion in 2019/2020 was circular, rising to 5 per cent when COVID-19 pandemic stimulus spending is included. Corporate sector linear economy spending was about US$35 trillion in 2019/2020, with the circular economy's share of this only about 3 per cent each year (Schröder and Raes 2021; Lawlor and Spratt 2021).

Circular economy finance still suffers from unclear definitions of what constitutes circular investments and ambiguous or poorly defined metrics to evaluate investments and assess whether an activity, company or project contributes to circularity. Overall, most information about the environmental and social outcomes of circular investments is still inadequate. To avoid the risk of circular economy finance losing its effectiveness as it develops, for example, through the use of vague metrics and imprecise indicators, more oversight and benchmarking by regulators and financial standards bodies is required (Dewick et al. 2020).

Several initiatives are developing technical criteria to define circular economy finance. In the Kingdom of the Netherlands, the FinanCE working group consisting of private banks such as ABN AMRO, ING and Rabobank introduced the Circular Economy Finance Guidelines, which contain prescriptions on the use of investments, impact assessment and process evaluation (FinanCE 2018). Banks are developing internal circular economy standards, metrics and instruments to measure the level of circularity of investments and clients (Intesa San Paolo 2022). UNEP-FI has developed support tools for financial institutions to set targets for circular economy and resource efficiency and to embed circularity in climate action plans (United Nations Development Programme Finance Initiative, 2023; United Nations Development Programme Finance Initiative, 2024).

A road map for circular finance for 2030, developed by a multi-stakeholder group including financial institutions and experts (Circle Economy, 2022), highlights the need to assess both existing linear risks associated with existing economic systems and new circular risks, such as the economic viability of circular business models. The linear risk of continuing to do business under the unsustainable assumption of infinite resources must be explicitly included in financing decisions. One of the current obstacles to scaling up investments into

circular technologies and business models is the perception of high-risk investments and low returns for investors. Insufficient investment and the perceived risks associated with circular business models hinder progress towards a circular economy, particularly for small and medium-sized enterprises and start-ups, which account for the largest share of businesses with financial needs (Aranda-Usón et al. 2019).

Circular economy road maps provide the strategic direction and investment priorities that are essential for driving financing solutions. Effective implementation will require funding from both public and private sources, particularly for national action plans and policies. For example, Lithuania and Spain have estimated a required budget of around €4 billion and €1.5 billion, respectively, to deliver on the circular road map and strategy commitments. Spain dedicated €850 million from its COVID-19 recovery and resilience plan to support its circular economy strategy. Circular economy road map financing for developing countries remains a particular gap; for example, Rwanda estimated the need for US$211 million (Ministry of Environment, Rwanda and UNDP 2022), while Ghana estimates US$2.5 billion (Barrie et al. 2024).

The following actions are proposed to scale up existing circular finance initiatives, address barriers to mainstreaming circular finance and enable a shift in financial risk-assessment and accounting frameworks.

Action 1: Adopt environmental accounting frameworks to measure the impacts of investments and finance decisions on non-financial capital, such as natural and social capital

Current accounting practices and frameworks are rooted in an economy in which value is created by physical capital, a hallmark of the industrial linear manufacturing economic era (Watson, Zochowski and McGarvey 2021). A broader focus on non-financial capital, known as intangibles, in accounting practices and reporting can help reflect the full value of circular investments and companies, exposing the effects, risks and liabilities of extractive practices and linear business models (Ellen MacArthur Foundation 2020). The circular economy can be a de-risking strategy for investors and businesses. During the COVID-19 pandemic, European circular businesses and assets demonstrated stronger financial performance and were more effective at mitigating negative impacts than their non-circular counterparts (Zara, Bellardini and Gobbi 2021). One of the key barriers to attracting most institutional investors, such as pension funds and insurance companies, to invest in natural capital is the lack of financial returns (Lamont 2021). Instead, investments in regenerative solutions that build natural capital have financial benefits in terms of avoided costs and a wider range of beneficiaries, not only the investors. Organizations such as the International Accounting Standards Board and the International Sustainability Standards Board, along with financial regulators, including central banks, play a key role in developing and adopting internationally accepted financial accounting frameworks that support circular and nature-positive finance (International Accounting Standards Board, 2021). Including the effects of investment on natural and social capital will be crucial in highlighting the social and environmental costs of investment decisions and direct investments towards regenerative solutions that rebuild natural capital.

Action 2: Build capacity within financial regulators, national institutions and across the finance sector to understand linear risks and the value proposition of circular business models

Building capacity will involve increasing targeted training for accountants, legal specialists and fiscal experts to navigate the added layers of complexity that circular economy investments entail. Enhanced understanding and capacity are key to enabling financial institutions to develop and offer new financial products for circularity. The financial industry, corporate clients and investees will need to actively engage with and build awareness of resource efficiency, the circular economy market, material flows and changing consumer demand. Risk policies can be adapted to manage linear risks and identify circular business opportunities by applying the 9R model in risk policies, financial product development and client engagement (UNEP 2020a). Finance institutions must develop training courses and materials to retrain staff and risk analysts. Similarly, universities should incorporate circular finance modules into their curricula to train the next generation of experts and risk analysts. To achieve this, universities should be encouraged to develop specialized programmes in circular finance, particularly within non-environmental faculties such as economics, law, administration, accounting, finance and business, focusing on regenerative solutions that restore and enhance natural capital.

Action 3: De-risk and develop new loan and investment portfolios based on the needs of circular businesses

Developing appropriate financing solutions with more risk capital for early-stage circular companies, small and medium-sized enterprises, and start-ups will be essential. Blended finance instruments that leverage both public and private sector resources can help mitigate risks associated with circular business models and accelerate the diffusion of technology. Blended finance reduces risk exposure and improves the financial feasibility and economic profitability of circular investment projects, especially in developing countries, while innovative investment portfolios can also address the risks and returns associated with regenerative practices (Nature Positive Initiative 2025). Supported by local and national government actions using concessionary finance, blended finance can attract commercial capital into the waste management sector in developing markets and make them more attractive to investors (Systemiq 2023). An example of such a finance mechanism is the African Development Bank's trust fund designed to integrate circular economy principles – the Africa Circular Economy Facility. Established in 2022 with support from the Government of Finland and the Nordic Development Fund, the facility also receives backing from corporate foundations (Africa Circular Economy Facility 2025).

Especially for small and medium-sized enterprises, a combination of an organization's own financial resources, the availability of private credit, low-interest loans and public funding sources has had a positive effect on stimulating the implementation of circular economy initiatives in businesses (Aranda-Usón et al. 2019). Other strategies include reorienting loans and investments towards more circular technologies and business models, developing sectoral knowledge and competencies to identify best practices for circular economy business models and financing opportunities, and applying sectoral metrics in financial decision-making.

Action 4: Making financial information relating to material circularity of finance and investment portfolios publicly available.

Adopting circular metrics in financing and reporting will be necessary to increase transparency, enabling external verification and benchmarking and reducing false green claims (Circle Economy 2022). Circular finance metrics will need to include transition metrics and targets related to banks' support to companies shifting from linear models to circular business models (UNEP 2023b). Assessing and incorporating linear risks into financial decision-making involves thoroughly analysing the long-term risks associated with linear investments and developing incentive-compatible solutions to counter short-termism in investment decisions. Development and adoption of additional evaluation metrics will be needed to account for and reduce the risk of stranded assets linked to linear sectors (Schröder and Raes 2021). The outcome will be accurate, publicly available information relating to the circularity of finance and investment portfolios. Financial regulators, in close dialogue with commercial banks, multilateral development banks, and investment and pension funds, need to lead this action.

Action 5: International adoption of green bonds and sustainable finance taxonomies with circular economy criteria

Green bonds can facilitate investment into the circular economy by providing dedicated financing for projects that promote resource efficiency, recycling infrastructure and circular production models. For example, the Green Bond Guidelines in Japan that were updated in 2023 include eligibility criteria aligned with the country's Sound Material-Cycle Society strategy, supporting projects such as recycling systems and resource-efficient manufacturing (The Ministry of the Environment Japan 2025). Multiple countries have adopted sustainable finance taxonomies to shift investments towards circular economy activities and businesses. The International Platform on Sustainable Finance has furthered work on the Common Ground Taxonomy, which contributes to the development of technical criteria and extends their scope and coverage (International Platform on Sustainable Finance 2023). Industry initiatives such as the Partnership for Carbon Accounting Financials and their GHG accounting and reporting standards for the financial industry also support taxonomy developments (Partnership for Carbon Accounting Financials 2021). International taxonomy harmonization and adoption will enable the use of classifications across countries and value chains on circular activities and investments. Cross-jurisdictional interoperability and comparability of taxonomies will need to align with environmental policies. As part of the environmental objectives and technical screening criteria in taxonomies, circular economy metrics need to be developed and adopted

across countries and jurisdictions. As countries work towards standardizing taxonomy frameworks, leveraging digital tools and technologies such as blockchain, artificial intelligence and data analytics can significantly improve the efficiency, transparency, and accuracy of circular economy metrics (Mair and Reilly 2020; International Platform on Sustainable Finance 2023). The stakeholders implementing this action will need to include national financial regulators, expert groups and financial institutions. To improve taxonomy usability and data infrastructure, governments and central banks will need to provide targeted financial and capacity-building support to stakeholders most affected by the taxonomies in terms of adopting the use of circular economy metrics, data-collection and reporting processes.

Action 6: Establish a Global Circularity Fund to enable a just transition to circularity and to support developing countries in the transition

Leveraging circular economy finance to support Sustainable Development Goals implementation will be crucial to achieving socially inclusive development and supporting developing countries. Explicitly including nature-positive goals in a Global Circularity Fund framework would support developing countries in adopting regenerative bioeconomy practices. Several multilateral development banks have already established lending portfolios focused on the circular economy. For example, the European Investment Bank provided EUR 3.4 billion from 2018 to 2022 to co-finance 118 circular economy projects in a variety of sectors, including waste management, industry and services and the bioeconomy (European Investment Bank 2023). This amount is minimal compared to total financing of EUR 65.15 billion in 2022 (European Investment Bank 2022). Circular development finance needs to scale up further to support value-adding economic opportunities in sectors such as remanufacturing and refurbishment and the recovery, recycling and processing of secondary materials. The Global Environment Facility highlighted the circular economy in the GEF-7 strategy within the International Waters and the Chemicals and Waste focal areas, as well as within the Sustainable Cities Impact Program (Global Environment Facility 2018). The Global Environment Facility can assist developing country governments in creating the enabling environments for private-public partnerships and effective regulations and public services. Multilateral development finance needs to prioritize projects that contribute to inclusive circular development to create jobs, empower, and address social and environmental challenges, aligning with broader just-transition objectives and the Sustainable Development Goals. For example, the G20's Global Infrastructure Hub has identified circular infrastructure as one of its priorities and will need to develop appropriate financing instruments (Global Infrastructure Hub 2023). Furthermore, a global circularity fund could cover financing needs to address global plastic pollution and link to mechanisms such as a "polymer premium" – a small standardized fee imposed on producers of primary plastic polymers that would be used to fund waste management in developing countries (Minderoo Foundation 2024).

Action 7: Develop and implement disinvestment strategies to avoid linear stranded assets

Given that most finance continues to go towards linear extractive business models, lessons can be applied from the climate finance sector, such as disinvestment initiatives from fossil fuels (Plantinga and Scholtens 2021). Divestment should be considered a last resort; however, it may also be necessary for addressing challenges within the linear economy. New stranded asset classes are emerging, including plastics feedstock production, which carries high economic risks for banks that invest in companies that produce plastic (ClientEarth, 2022). Disinvestment strategies from business models of planned obsolescence and extractive sectors would need to complement the investments towards resource recovery businesses and manufacturers that design for product longevity. Potential changes in financial accounting will include adapting approaches to depreciation and residual value calculation for assets with multiple-use cycles.

15.2.4 Solution pathway 4: Reform of the international trade system

Achieving a near-zero waste circular economy will require significant changes in the international trade system. While local resource loops and circular solutions are essential, international trade of primary and secondary resources, goods and services remains crucial to meeting the demands of different countries and regions, ultimately enabling a more inclusive global circular economy.

Based on data from United Nations COMTRADE, the global value of trade in secondary materials, including

second-hand items, waste, scrap, and residues, increased from US$94 billion to US$302 billion between 2000 and 2020 (Chatham House, 2020). Circular trade encompasses any international trade transaction, either material or immaterial, that contributes to circular economy activities at the local, national and global levels. It includes trade in circular-economy-enabling goods, services and intellectual property; second-hand goods for reuse, repair, remanufacturing or recycling; refurbished and remanufactured goods; secondary raw materials (biotic and abiotic); and non-hazardous waste, scrap and residues (biotic and abiotic) that can be safely recovered or valorized (Barrie and Schröder 2022).

Circular trade offers many economic, environmental and social benefits. Trade in circular-economy-enabling goods, services and intellectual property allows countries and companies to access the necessary knowledge, skills and equipment to implement new circular business models or conduct reuse, repair, remanufacturing and recycling activities. Trade in used goods for reuse, repair or remanufacturing enables more affordable access to essential goods and services for those in secondary markets and generates local demand for industry and employment (Barrie et al. 2022). Trade in secondary raw materials and waste destined for recovery enables the aggregation of materials in areas of highest demand to maximize economies of scale, making it economically attractive to transform waste into resources for new production. Circular bioeconomy trade encompasses the exchange of biodiversity-positive goods and services, including products derived from regenerative agricultural practices and products contributing to ecosystem restoration.

However, poorly regulated trade in waste has negative implications. Many grey areas and loopholes currently exist in the global trading system, allowing for high levels of illicit waste shipments, resulting in pollution, and increasing human exposure to toxic chemicals. Illegal shipment of waste is a serious and growing crime globally (The International Criminal Police Organization [INTERPOL] 2020). It comes in many forms, including transporting waste through organized criminal networks, mixing different types of waste, declaring hazardous waste as non-hazardous, or classifying waste as second-hand goods (Tan et al. 2018; United Nations Office on Drugs and Crime [UNODC] 2022). While illicit waste trafficking generates an estimated US$10 billion to US$12 billion annually, the clean-up costs for local governments from waste crimes are often far higher (Financial Action Task Force 2021). Illegal waste shipments that manage to evade Customs inspections are commonly burned in open landfill sites or dumped in the environment, polluting air, waterways and soils and threatening the health of local communities.

In July 2017, China mandated a strict ban on waste imports for materials such as plastics, paper, glass, and even scrap metal (Ryter et al. 2021). Since 2018, countries in Southeast Asia, including Indonesia, Malaysia, Thailand and Viet Nam, have become the top destinations for both legal and illegal waste (UNODC 2024). Countries are taking unilateral action to tackle the issue. For example, in January 2025, Thailand banned the import of plastic waste, and Brazil banned the import of solid waste (Laville 2025; Baker McKenzie 2025).

Toxic e-waste is often shipped to developing countries where regulation is lax. China processed about 70 per cent of the world's e-waste in 2000; the rest went to India and other countries in Eastern Asia and Africa, including Ghana and Nigeria (Sun, Schnoor and Zeng 2022). The illegal export of e-waste from developed countries to developing countries poses significant environmental and health risks to humans. The World Health Organization has highlighted the serious health impacts of "digital dumpsites" and e-waste recycling on women and children, including adverse birth outcomes, impaired neurological development, and increased risks of cancer (World Health Organization 2024).

Trade in used linear goods can have mixed results and potential negative consequences, particularly for developing countries. High volumes of used goods can flood secondary markets, threatening local industries and overwhelming local waste management systems. Africa is the leading destination for second-hand textiles, with the Sub-Saharan region being the world's largest destination for second-hand clothing, receiving nearly 34 per cent of total world exports in 2021 (Fibre2fashion 2021). While it provides access to affordable clothing and creates job opportunities in trade, distribution, repairs, laundry services and upcycling, importing low-quality items has created a significant environmental challenge (Sumo et al. 2023). Overdependence on second-hand trade flows may also increase exposure to supply chain risks and shocks. As industrialized countries transition to a circular economy, the developing world continues to receive legacy second-hand goods created within the linear economy. Such trade risks locking

Credit: frimufilms/Envato

a domestic market into inefficient and hazardous products that potentially undermine local economic resilience and waste mitigation efforts.

A concerted global effort is therefore required to ensure the circular trade regime evolves in a way that fosters sustainable environmental outcomes, equity, inclusivity and mutually beneficial cooperation. The following steps and actions are proposed to overcome these challenges and create a circular trade system.

Action 1: Expand existing mechanisms and support long-term initiatives to tackle illegal waste trade

To genuinely tackle the trade in illegal waste, a long-term, well-resourced and globally coordinated approach to policing is necessary. Such an approach could build on the work by UNEP WasteForce (UNEP 2020b), the Green Customs Initiative and findings from the DEMETER Operation of the World Customs Organization (World Customs Organization [WCO] 2022). It would need to be coordinated by existing organizations working on the issue, including Europol, INTERPOL, the Secretariat of the Basel Convention, the UN Office on Drugs and Crime, UNEP and the WCO. Waste crime units require further funding and capacity-building to coordinate actions internationally and crack down on transnational criminal networks. Individual governments must also commit to promptly reporting incidents of illegal waste crime. Combating international waste trafficking will require mutual legal assistance, law enforcement cooperation and extraditions (UNODC 2022).

Action 2: Improve legal definitions, processes and procedures of the Basel Convention, such as the Prior Informed Consent procedure

At the global level, the Basel Convention, as a multilateral environmental agreement, has a particular focus on protecting human health and the environment by preventing shipments of hazardous waste from OECD to non-OECD countries. Several rules and procedures under the Basel Convention are ambiguous, and some Parties face challenges with domestic implementation, for example, in distinguishing the types of waste. The Basel Convention must establish clear legal definitions that distinguish between waste and secondary resources to ensure effective regulation and implementation. A key mechanism of the Basel

Convention for achieving transparent and effective transboundary shipments is the prior informed consent (PIC) procedure, which requires exporters of hazardous waste to obtain prior consent from the competent authority in the recipient country. Efforts are under way to develop a digital approach for PIC that would enhance certain aspects of the procedure, although additional measures will still be needed to address the remaining challenges. Building on existing efforts in this area, a dedicated capacity-building initiative is needed to support developing countries in establishing the necessary infrastructure, training and resources to implement and enforce PIC requirements effectively. Furthermore, national regulations need to align with international PIC requirements to prevent inconsistencies in waste classification and trade controls.

Action 3: Work towards internationally shared definitions for the trade of circular goods and services

Shared or mutually recognized definitions and classifications for circular goods are crucial for enabling efficient trade that supports the transition to a circular economy. Yet there remains an absence, or divergence in the interpretation, of definitions and classifications of goods in terms of their circularity (Barrie and Schröder 2022). International organizations like the World Trade Organization (WTO) and the International Trade Commission have important roles in ensuring that circular economy-relevant information is captured in transboundary trade flows in a way that is globally interoperable. The Harmonized System (HS) codes are a key pillar of the tariff infrastructure for international trade. These codes predate circular economy considerations and are currently considered limited for circular goods, requiring updates and improvement (UNECE 2022). As new circular product categories and innovations emerge in the coming years and decades, HS codes will need to be continuously revised. Alongside other measures, such as trade facilitation frameworks for recyclable goods and materials and new or revised classifications for circular-enabling goods, HS codes system reform will be a critical tool in scaling circularity at a global level (Barrie and Grooby 2023).

Action 4: Embed circularity and inclusivity within bilateral and regional trade and economic cooperation agreements

Bilateral and regional trade agreements are a potential vehicle for advancing the trade and circular economy agenda among willing trading partners (Yamaguchi, 2021). Embedding circularity across the full spectrum of trade and economic cooperation agreements will be necessary to transform the global trade system. Specific actions that governments can take in the short to medium term include strengthening the Trade and Sustainable Development chapters of trade agreements for circularity by including more explicit commitments to cooperation on circularity as an essential element of all future trade agreements (Blot and Watkins 2022). They can also encourage participation in the development and implementation of international circular economy standards, clarifying areas for mutual investment in the circular economy, such as preserving the right to establish non-discriminatory regulations and public procurement processes, as well as promoting best practices. Reducing tariffs on technologies essential for circular economy activities, such as advanced recycling, material recovery and pollution control, would be a critical step. These technologies, despite their substantial contribution to circularity, often face high import duties that hinder their wider deployment (Barrie et al. 2022; ISO 2022).

Action 5: Harmonizing different national standards and policies for product circularity

Diverse standards and definitions related to a circular economy impede trade and increase the cost of compliance of companies. The primary challenge in developing national circular economy standards and regulations is regulatory divergence and sometimes contradictory requirements across different jurisdictions. The classifications of hazardous waste, non-hazardous waste and non-waste goods destined for reuse, repair and refurbishment often differ from country to country. This divergence generates additional costs for companies and disincentivizes investment in circular solutions. This points towards mapping of national circular economy standards with implications for trade and countries moving towards greater alignment. Including a circular economy-related policy as an environmental category within the WTO notification system would help improve the mapping of circular economy standards and regulations. Building on the WTO's existing Trade and Environmental Sustainability Structured Discussions, where the circular economy is only covered by a

Credit: wirestock/Envato

working group, the WTO should raise the importance of circular trade by establishing a formal forum where countries can systematically and openly discuss and share circular policies (WTO 2025). Alongside this, support is required to build the capacity of countries to report more frequently and accurately on such policy developments (Barrie et al. 2022).

Action 6: Incentivize mining companies to channel traded materials into circular products and infrastructure by prioritizing the development of long-lasting material stocks

While the focus is currently on rents from the use of the products and materials, future value lies in building up a stock of materials over the coming decades in the built environment, infrastructure and technology assets. Circular trade will allow substantial resource stocks to accumulate, which in time could significantly increase in value and become traded commodities. Circular trade could alleviate the pressure of current mining companies focused on the extraction of natural resources and reduce dependence on primary raw materials. Shifts to materials and resource leasing models, as already practised for high-value materials such as platinum, could be applied to battery materials, ensuring materials return for recovery and reuse at the end of life. New materials-as-a-service models could encourage circularity and the building of stock across commodity value chains. It will require a commitment from product manufacturers to return these materials and components, and will motivate industrial design of finished goods with longer lifetimes (Mundell n.d.; Silverman 2024). Policies can incentivize mining sector actors through the adoption of performance-based contracts, where mining companies lease metals rather than sell them outright, or implementation of deposit-refund schemes, where companies recover financial guarantees if they retrieve and recycle materials at end of life. International resource leasing could contribute to transparent and accountable mineral resource governance (Hagan et al. 2021). Materials-as-a-service models would allow developing country governments and society more broadly to retain control over natural resources while providing incentives for stock management and circularity – thus enforcing circular economy practices along the value chain and promoting product innovation.

15.2.5 Solution pathway 5: Circular society pathway

Citizens play a critical role in creating a circular society (Jaeger-Erben et al. 2021; Böhm et al. 2023) due to their behaviour in purchasing, using and discarding products (EEA 2022). Unlike other stakeholders in product

value chains, such as manufacturers, distributors or recyclers, who are relatively predictable because they are strongly driven by monetary rewards and legislative requirements, consumer behaviour is more difficult to anticipate (Shevchenko et al. 2023). The habits and decisions of individuals are embedded in interconnected contexts, including infrastructure, costs, societal norms, and collective and individual values (UNEP 2020a).

Enhancing the capacity of individuals and households to use and preserve objects is relevant but insufficient, as it strips products out of their broader consumption context (Rinkinen and Shove, 2023). Where circular economy efforts are centred on the characteristics and life cycles of consumer goods, questions about the constitution of demand and likely longer-term trends risk being overlooked (Rinkinen, Shove and Marsden 2020). Consumer goods and other objects do not exist in isolation but are part of a broader material culture within a society (Rinkinen, Jalas, and Shove 2015). The meaning and role of objects are interwoven with their social and cultural valuation (Appadurai 1986). Patterns of consumption are rooted in social practices which in turn reproduce these practices of routinized behaviour (Warde 2005; Schatzki 2019). Social practices are a result of how materials and physical infrastructures link with non-material elements such as mental activities, social relations, states of emotion, understanding, know-how, and motivational knowledge (Haberl et al. 2021). Materials, meaning, and competence have been identified as three main types of elements here (Watson and Pantzar 2012), and social change will depend on their linkage in the given context. Cultural intermediaries like advertisers are crucial to shaping perceptions and aspirations beyond the material value of products and services (Kennedy and Givens 2019; Frig and Jaakkola 2023).

Opportunities for citizen participation and civic engagement at the local level can result in enhanced resource efficiency, increased transparency and community engagement promoting sustainable practices such as recycling and energy conservation (Belleville and Miller 2020). Grass-roots community initiatives empower citizens to change systems and strengthen local knowledge and the practices of Indigenous Peoples. Examples of existing collective circular initiatives by citizens include local repair cafés (Charter 2020; Moalem and Mosgaard 2021b), peer-to-peer swap and sharing initiatives (Henry et al. 2021), recycling social enterprises, and community composting (Marchesi and Tweed 2021). Some of these are oriented around social and solidarity economies that prioritize well-being and equity (Villalba-Eguiluz et al. 2023). These community initiatives can function as living laboratories to enable circularity at the local level and create groups of interest that can collectively overcome the constraints that individuals face (Hobson 2020).

Making products and resources circular is not necessarily equivalent to achieving lower material footprints as it can cause rebound effects (Zink and Geyer 2017; Ottelin, Cetinay and Behrens 2020). Material circularity, as such, does not offset the growing demand for goods and services driven by population growth and affluent lifestyles; consumers might even be inspired to buy more if they know there is a viable refurbishment or recycling route (Bocken, Niessen, and Short, 2022). Refurbishment, repair, take-back schemes and digital tools all have their own energy and resource needs. A truly transformative circular economy movement must counteract consumerism and prioritize the quality of life and social well-being by aiming to meet the need for a comfortable life while not needlessly striving to satisfy infinite human material wants (Niessen and Bocken 2021). Sufficiency, also referred to as living-well-on-less (Figge, Young and Barkemeyer 2014) or self-restraint consumption (Figge and Thorpe 2023), is a multi-dimensional challenge that comprises changes in societal values, attitudes, decisions and behavioural routines in everyday practices (Spangenberg and Lorek 2019). For example, if squandering resources became as socially stigmatized as cigarette smoking, less resource-intensive ways of signalling status would emerge (Spangenberg and Lorek 2019). A growing body of evidence suggests that high levels of human well-being can be achieved with lower resource use. Research shows that well-being gains saturate with rising energy and resource consumption (Steinberger and Roberts 2010). It is necessary to utilize well-being indicators to link the transition to circularity with societal transformation (Schröder, Lemille, and Desmond 2020; Velenturf and Purnell 2021).

The actions that follow will help ingrain the circular economy as an aspirational model for societies. They address circularity literacy (Actions 1, 2), infrastructures and materials to support circular behaviour (Actions 3, 4), the shaping of cultural values and social norms (Actions 5–8), and citizen empowerment (Actions 9).

Credit: JuiceFlair/Envato

Action 1: Integrate CE principles into educational curricula from primary schools through to tertiary institutions

Culturally appropriate education and awareness-raising play a crucial role in promoting sustainable practices. Historically, education has contributed to perpetuating the linear economy, promoting industrialization and consumption-driven lifestyles without sufficient consideration for environmental preservation (Jackson, 2009). A transition to a circular economy requires a fundamental shift in mindset and social practices, which can be achieved through education at different levels. Ministries of Education need to integrate circular economy principles into the educational curricula from primary schools through to tertiary institutions, and specialized teaching staff is needed. Funds for schools to implement circular economy activities support success, and the involvement of third parties, including parents, contributes to mainstreaming practices into the broader society and across generations. Circular economy education should be incorporated across disciplines, including economics, engineering and environmental sciences, as a way of preparing and equipping professions to work within the circular economy framework. Municipalities, non-governmental organizations and customary organizations of Indigenous Peoples and local communities can set up initiatives to enhance citizens' circular economy knowledge and public awareness by organizing collective workshops and providing culturally appropriate education materials (Scalabrino, Navarrete Salvador and Oliva Martínez 2022). Data from circularity monitoring is also required to inform citizens about the status of the shift towards a circular economy in their country, as well as specific topics (UNEP 2024b).

Action 2: Training and skills development for workers and citizens to create, use, maintain and repair circular products

More than one third of citizens in the European Union have never used repair services, and most have not rented, leased, or purchased second-hand products (European Commission et al., 2018). This reflects a broader global trend prevalent in consumer-driven economies. Reasons include not only a lack of information but also a lack of competency and specialist skills, inadequate infrastructure such as repair service points, and insufficiently developed markets for second-hand products or sharing services.

Chambers of commerce, professional networks, and ministries of small and medium-sized enterprises could set up training and certification programmes which can be linked to the development of entrepreneurial skills. Civil society initiatives also play a role in skills development, such as citizen-led repair cafés to promote community repair and, as a co-benefit, provide citizens with a voice in preventing waste and combating environmental degradation. The repair café movement has spread worldwide, with over 2,000 repair cafés now in 37 countries (Moalem and Mosgaard 2021a). The availability of spare parts at reasonable cost and product designs that offer repairability are key enablers to strengthen this movement further.

Action 3: Put in place enabling infrastructures for circular behaviour

Unlike the linear economy, where there is little consideration for how a product is used once purchased, the circular economy needs to factor in consumer behaviour along the product life cycle (Wastling, Charnley and Moreno 2018). Infrastructures integrate social, technical, economic and ecological systems and are key to shaping material flows, including those that influence daily life patterns (Nogueira et al., 2020). At a macro level, product take-back schemes enable circular behaviour, and public-private partnerships can leverage company financing and logistics. Experiences from the Japanese Sound Material-Cycle Society's efforts suggest local governments hold a key position in supporting pro-circular behaviour (Ministry of the Environment Japan 2014). For a successful transition at the local level, local governments can strengthen their capacity with trained professionals and adequate financial resources. Local governments also need to collaborate effectively with citizens and ensure easy and reliable access to repair, reuse or refill schemes, as well as sharing services and composting (Cohen and Kietzmann 2014; Kireeva et al. 2021). To explore infrastructural gaps and effectively co-create solutions, a quadruple helix approach (Hysa et al. 2020; Roman et al. 2020) is instrumental in bringing together civil society, local governments, businesses and the knowledge sector. Municipalities, Indigenous Peoples, local communities, women, youth or civil society organizations can lead these initiatives.

Action 4: Use digital technologies to provide life-cycle product information to consumers in easy-to-understand ways

Digital technologies can help validate the sustainability claims of products and shift consumer behaviour into a circular one (Sánchez-García et al. 2024). Governmental bodies such as ministries of industry can foster the development of digital product information and labels in an easy-to-understand way that is comfortably accessible for citizens, such as using QR codes. Independent third-party certification bodies need to ensure the transparency and accuracy of information to avoid greenwashing.

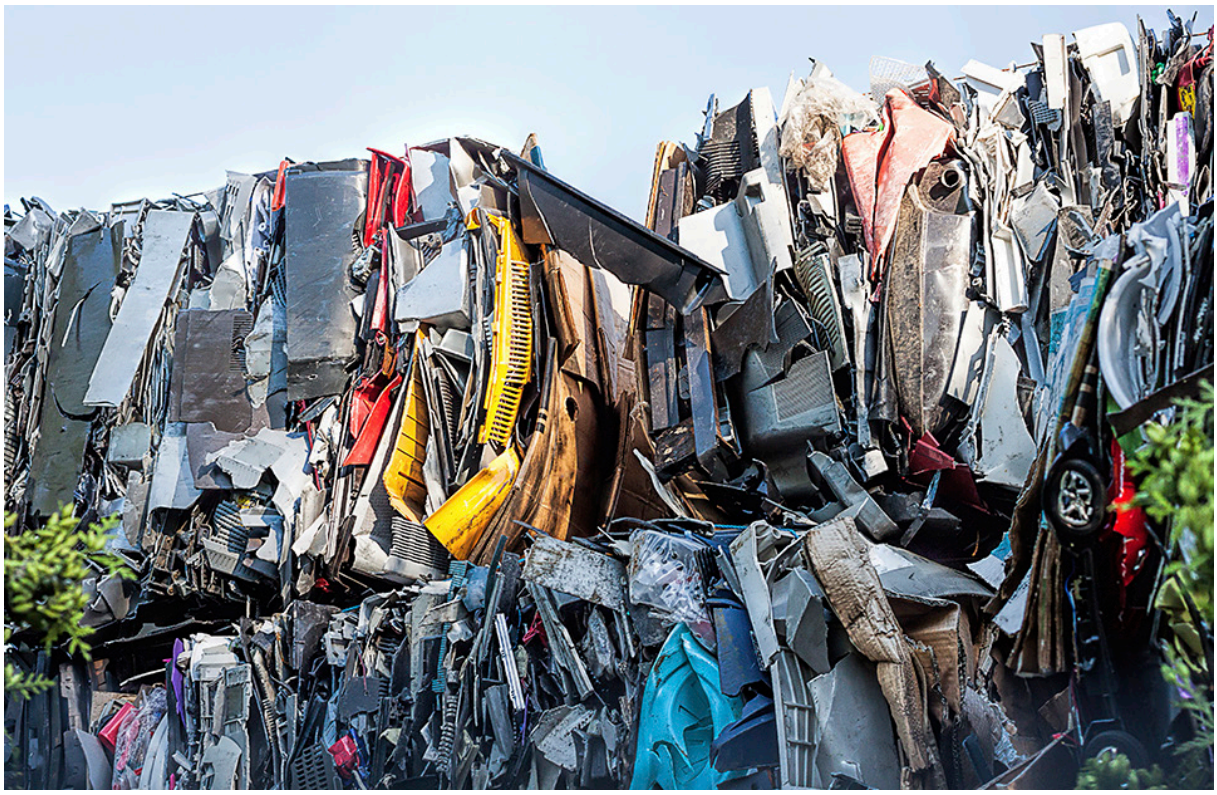
Action 5: Foster societal-wide dialogues on alternative social practices, culture and lifestyles, and support social innovation at the community level

For widespread societal embedding, including in multicultural areas, circular economy practices need to find their place in daily life among the manifold practices that compete for individuals' time and resources (Huber 2017). Engaging citizens in dialogues about lifestyles can be initiated both by civil society and the public sector to raise awareness and promote mindfulness about consumption patterns. This will play a crucial role in shaping cultural norms and values, as a collective shift would likely create a milieu that fosters circular principles (Kasser and Gonick 2018). Ultimately, this fosters policies and governance structures that shift from consumerism towards circularity.

Simultaneously, supporting social innovation – whether through financial incentives, policy support or knowledge-sharing – empowers citizens to have agency and influence when engaging in local collective action (Hoppe and Warbroek, 2021) and mobilizes society's creativity. These support measures are necessary for both start-ups and existing initiatives, including those that support Indigenous Peoples and local communities, as well as women and youth. Indigenous cultural and community-centred values, traditions such as resource sharing, and practices such as caring for nature offer lessons on how collective values and collaboration can support sustainability (Brondízio et al. 2021; Greene, Hobson and Jaeger-Erben 2024).

Action 6: Promote traditional practices and Indigenous Knowledge on lifestyles for well-being and sustainability

Indigenous sociobiocultural systems are rich in circular practices and innovations (Case Study 2). Understanding and integrating their principles, including the significant contributions of women, can strengthen the social, economic, customary and cultural pillars of a modern



Credit: ©UNEP

circular economy and promote the pursuit of well-being. The customary governance system, collective ownership and biocultural self-determination with participatory decision-making processes of Indigenous Peoples are important elements (Rai 2018). Indigenous Peoples are mostly collective, cosmologic, traditional and are more likely to consider the present and future impacts that their actions have on others and the environment, rather than focusing on immediate self-gratification or rewards. Practices that align with modern societies are more likely to be taken up across the broader non-Indigenous population. Such practices can be effectively promoted by non-governmental organizations, Indigenous institutions and academic entities.

Action 7: Develop communication strategies and campaigns that promote behaviour change, engage with cultural intermediaries and restrict advertising of linear products

A negative perception of a circular good or service, such as perceiving repaired products as lower quality or less fashionable, is a key barrier to the adoption of pro-circular practices (Houston et al. 2018). Looking at a product with some degree of favour or disfavour is a learned attitude, while perceptions express a person's beliefs about a product's characteristics (Muranko et al. 2019). These represent changeable evaluations and can be shaped through science-backed campaigns initiated by public bodies or non-governmental organizations to ensure credibility and effectiveness. Cultural intermediaries, such as advertisers and influencers, influence consumer perceptions of goods and practices that appear aspirational, and they are well-positioned to promote sustainable consumption choices among different societal groups.

Advertising exerts a profound influence on consumers' preferences for specific products and lifestyles (Vaughn 2000). Curbing the demand for environmentally detrimental products fosters a culture of sustainable consumption. Advertisements for linear products can be banned or organized in a way that communicates their harmful effects to consumers, for example, through successful laws against the advertisement of cigarettes (Kasza et al., 2011). Restricting advertising for high-impact linear product categories reduces the allure of these unsustainable choices and encourages producers to seek circular options in their processes as a way of leading the competition. Effective measures include legislative regulations related to advertising and for national advertising standards agencies to oversee the implementation. An internationally agreed list of harmful linear product categories would facilitate this action.

Action 8: Include circularity metrics and human well-being indicators into socioeconomic planning and participatory decision-making

Comprehensive circularity metrics and sound data are essential to support policy designs and decision-making and to inform citizens about the status of the shift towards the circular economy. Many varied indices and frameworks are used to capture circularity, with partially contradictory results (Corona et al. 2019). Efforts to consolidate approaches and make them policy-relevant are ongoing (UNEP, 2024b) and warrant a significant effort. Circularity metrics based solely on the degree of material recirculation are easier to apply and may play a significant role in increasing public awareness; however, they are not suitable for measuring the absolute decrease in resource use and do not accurately reflect sustainability (Corona et al. 2019). Currently, there is no comprehensive framework to assess the positive or negative social effects of circular economy strategies (Padilla-Rivera et al. 2021) and whether the shift to a circular economy is actually improving people's lives and well-being. More clarity is required on how to effectively integrate such indicators in social, economic and cultural planning, both at national and local levels. The well-being of vulnerable groups, including people with disabilities, must also be taken into account.

Action 9: Reward individuals for their active participation and engagement as consumers, citizens, workers, carers and community members

Consumer studies and behavioural research have shown that individuals are generally willing to engage in circular practices, such as repair, sharing and buying second-hand; however, in practice, the numbers are comparatively low (Trinomics 2018; Hobson 2020). Rewarding individuals for their active engagement increases their commitment and motivation (Korsunova, Horn and Vainio 2021), and both monetary and non-monetary reward schemes can be set up by local governments or civil society initiatives. An example is the Repair Bonus Policy introduced in Austria in 2023, where 50 per cent of the repair costs of electronics are covered by the Government's COVID Recovery Fund (Hoppe and Warbroek 2021; Bell 2023; Edler, Ostertag and Schuler 2023).

15.2.6 Combinations of solutions to achieve desired goals

The transformation from a linear to a circular economy involves implementing a range of subsystem level solutions and integrating various pathways to drive comprehensive system-wide change. This requires breaking down silos and fostering synergy between actions and approaches to achieve full system transformation, aligning with the four goals outlined in Section 15.1.2.

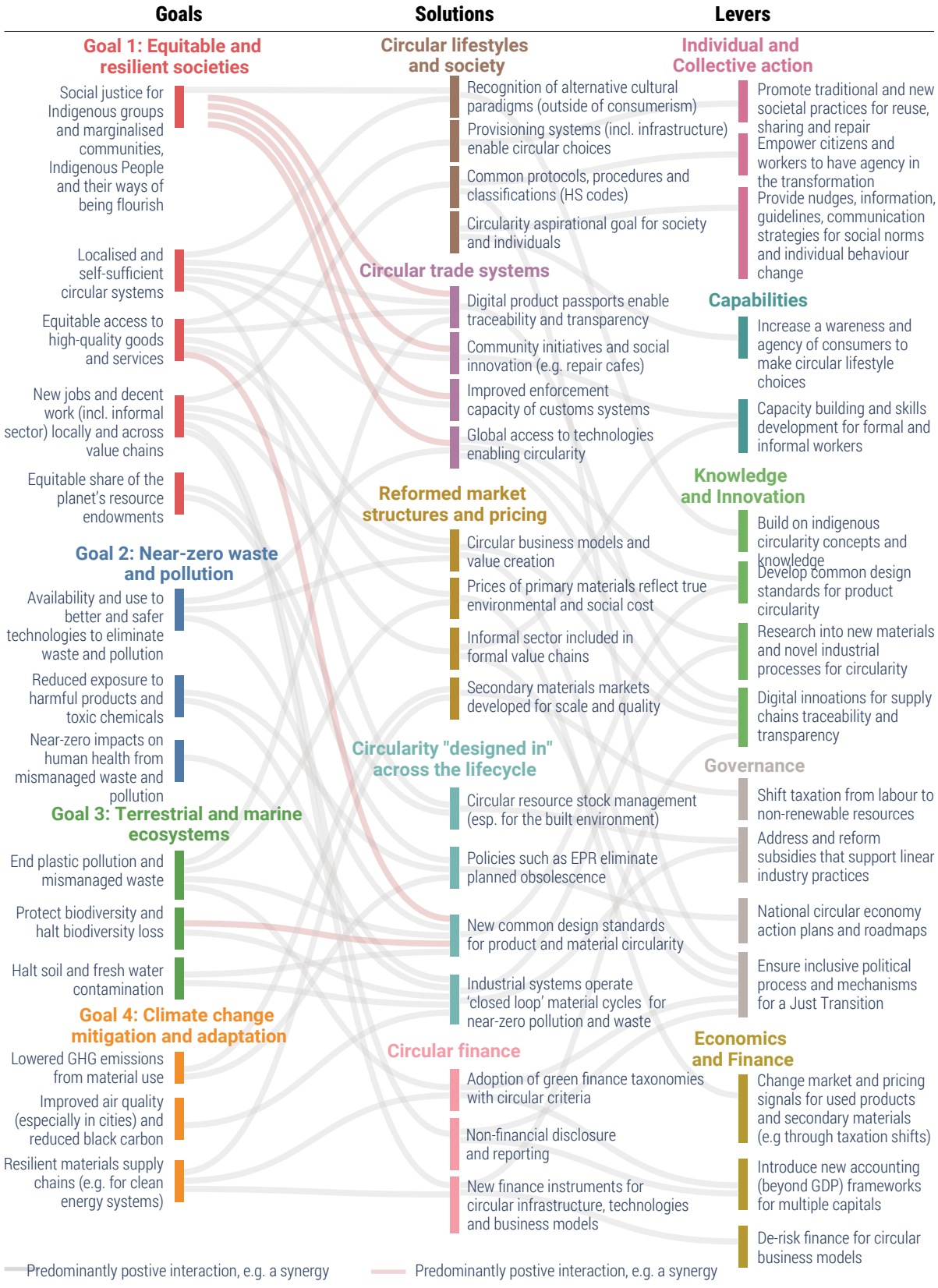
Based on the assessments of the experts involved in the GEO-7 process, the enabling conditions for this include, but are not limited to, a mutually reinforcing combination of cross-cutting levers and actions as follows:

1. setting prices to reflect full costs while mitigating impacts on low-income groups
2. using digital technologies such as digital product and material passports to enable traceability and data to establish and monitor full cost pricing
3. co-designing and implementing extended producer responsibility policies
4. harmonizing eco-design standards that assist intelligent assembly and disassembly of products, components and materials
5. de-risking investments in infrastructure, which supports reverse logistics and small businesses and local economies
6. promoting the rapid uptake and diffusion of technologies enabling circularity, especially for developing countries
7. building capacity of workers in informal sectors to reduce exposure to hazardous materials
8. empowering citizens and workers to have agency in the transition enables emergence of bottom-up solutions and local job creation
9. recognizing Indigenous rights and building on Indigenous circular knowledge systems will directly benefit communities and human beings

Cross-cutting solutions, such as international coordination on national circular economy action plans, trade agreements and capacity-building initiatives, ensure that the transition to a circular economy supports global development objectives and the Sustainable Development Goals. Additionally, including Indigenous Peoples, women, youth, and persons with disabilities in decision-making processes helps to foster

social justice and resilience, ensuring that circular systems benefit all. These levers and policy arenas reinforce each other and contribute to the four goals. Mixed interactions and potential trade-offs exist between actions that promote global circular trade and those that create localized circular economic systems. **Figure 15.7** provides more detail.

Figure 15.7: Simplified overview of interactions between levers, solutions and goals of the circular economy solution pathways and actions



15.3 Solutions case studies

The following two case studies were selected to highlight diverse approaches to the circular economy. China, as the world's second-largest economy, has a structured industrial circular economy policy, offering insights into large-scale implementation (**Box 15.1**).In contrast, the Indigenous case study showcases nature-based solutions, emphasizing regenerative practices (**Box 15.2**). While the circular economy spans many sectors and geographies, these examples illustrate both high-level industrial policyframeworks and community-driven models based on Indigenous Knowledge.

Box 15.1: Waste management and the zero-waste cities programme in China

China is not only the world's largest producer and consumer of electronics but also the most seriously polluted by illegal e-waste imports and informal recycling in the 1990s (Li et al. 2015). Historically, most e-waste was diverted into informal recycling channels, making it economically unviable for many formal companies to sustain operations based on the limited volumes they were able to collect and process. The efficiency and viability of formal recycling are subject to various national legislations, technical capacity and actual throughput, and consumer participation. The EPR principle is integrated through the old-for-new policy and the e-waste producer-pays funding (Zeng et al. 2017). Financial incentives are crucial to enable the flow of waste to the formal routes successfully.

The technical recycling process is crucial in achieving a high material recycling rate. After a two-decade journey, China has established more than 100 licensed companies engaged in high-quality e-waste dismantling and recycling lines for waste printed- circuit boards, liquid crystal displays, toner cartridges, computers and refrigerators. Substituting materials in electronics and reducing toxicity through green design and environmentally sound disposal are among the most impactful strategies for enhancing the recovery of secondary resources from e-waste. Enhancing eco-design and promoting design for recycling can be enabled through altering materials and components, developing longer-life and more durable equipment, and taking responsibility for safe recycling pathways. Formal recycling facilities are now available throughout the country, and informal e-waste recycling is shrinking. The national e-waste recycling rate in 2020 reached 40–50 per cent (Sun et al. 2022). Overall, the idea of "Control-Alt-Delete" (Li et al. 2015), which targets the combined effect of controlling waste flows, altering the characteristics of electronics, and deleting e-waste-related toxicity, has proved successful.

China also launched a Zero-waste City pilot programme in 2019, and this initiative expanded to more than 100 cities in 2022. The goal is to establish a sound circularity system to achieve fully environmentally sustainable cities by 2050. Under the Government's green development plan, the country has made significant progress in minimizing solid waste generation and maximizing waste recycling in urban areas. Since 2021, China has promulgated the Work Plan for Zero-waste Cities in the Fourteenth Five-Year Plan, which identifies 113 cities and 8 special zones as zero-waste cities. The Zero-waste City programme is considered one of the world's largest long-term recycling initiative, as well as the most extensive city-improvement programme (Lee et al. 2020).

Box 15.2: Circular practices used by Indigenous Peoples and traditional or local communities

Many circular practices exist in traditional and Indigenous communities and predate modern technologically oriented iterations of the circular economy. Indigenous practices – whether in building materials, such as Maasai huts made from natural resources and waste or resource-sharing systems – emphasize regeneration by ensuring cyclical use of resources without depleting ecosystems. Components of Indigenous socio-biocultural systems share principles that prioritize healthy socioeconomic, moral, ritual, spiritual, epistemological, lingual, sentimental, ethical, and ecological biocultural and customary relationships with "Mother Nature" and "Mother Earth", supported by appropriate ecological regeneration. These principles can inform a modern circular economy for the protection of biodiversity, lands, waters, territories of Indigenous Peoples, food, health systems and human well-being. Examples of Indigenous embedded relationships with natural systems can provide insights in understanding and informing circular economy transitions today. For instance, in the case of Hawaii, the concepts and practices meant by certain words – such as aloha for acknowledgement, āina for love of the land, and Ōiwi for native or durable values – can be taken as interventions that address the underdeveloped social and cultural pillars of the circular economy. Indigenous approaches to sustainability promote regenerative relationships, for example, the ancestral Hawaiian economic system that mirrored the natural structures of the water cycle (Beamer et al. 2023).

Credit: ©UNEP

Indigenous principles encompass a profound sense of unity and interconnectedness between nature and humans and emphasize the importance of giving back to nature. Indigenous practices, such as shifting cultivation and the rotation of cultivated plots of land – used to manage tropical forests in many regions of the world, including Africa, South and Southeast Asia, the Amazon and New Guinea – facilitate the natural regeneration of soils and vegetation (Mazzocchi 2020). In the Western Ghats of southern India, the traditional collection and production of non-timber forest products, such as wild species, honey, amla, soap, nuts and berries, are helping to ensure the management of forest resources in the reserve while sustaining the livelihoods of Indigenous communities (Craigen 2021).

In Asia, the Nepal Indigenism Mondhum Biocultural for Restoration and Biodiversity Conservation Initiative on Landscapes promotes customary governance and circular approaches to agroecology (Rai, 2023), aligning with the Kunming-Montreal Global Biodiversity Framework's Indigenous and traditional territories Target 3 in the National Biodiversity Strategy and Action Plan. Indigenous communities' resource and biobased material flows are mostly local or regional and organized in circular and regenerative patterns.

All ecological communities are defined and maintained through the cyclical exchange of resources among members, establishing collaborative relationships that encourage diversity and facilitate the sharing of abundance, maintaining systemic health (De Nardin 2022). Furthermore, Indigenous concepts and philosophies such as the African Ubuntu can provide alternative frameworks to address common global problems caused by linear extractive economies and their effects, such as climate change and environmental degradation (Van Niekerk 2022; Fernández 2022).

Ancestral multidimensional visions of circularity have guided many Indigenous Peoples' lifeways, values, spirituality, community structures and vernacular architecture. Maasai communities on the border of Kenya and the United Republic of Tanzania have lived off-grid for centuries and are one of the best examples of communities with circular ways of life. Traditional Maasai are semi-nomadic pastoralists who range cattle in the Dry Lands looking for fresh grazing. Maasai do not hunt or fish; they are deeply connected with their cattle herds and the arid or semi-arid landscapes, which provided for most of their needs before their traditional lifeways were disrupted by colonialism and climate change (Marty et al. 2023). Maasai living in rural areas use cattle dung as fuel, fertilizer and as a building material for their homes. A mixture of cow dung, urine, and natural materials is used to build their circular huts, known as manyatta. The dung plaster keeps the inside of the huts cool. More recently, waste plastic bottles have been used to reinforce the structures and offer additional rain protection (Kamweru 2023). Maasai bomas or villages are circular arrangements of manyatta huts around a central corral where cattle are kept and manure is stored. The circular arrangement of the huts fosters community-centred values of equality, and the bomas radiate outwards as families grow. The surrounding solid fences, made of thorny acacia tree branches, protect families and livestock from wildlife (Rukwaro and Mukono 2001).

Indigenous practices, such as traditional building design, can help restore degraded relationships between humans and nature. These ancestral frameworks highlight the importance of embedding reciprocity and restoration into economic systems, providing scalable models for modern regenerative development. However, the traditional way of life of the Maasai and many other Indigenous Peoples is increasingly under threat and will require active support to sustain and strengthen these practices within a modern circular economy framework.

15.4 Synergies and trade-off interactions with other systems

Energy system:

As highlighted by the Secretary-General's Panel on Critical Energy Transition Minerals (United Nations, 2024), the transition to a low-carbon energy system will require circular economy practices to avoid significant increases in extractive activities and waste generation, as well as a shortage of critical energy transition minerals. End-of-life solar photovoltaic panels, wind turbine blades, and electric vehicle batteries will become high-volume waste streams within the next two decades, and effective collection and recycling schemes and material valorization infrastructures are largely missing. Worldwide annual solar photovoltaic waste generation is estimated to increase from 0.3 million to 9.6 million tons between 2016 and 2050 (Chowdhury et al. 2020), and is projected to accumulate to between 60 million and 78 million tons by 2050 in the absence of recycling (Divya et al. 2023). Far greater advances are needed in the design of materials for disassembly and recyclability. For example, the carbon/glass-fibre-reinforced composite materials used in current wind turbine blades hinder any economically viable recycling (Khalid et al., 2023). End-of-life electric vehicle batteries present their own unique challenges, including the risk of fires in conventional e-waste recycling facilities, the rapid evolution of material compositions for new battery technologies, and highly variable market prices for recycled materials (Harper et al. 2019; Tembo, Dyer, and Subramanian 2024). Synergies with renewable energy deployment can be unlocked by repurposing electric vehicle batteries for stationary energy storage (Jaimes and Maroufi, 2020; Colarullo and Thakur,

2022). A decarbonized energy system and the circular economy have a critical synergistic potential through hydrogen because hydrogen availability and CO_2 valorization are intrinsically interlinked (Do et al. 2022). A wide variety of other circular economy technologies support energy security, such as the energetic valorization of residual plant biomass. For some, the full potential remains to be explored, including the generation of hydrogen from waste (Aziz, Darmawan, and Juangsa, 2021).

Food system:

Several circular solutions support food system transformation, including Indigenous food systems (Forest Peoples Programme 2016; Levkoe, Ray and McLaughlin 2019), food waste reduction (Vittuari et al. 2023), valorization for biofertilizers or upcycling into high-value biochemicals (Said et al. 2023; Patel et al. 2024; Aït-Kaddour et al. 2024), which enables nutrient cycling and the restoration of soil health (Villamagna, Angermeier and Bennett 2013; Palansooriya et al. 2023). Technologies such as black soldier fly bioconverters, which produce animal feed, support food security and the incomes of smallholder farmers (Mlambo et al. 2023). Regenerative agricultural practices and the repurposing of urban spaces for community agriculture are integral to the transition to a circular economy. The combinations of circular practices can also promote and revitalize Indigenous food and agricultural systems and customary practices.

Environment system:

The circular economy as an ecological transformation of the economic system promises both human well-being and the regeneration of environmental system (Jabbour et al. 2020; Yang et al. 2023). The circular economy in combination with a sustainable bioeconomy (Chapter 18) can benefit biodiversity and ecosystem health through three key mechanisms: the reduction of extraction and primary resource use, prevention of pollution by eliminating waste and use of hazardous substances and biodiversity-friendly sourcing of resources (Ellen MacArthur Foundation 2021a; Günther et al. 2023). The use of biobased materials as substitutes (Asgher et al. 2020) includes seaweed farming, which serves as a regenerative aquaculture practice that not only provides a sustainable source of food and biobased materials but also delivers nature-positive outcomes by enhancing marine biodiversity and improving water quality (White 2023). Furthermore, regenerative design approaches in the built environment can create nature-positive outcomes for environmental system.

However, reducing natural resource extraction is vital (UNEP 2024a). The efficiency of natural resource utilization, along with ecosystem restoration and regeneration, can be enhanced by implementing a circular bioeconomy (Abad-Segura et al. 2021). There are risks, however, that the shift to biobased resources creates additional pressures on the environmental system. The effects of the circular economy on biodiversity are still not well understood and are particularly challenging to assess (Ruokamo et al. 2023). The uptake of biomass to replace mineral resources is part of the circular economy, but this might imply deforestation and biodiversity decline, and the water needed for additional biomass growth could exceed sustainable supply levels (Giampietro and Funtowicz 2020). Among others, the circular bioeconomy utilizes biological processes to recover valuable materials, such as rare earth elements, from industrial and electronic waste through biomining (Opare, Struhs, and Mirkouei, 2021). Circular bioeconomy solutions, such as biogas generation from organic residues, are already widely adopted technologies to supply electricity, heat or other forms of energy. The circular bioeconomy also supports ecosystem health by making the best possible use of each unit of the conditionally renewable resource biomass, for example, through a cascading use of biological resources.

References

Abad-Segura, E., Batlles-delaFuente, A., González-Zamar, M.-D. and Belmonte-Ureña, L.J. (2021). Implications for Sustainability of the Joint Application of Bioeconomy and Circular Economy: A Worldwide Trend Study. Sustainability 13(13), 7182. https://doi.org/10.3390/su13137182

Abinandan, S. and Shanthakumar, S. (2015). Challenges and opportunities in application of microalgae (Chlorophyta) for wastewater treatment: A review. Renewable and Sustainable Energy Reviews 52(C), 123-132. https://doi.org/10.1016/j.rser.2015.07.086

Abuzied, H., Senbel, H., Awad, M. and Abbas, A. (2020). A review of advances in design for disassembly with active disassembly applications. Engineering Science and Technology, an International Journal 23(3), 618-624. https://doi.org/10.1016/j.jestch.2019.07.003

Adiansyah, J.S., Rosano, M., Vink, S. and Keir, G. (2015). A framework for a sustainable approach to mine tailings management: disposal strategies. Journal of Cleaner Production 108, 1050-1062. https://doi.org/10.1016/j.jclepro.2015.07.139

African Circular Economy Alliance (2021). Five big bets for the circular economy in Africa. https://www.weforum.org/publications/five-big-bets-for-the-circular-economy-in-africa-african-circular-economy-alliance/

Africa Circular Economy Facility Africa Circular Economy Facility. https://www.afdb.org/en/news-keywords/africa-circular-economy-facility-acef

African Union (2023). Summary of the African leaders Nairobi declaration on climate change and call to action. https://au.int/sites/default/files/documents/43682-doc-AU_Nairobi_Declaration_Action_1.pdf

Aït-Kaddour, A., Hassoun, A., Tarchi, I., Loudiyi, M., Boukria, O., Cahyana, Y. et al. (2024). Transforming plant-based waste and by-products into valuable products using various "Food Industry 4.0" enabling technologies: A literature review. Science of The Total Environment 955, 176872. https://doi.org/10.1016/j.scitotenv.2024.176872

Andersson, M., Ljunggren Söderman, M. and Sandén, B.A. (2019). Challenges of recycling multiple scarce metals: The case of Swedish ELV and WEEE recycling. Resources Policy 63, 101403. https://doi.org/10.1016/j.resourpol.2019.101403

Aparcana, S. (2017). Approaches to formalization of the informal waste sector into municipal solid waste management systems in low- and middle-income countries: Review of barriers and success factors. Waste Management 61, 593-607. https://doi.org/10.1016/j.wasman.2016.12.028

Appadurai, A. (1986). The Social Life of Things: Commodities in Cultural Perspective. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511819582

Aranda-Usón, A., Portillo-Tarragona, P., Marín-Vinuesa, L.M. and Scarpellini, S. (2019). Financial Resources for the Circular Economy: A Perspective from Businesses. Sustainability 11(3). https://doi.org/10.3390/su11030888

Arya, A. and Bhutani, A. (2023). Study on items shipped for reuse and extended producer responsibility fees. https://eeb.org/wp-content/uploads/2023/05/items-shipped-for-reuse-and-EPR-fees_EEB-2023-.pdf

Asgher, M., Qamar, S.A., Bilal, M. and Iqbal, H.M.N. (2020). Bio-based active food packaging materials: Sustainable alternative to conventional petrochemical-based packaging materials. Food Research International 137, 109625. https://doi.org/10.1016/j.foodres.2020.109625

Aurisano, N., Weber, R. and Fantke, P. (2021). Enabling a circular economy for chemicals in plastics. Current Opinion in Green and Sustainable Chemistry 31, 100513. https://doi.org/10.1016/j.cogsc.2021.100513

Aziz, M., Darmawan, A. and Juangsa, F.B. (2021). Hydrogen production from biomasses and wastes: A technological review. International Journal of Hydrogen Energy 46(68), 33756-33781. https://www.sciencedirect.com/science/article/pii/S0360319921029189

Baker McKenzie (2025). Brazil: National Solid Waste Policy is amended to ban the import of solid waste, with exceptions. https://insightplus.bakermckenziecom/bm/environment-climate-change_1/brazil-national-solid-waste-policy-is-amended-to-ban-the-import-of-solid-waste-with-exceptions

Balanay, R. and Halog, A. (2021). A Review of Reductionist versus Systems Perspectives towards 'Doing the Right Strategies Right' for Circular Economy Implementation. Systems 9 (2). https://doi.org/10.3390/systems9020038

Baloyi, R.B., Gbadeyan, O.J., Sithole, B. and Chunilall, V. (2023). Recent advances in recycling technologies for waste textile fabrics: a review. Textile Research Journal 94(3-4), 508-529. http://dx.doi.org/10.1177/00405175231210239

Barrie, J. and Grooby, G. (2023). Going circular. Berlin: pertext. https://library.fes.de/pdf-files/international/20579.pdf

Barrie, J., Latif, L.A., Albaladejo, M., Barsauskaite, I., Kravchenko, A., Kuch, A. et al. (2022). Trade for an inclusive circular economy. Chatham House. https://www.chathamhouse.org/sites/default/files/2022-06/2022-06-15-inclusive-circular-trade-barrie-et-al.pdf

Barrie, J., Salminen, I., Schroeder, P. and Stucki, J. (2024). National circular economy roadmaps: A global stocktake 2024. Vienna: UNIDO. https://www.unido.org/sites/default/files/unido-publications/2024-05/UNIDO_National%20circular%20economy%20roadmaps_v07.pdf

Barrie, J. and Schröder, P. (2022). Circular Economy and International Trade: a Systematic Literature Review. Circular Economy and Sustainability 2(2), 447-471. https://link.springer.com/article/10.1007%2Fs43615-021-00126-w

Beamer, K., Elkington, K., Souza, P., Tuma, A., Thorenz, A., Köhler, S. et al. (2023). Island and Indigenous systems of circularity: how Hawai'i can inform the development of universal circular economy policy goals. Ecology and Society 28(1). https://doi.org/10.5751/ES-13656-280109

Bell, B. (2023). 'Austrian government launches repair scheme for electronic goods'. BBC https://www.bbc.com/news/world-europe-67777814

Accessed 12 august 2025

Belleville, A.D. and Miller, L. (2020). Involving citizens in circular economy. Interreg Europe CECI and European Union. https://projects2014-2020.interregeurope.eu/fileadmin/user_upload/tx_tevprojects/library/file_1617012842.pdf

Blot, E. and Watkins, E. (2022). Trade in support of circular economy. Institute European Environmental Policy. https://ieep.eu/wp-content/uploads/2022/12/CE-and-trade_Synthesis-report.pdf

Bocken, N.M.P., de Pauw, I., Bakker, C. and Van der Grinten, B. (2016). Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering 33(5), 308-320. https://www.researchgate.net/publication/309699661_Product_design_and_business_model_strategies_for_a_circular_economy

Bocken, N.M.P., Niessen, L. and Short, S.W. (2022). The Sufficiency-Based Circular Economy—An Analysis of 150 Companies. Frontiers in Sustainability 3. https://doi.org/10.3389/frsus.2022.899289

Böhm, S., Ho, C., Holmes, H., Manolchev, C., Rödl, M. and Spekkink, W. (2023). 14 Circular society activism: prefigurative communities in everyday Circular Economy action. Handbook of the Circular Economy. Allen, A., Stefano, P. and Fiona, C. (eds.). Berlin, Boston: De Gruyter. https://api.pageplace.de/preview/DT0400.9783110723373_A46699962/preview-9783110723373_A46699962.pdf

Bour, A., Budde Christensen, T., Hunka, A.D., Palmqvist, A., Skjold, E. and Syberg, K. (2023). Implications of circular textile policies for the future regulation of hazardous substances in textiles in the European Union. Science of The Total Environment 896, 165153. https://doi.org/10.1016/j.scitotenv.2023.165153

Bragança, L., Griffiths, P., Askar, R., Salles, A., Ungureanu, V., Tsikaloudaki, K. et al. (2025). Circular economy design and management in the built environment. Springer Cham. https://pure.ulster.ac.uk/en/publications/circular-economy-design-and-management-in-the-built-environment-a

Braz, A.C. and Marotti de Mello, A. (2022). Circular economy supply network management: A complex adaptive system. International Journal of Production Economics 243, 108317. https://doi.org/10.1016/j.ijpe.2021.108317

Breschi, T. (2024). Germany's 2024 national circular economy strategy: A path to sustainability and growth. https://www.revalu.io/journal/germanys-2024-national-circular-economy-strategy-a-path-to-sustainability-and-growth

Brondízio, E.S., Aumeeruddy-Thomas, Y., Bates, P., Carino, J., Fernández-Llamazares, Á., Ferrari, M.F. et al. (2021). Locally Based, Regionally Manifested, and Globally Relevant: Indigenous and Local Knowledge, Values, and Practices for Nature. Annual Review of Environment and Resources 46, 481-509. https://doi.org/10.1146/annurev-environ-012220-012127

Brown, A. and Börkey, P. (2024). Extended producer responsibility in the garments sector. OECD Environment Working Papers 253. https://dx.doi.org/10.1787/8ee5adb2-en

Buch, R., Marseille, A., Williams, M., Aggarwal, R. and Sharma, A. (2021). From Waste Pickers to Producers: An Inclusive Circular Economy Solution through Development of Cooperatives in Waste Management. Sustainability 13(16), 8925. https://doi.org/10.3390/su13168925

Bucknall, D.G. (2020). Plastics as a materials system in a circular economy. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 378(2176), 20190268. https://doi.org/10.1098/rsta.2019.0268

Capodaglio, A.G. (2023). Biorefinery of Sewage Sludge: Overview of Possible Value-Added Products and Applicable Process Technologies. Water 15(6), 1195. https://doi.org/10.3390/w15061195

Capra, F. and Jakobsen, O.D. (2017). A conceptual framework for ecological economics based on systemic principles of life. International Journal of Social Economics 44(6), 831-844. https://doi.org/10.1108/IJSE-05-2016-0136

Centobelli, P., Cerchione, R., Vecchio, P.D., Oropallo, E. and Secundo, G. (2022). Blockchain technology for bridging trust, traceability and transparency in circular supply chain. Information & Management 59(7), 103508. https://doi.org/10.1016/j.im.2021.103508

Charter, M. (2019). Designing for the Circular Economy. Routledge. https://www.routledge.com/Designing-for-the-Circular-Economy/Charter/p/book/9781138081017#

Charter, M. (2020). Repair Cafés: Implementing Circular Economy Innovation (Impact). University for Creative Arts. https://research.uca.ac.uk/id/eprint/5589

Chatham House, T.R.I.o.I.A. (2020). Circular economy.earth. https://circulareconomy.earth/trade

Chen, D.M.-C., Bodirsky, B.L., Krueger, T., Mishra, A. and Popp, A. (2020). The world's growing municipal solid waste: trends and impacts. Environmental Research Letters 15(7), 074021. https://dx.doi.org/10.1088/1748-9326/ab8659

Chen, Z., Feng, Q., Yue, R., Chen, Z., Moselhi, O., Soliman, A. et al. (2022). Construction, renovation, and demolition waste in landfill: a review of waste characteristics, environmental impacts, and mitigation measures. Environmental Science and Pollution Research 29(31), 46509-46526. https://doi.org/10.1007/s11356-022-20479-5

Chertow, M.R. (2000). INDUSTRIAL SYMBIOSIS: Literature and Taxonomy. Annual Review of Environment and Resources 25, 313-337. https://doi.org/10.1146/annurev.energy.25.1.313

Chertow, M.R. and Ashton, W. (2009). Chapter 6: The Social Embeddedness of Industrial Symbiosis Linkages in Puerto Rican Industrial Regions. https://doi.org/10.4337/9781848449060.00015

Choo, G., Wang, W., Cho, H.-S., Kim, K., Park, K. and Oh, J.-E. (2020). Legacy and emerging persistent organic pollutants in the freshwater system: Relative distribution, contamination trends, and bioaccumulation. Environment International 135, 105377. https://doi.org/10.1016/j.envint.2019.105377

Choudhury, R.R., Islam, A.F. and Sujauddin, M. (2024). More than Just a Business Ploy? Greenwashing as a Barrier to Circular Economy and Sustainable Development: a Case Study-Based Critical Review. Circular Economy and Sustainability 4(1), 233-266. https://doi.org/10.1007/s43615-023-00288-9

Chowdhury, M.S., Rahman, K.S., Chowdhury, T., Nuthammachot, N., Techato, K., Akhtaruzzaman, M. et al. (2020). An overview of solar photovoltaic panels' end-of-life material recycling. Energy Strategy Reviews 27, 100431. https://doi.org/10.1016/j.esr.2019.100431

Churkina, G., Organschi, A. and Reyer, C.P.O. (2020). Buildings as a global carbon sink. https://doi.org/10.1038/s41893-019-0462-4

Circle Economy (2022). Roadmap Circular Finance 2030. https://assets-global.website-files.com/5d26d80e8836af2d12ed1269/620118bd0e16dd0ade090748_20220202%20-%20PDF%20Finance%20Roadmap%20-%20Digest%20EN.pdf

ClientEarth (2022). World's top banks risk billions by investing in plastics – new report. https://www.clientearth.org/latest/press-office/press/world-s-top-banks-risk-billions-by-investing-in-plastics-new-report/#:~:text=The%20report%2C%20from%20Belgian%20sustainable,petrochemical%20companies%20INEOS%20and%20Borealis

Climate Leadership Council (2024). Carbon dividends. https://clcouncil.org/our-solutions/carbon-dividends/. Accessed: 15 October 2024

Coady, D., Parry, I., Le, N.-P. and Shang, B. (2019). Global Fossil Fuel Subsidies Remain Large: An Update Based on Country-Level Estimates. IMF Working Papers 19, 1. https://doi.org/10.5089/9781484393178.001

Cohen, B. and Kietzmann, J. (2014). Ride On! Mobility Business Models for the Sharing Economy. Organization & Environment 27(3), 279-296. https://doi.org/10.1177/1086026614546199.

Colarullo, L. and Thakur, J. (2022). Second-life EV batteries for stationary storage applications in Local Energy Communities. Renewable and Sustainable Energy Reviews 169, 112913. https://doi.org/10.1016/j.rser.2022.112913

Community Wealth Building (2021). Community wealth building: a history. https://cles.org.uk/wp-content/uploads/2021/08/CWB-a-history-FINAL2.pdf

Corona, B., Shen, L., Reike, D., Rosales Carreón, J. and Worrell, E. (2019). Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. Resources, Conservation and Recycling 151, 104498. https://doi.org/10.1016/j.resconrec.2019.104498.

Cottom, J.W., Cook, E. and Velis, C.A. (2024). A local-to-global emissions inventory of macroplastic pollution. Nature 633(8028), 101-108. https://doi.org/10.1038/s41586-024-07758-6

Craigen, A. (2021). For a truly circular economy, we need to listen to indigenous voices. https://www.undp.org/blog/truly-circular-economy-we-need-listen-indigenous-voices2023

De Angelis, R. (2022). Circular economy business models as resilient complex adaptive systems. Business Strategy and the Environment 31(5), 2245-2255. https://doi.org/10.1002/bse.3019

De Nardin, A.C.F. (2022). Relações entre biomimética, pensamento sistêmico e conhecimento ecológico tradicional: Um guia para tomada de decisões arquitetônicas regenerativas. UNIVERSIDADE FEDERAL DE SANTA MARIA http://repositorio.ufsm.br/handle/1/28305

De Sadeleer, N. (2020). Environmental law principles: From political slogans to legal rules. Oxford University Press. https://global.oup.com/academic/product/environmental-law-principles-9780198844358?cc=us&lang=en&

Dewick, P., Bengtsson, M., Cohen, M.J., Sarkis, J. and Schröder, P. (2020). Circular economy finance: Clear winner or risky proposition? Journal of Industrial Ecology 24(6), 1192-1200. https://doi.org/10.1111/jiec.13025

Dewick, P., de Mello, A.M., Sarkis, J. and Donkor, F.K. (2022). The puzzle of the informal economy and the circular economy. Resources, Conservation and Recycling 187, 106602. https://doi.org/10.1016/j.resconrec.2022.106602

Divya, A., Adish, T., Kaustubh, P. and Zade, P.S. (2023). Review on recycling of solar modules/panels. Solar Energy Materials and Solar Cells 253, 112151. https://doi.org/10.1016/j.solmat.2022.112151.

Do, N.T.Q., Haag, S., Castillo-Weltter, F. and Gunther, A. (2022). Flexible and Sustainable Methanol Production Including Option with Green Hydrogen. Computer Aided Chemical Engineering 49, 775-780. https://doi.org/10.1016/B978-0-323-85159-6.50129-9

Domenech, T., Bleischwitz, R., Doranova, A., Panayotopoulos, D. and Roman, L. (2019). Mapping Industrial Symbiosis Development in Europe_ typologies of networks, characteristics, performance and contribution to the Circular Economy. Resources, Conservation and Recycling 141, 76-98. https://doi.org/10.1016/j.resconrec.2018.09.016

Domenech, T. and Ekins, P. (2019). Making Materials Work for Life – Introducing Producer Ownership. Systemiq (ed.). https://www.systemiq.earth/wp-content/uploads/2020/02/Producer-Ownership-Project-LAUNCH-White-Paper.pdf

Driver, J.G., Bernard, E., Patrizio, P., Fennell, P.S., Scrivener, K. and Myers, R.J. (2024). Global decarbonization potential of CO2 mineralization in concrete materials. Proceedings of the National Academy of Sciences 121(29), e2313475121. https://doi.org/10.1073/pnas.2313475121

Dunant, C.F., Joseph, S., Prajapati, R. and Allwood, J.M. (2024). Electric recycling of Portland cement at scale. Nature 629(8014), 1055-1061. https://doi.org/10.1038/s41586-024-07338-8

Edler, J., Ostertag, K. and Schuler, J. (2023). Social innovation, transformation, and public policy: towards a conceptualization and critical appraisal. Science and Public Policy 51(1), 80-88. https://doi.org/10.1093/scipol/scad054

Ellen MacArtchur Foundation (2020). Financing the circular economy: Capturing the opportunity. https://bbia.org.uk/wp-content/uploads/2020/12/Financing-the-circular-economy.pdf

Ellen MacArtchur Foundation (2021a). The Nature Imperative: How the circular economy tackles biodiversity loss. https://www.ellenmacarthurfoundation.org/biodiversity-report

Ellen MacArtchur Foundation (2024). An innovation pathway to decarbonization: circular economy solutions for policymakers and industry in the US. https://www.oliverwyman.com/content/dam/oliver-wyman/v2/publications/2024/apr/an-innovation-pathway-to-decarbonization-circular-economy-solutions-for-policymakers-and-industry-in-the-US.pdf

Ellen MacArthur Foundation (2015). Growth within: A circular economy vision for a competitive Europe. https://www.ellenmacarthurfoundation.org/growth-within-a-circular-economy-vision-for-a-competitive-europe.

Ellen MacArthur Foundation (2017). A New Textiles Economy: Redesigning fashion's future. https://www.ellenmacarthurfoundation.org/a-new-textiles-economy

Engels, J., Schönhardt, M., Witt, K.J., Benkovics, I., Berta, Z., Csövári, M. et al. (2004). Tailings management facilities - intervention actions for risk reduction. European Research and Technological Development Project Report. https://www.tailsafe.com/pdf-documents/TAILSAFE_Intervention_Actions.pdf

Esposito, E., Dellamuzia, L., Moretti, U., Fuoco, A., Giorno, L. and Jansen, J. (2019). Simultaneous production of biomethane and food grade CO2 from biogas: An industrial case study. Energy & Environmental Science 12, 281-289. https://doi.org/10.1039/C8EE02897D

European Comission (2023a). Batteries. https://environment.ec.europa.eu/topics/waste-and-recycling/batteries_en. Accessed: 1 September 2024.

European Comission (2023b). ICT task force study. https://op.europa.eu/en/publication-detail/-/publication/6d2b8bb5-1627-11ee-806b-01aa75ed71a1/language-en

European Comission (2024). Ecodesign for Sustainable Products Regulation. https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/ecodesign-sustainable-products-regulation_en

European Commission (2018). Assessment of measures to reduce marine litter from single use plastics – Final report and annex. Publications Office. https://doi.org/10.2779/500175

European Commission, Consumers, H.A., Food Executive, A., Cerulli-Harms, A., Porsch, L., Suter, J. et al. (2018). Behavioural study on consumers' engagement in the circular economy – Executive summary. https://data.europa.eu/doi/10.2818/921596

European Economic Area (2023). Economic instruments and separate collection systems — key strategies to increase recycling. https://www.eea.europa.eu/publications/economic-instruments-and-separate-collection Accessed: 18 October 2024

European Environment Agency (2022). Expanding the knowledge base around the role of consumers in the circular economy. https://www.eea.europa.eu/publications/influencing-consumer-choices-towards-circularity/role-of-consumers-in-the-ce

European Environment Agency (2023). The benefits to biodiversity of a strong circular economy. https://www.eea.europa.eu/publications/the-benefits-to-biodiversity

European Investment Bank (2022). The EIB in numbers. https://www.eib.org/en/about/key-figures/index#:~:text=Financial%20Report%202022,EIB%20and%20the%20EIB%20Group

European Investment Bank (2023). Circular economy overview 2023. https://www.eib.org/en/projects/topics/energy-natural-resources/circular-economy/index.htm

Ferasso, M., Beliaeva, T., Kraus, S., Clauss, T. and Ribeiro-Soriano, D. (2020). Circular economy business models: The state of research and avenues ahead. Business Strategy and the Environment 29(8), 3006-3024. https://doi.org/10.1002/bse.2554

Fernandes, S.d.C., Pigosso, D.C.A., McAloone, T.C. and Rozenfeld, H. (2020). Towards product-service system oriented to circular economy: A systematic review of value proposition design approaches. Journal of Cleaner Production 257, 120507. https://doi.org/10.1016/j.jclepro.2020.120507

Fernández, L.G.G. (2022). Toward the production of contextual built environments: Unfolding building materials' sociocultural meanings in a Maasai community. https://doi.org/10.51303/jtbau.vi3.610

Ferraz, D. and Pyka, A. (2023). Circular economy, bioeconomy, and sustainable development goals: a systematic literature review. Environmental Science and Pollution Research. https://doi.org/10.1007/s11356-023-29632-0

Fibre2fashion.com Second-hand clothing in Africa: Opportunities and challenges. https://static.fibre2fashion.com/articleresources/PdfFiles/94/Second-hand%20clothing%20in%20Africa%20Opportunities%20and%20challenges_9387.PDF

Figge, F. and Thorpe, A.S. (2023). Circular economy, operational eco-efficiency, and sufficiency. An integrated view. Ecological Economics 204, 107692. https://doi.org/10.1016/j.ecolecon.2022.107692

Figge, F., Young, C. and Barkemeyer, R. (2014). Sufficiency or efficiency to achieve lower resource consumption and emissions? The role of the rebound effect. Journal of Cleaner Production 69, 216–224. https://doi.org/10.1016/j.jclepro.2014.01.031

FinanCE (2018). Circular Economy Finance Guidelines. https://circulareconomy.europa.eu/platform/en/toolkits-guidelines/circular-economy-finance-guidelines

Financial Action Task Force (2021). Money Laundering from Environmental Crime. https://www.fatf-gafi.org/content/dam/fatf-gafi/reports/Money-Laundering-from-Environmental-Crime.pdf

Forest Peoples Programme (2016). Annual Review 2026. http://www.forestpeoples.org/sites/default/files/documents/fppreview2016internet.pdf

Frig, M. and Jaakkola, M. (2023). Between conspicuous and conscious consumption: The sustainability paradox in the intermediary promotional work of an online lifestyle site. Journal of Consumer Culture 24(1), 3-23. https://doi.org/10.1177/14695405231170684

Fuller, R., Landrigan, P.J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M. et al. (2022). Pollution and health: a progress update. The Lancet Planetary Health 6(6), e535-e547. https://doi.org/10.1016/S2542-5196(22)00090-0

Garrido-Hidalgo, C., Ramirez, F.J., Olivares, T. and Roda-Sanchez, L. (2020). The adoption of internet of things in a circular supply chain framework for the recovery of WEEE: the case of lithium-ion electric vehicle battery packs. Waste Management 103, 32-44. https://doi.org/10.1016/j.wasman.2019.09.045

Gebremariam, A.T., Di Maio, F., Vahidi, A. and Rem, P. (2020). Innovative technologies for recycling End-of-Life concrete waste in the built environment. Resources, Conservation and Recycling 163, 104911. https://doi.org/10.1016/j.resconrec.2020.104911

Geerts, R., Vandermoere, F. and Oosterlynck, S. (2020). The Functionality of Dissimilarity: Pro-Environmental Behavior through Heterogenous Networks. Social Sciences 9(12), 221. https://doi.org/10.3390/socsci9120221

Geissdoerfer, M., Morioka, S.N., de Carvalho, M.M. and Evans, S. (2018). Business models and supply chains for the circular economy. Journal of Cleaner Production 190, 712-721. https://doi.org/10.1016/j.jclepro.2018.04.159Geissdoerfer, M., Pieroni, M.P.P., Pigosso, D.C.A. and Soufani, K. (2020). Circular business models: A review. Journal of Cleaner Production 277, 123741. https://doi.org/10.1016/j.jclepro.2020.123741

Geng, Y., Sarkis, J. and Bleischwitz, R. (2023). How to build a circular economy for rare-earth elements. Nature. https://www.nature.com/articles/d41586-023-02153-z

Ghisellini, P., Cialani, C. and Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner Production 114, 11-32. https://doi.org/10.1016/j.jclepro.2015.09.007

Giampietro, M. and Funtowicz, S.O. (2020). From elite folk science to the policy legend of the circular economy. Environmental Science & Policy 109, 64-72. https://doi.org/10.1016/j.envsci.2020.04.012

Global Environment Facility (2018). Circular Economy. https://www.thegef.org/sites/default/files/publications/GEF%20Assembly_CircularEconomy%20Factsheet_6.19.18.pdf

Global Infrastructure Hub (2023). Advancing the circular economy through infrastructure. https://cdn.gihub.org/umbraco/media/5488/gi-hub-advancing-circular-economy-through-infrastructure-dec2023.pdf

Global Tailings Review (2020). Global industry standard on tailings management. https://globaltailingsreview.org/wp-content/uploads/2020/08/global-industry-standard_EN.pdf

Golinska-Dawson, P., Zysnarska, Z. and Pender, A. (2024). Assessment of the maturity of product-as-a-service business models for household appliances from the perspective of R strategies in Circular Economy. Procedia CIRP 122, 1083-1088. https://doi.org/10.1016/j.procir.2024.02.038

Gómez-Sanabria, A., Kiesewetter, G., Klimont, Z., Schoepp, W. and Haberl, H. (2022). Potential for future reductions of global GHG and air pollutants from circular waste management systems. Nature Communications 13(1), 106. https://doi.org/10.1038/s41467-021-27624-7

Good Things Foundation (2023). Public sector pioneers: Reusing IT equipment to bridge the digital divide. https://www.goodthingsfoundation.org/policy-and-research/research-and-evidence/research-2024/public-sector-reusing-tech-for-social-good

Göswein, V., Carvalho, S., Cerqueira, C. and Lorena, A. (2022). Circular material passports for buildings – Providing a robust methodology for promoting circular buildings. IOP Conference Series: Earth and Environmental Science 1122(1), 012049. https://iopscience.iop.org/article/10.1088/1755-1315/1122/1/012049

Government of Brazil (2022). National solid waste plan. https://www.fao.org/faolex/results/details/en/c/LEX-FAOC209254/

Government of China (2022). Measures for the prevention and control of environmental pollution caused by tailings. https://www.fao.org/faolex/results/details/en/c/LEX-FAOC209006

Greene, M., Hobson, K. and Jaeger-Erben, M. (2024). Bringing the circular economy home – Insights from socio-technical perspectives on everyday consumption. Cleaner and Responsible Consumption 12, 100157. https://doi.org/10.1016/j.clrc.2023.100157

Greenhouse Gas Protocol (2013). Scope 3 calculation guidance. https://ghgprotocol.org/sites/default/files/2023-03/Scope3_Calculation_Guidance_0%5B1%5D.pdf.

Groothuis, F. (2014). New era. New plan. Fiscal reforms for an inclusive, circular economy. Case study the Netherlands. https://ex-tax.com/wp-content/uploads/2019/09/The_Extax_Project_New_Era_New_Plan_report.pdf

Groothuis, F. (2022). The Taxshift: An EU Fiscal Strategy to Support the Inclusive Circular Economy. https://ex-tax.com/taxshift/

Gsell, M., Fischer, S., Müller, A., Rose, C., Sebis, G., Wilts, H. et al. (2024). Erarbeitung einer Messmethodik zum Umfang der Wiederverwendung von Produkten in Deutschland. https://www.umweltbundesamt.de/publikationen/erarbeitung-einer-messmethodik-umfang-der

Günther, J., Manshoven, S., Paleari, S., Fuchs, G., Carré, A. and Fischer-Bogason, R. (2023). ETC/CE Report 2023/7 Circular Economy and Biodiversity. https://www.eionet.europa.eu/etcs/etc-ce/products/etc-ce-report-2023-7-circular-economy-and-biodiversity#:~:text=This%20ETC%20CE%20report%20provides,(europa.eu)%22

Gupta, S. (2012). Integrating the informal sector for improved waste management. https://www.nswai.org/docs/Integrating%20the%20informal%20sector%20for%20improved%20waste%20management.pdf

Haberl, H., Schmid, M., Haas, W., Wiedenhofer, D., Rau, H. and Winiwarter, V. (2021). Stocks, flows, services and practices: Nexus approaches to sustainable social metabolism. Ecological Economics 182, 106949. https://doi.org/10.1016/j.ecolecon.2021.106949

Hagan, A.J., Tost, M., Inderwildi, O.R., Hitch, M. and Moser, P. (2021). The license to mine: Making resource wealth work for those who need it most. Resources Policy 74, 101418. https://doi.org/10.1016/j.resourpol.2019.101418

Hakanen, E. and Rajala, R. (2018). Material intelligence as a driver for value creation in IoT-enabled business ecosystems. Journal of Business & Industrial Marketing 33(6), 857-867. https://doi.org/10.1108/JBIM-11-2015-0217

Hannan, M.A., Abdulla Al Mamun, M., Hussain, A., Basri, H. and Begum, R.A. (2015). A review on technologies and their usage in solid waste monitoring and management systems: Issues and challenges. Waste Management 43, 509-523. https://doi.org/10.1016/j.wasman.2015.05.033

Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R. et al. (2019). Recycling lithium-ion batteries from electric vehicles. Nature 575(7781), 75-86. https://doi.org/10.1038/s41586-019-1682-5

He, M., Wu, H., & Zhang, Y. (2016). Effects of heavy metals on aquatic organisms. Environmental Science and Pollution Research 23(22), 22356-22367

Henry, M., Schraven, D., Bocken, N., Frenken, K., Hekkert, M. and Kirchherr, J. (2021). The battle of the buzzwords: A comparative review of the circular economy and the sharing economy concepts. Environmental Innovation and Societal Transitions 38, 1-21. https://doi.org/10.1016/j.eist.2020.10.008

Hicks, R. (2024). Recycled plastic at virgin prices? Asian recyclers say market volatility making it hard to meet brands' demands. https://www.eco-business.com/news/recycled-plastic-at-virgin-prices-asian-recyclers-say-market-volatility-making-it-hard-to-meet-brands-demands/

Hobson, K. (2020). Beyond the consumer: enlarging the role of the citizen in the circular economy. Handbook of the Circular Economy: Edward Elgar Publishing. https://EconPapers.repec.org/RePEc:elg:eechap:18519_36

Hogland, W., Marques, M. and Nimmermark, S. (2004). Landfill mining and waste characterization: a strategy for remediation of contaminated areas. Journal of Material Cycles and Waste Management 6(2), 119-124. https://doi.org/10.1007/s10163-003-0110-x

Höglund-Isaksson, L., Gómez-Sanabria, A., Klimont, Z., Rafaj, P. and Schöpp, W. (2020). Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe –results from the GAINS model. Environmental Research Communications 2(2), 025004. https://doi.org/10.1088/2515-7620/ab7457

Hoornweg, D., Bhada-Tata, P. and Kennedy, C. (2013). Environment: Waste production must peak this century. Nature 502(7473), 615-617. https://doi.org/10.1038/502615a

Hoosain, M.S., Paul, B.S., Kass, S. and Ramakrishna, S. (2023). Tools Towards the Sustainability and Circularity of Data Centers. Circular Economy and Sustainability 3(1), 173-197. https://doi.org/10.1007/s43615-022-00191-9.

Hoppe, T. and Warbroek, B. (2021). Agency of citizen collectives in sustainable transitions: The case of renewable energy cooperatives in Europe. Research handbook of sustainability agency 180-196. https://doi.org/10.4337/9781789906035.00018

Houston, J., Casazza, E., Briguglio, M. and Spiteri, J. (2018). Stakeholder views report : enablers and barriers to a circular economy. https://www.um.edu.mt/library/oar/handle/123456789/45816

Huber, A. (2017). Theorising the dynamics of collaborative consumption practices: A comparison of peer-to-peer accommodation and cohousing.

Environmental Innovation and Societal Transitions 23, 53-69. https://doi.org/10.1016/j.eist.2016.12.001

Hysa, E., Kruja, A., Rehman, N.U. and Laurenti, R. (2020). Circular Economy Innovation and Environmental Sustainability Impact on Economic Growth: An Integrated Model for Sustainable Development. Sustainability 12(12), 4831. https://doi.org/10.3390/su12124831

Iacovidou, E., Hahladakis, J.N. and Purnell, P. (2021). A systems thinking approach to understanding the challenges of achieving the circular economy. Environmental Science and Pollution Research 28(19), 24785-24806. https://doi.org/10.1007/s11356-020-11725-9

Intergovernmental Platform for Biodiversity and Ecosystem Services (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S.D. and Ngo, H.T. (eds.). Bonn, Germany, IPBES Secretariat, https://zenodo.org/record/6417333

International Accounting Standards Board (2021). Conceptual Framework for Financial Reporting. https://www.ifrs.org/content/dam/ifrs/publications/pdf-standards/english/2021/issued/part-a/conceptual-framework-for-financial-reporting.pdf

International Energy Agency (2023). Critical Minerals Market Review 2023. Paris. https://www.iea.org/reports/critical-minerals-market-review-2023.

International Energy Agency (2024). Global Critical Minerals Outlook. Paris https://www.iea.org/reports/global-critical-minerals-outlook-2024

International Energy Agency (2025). Interim Provisions on the Traceability Management of Power Battery Recycling in New Energy Vehicles. Paris. https://www.iea.org/policies/24953-interim-provisions-on-the-traceability-management-of-power-battery-recycling-in-new-energy-vehicles.

International Finance Corporations (2023). Building green. https://www.ifc.org/content/dam/ifc/doc/2023/building-green-sustainable-construction-in-emerging-markets.pdf

International Platform on Sustainable Finance (2023). International Platform on Sustainable Finance: Annual Report 2023. https://finance.ec.europa.eu/system/files/2023-12/231204-ipsf-annual-report_en.pdf

International Platform Sustainable Finance (2023). Common Ground Taxonomy: Technical Criteria Development. https://finance.ec.europa.eu/document/download/6a2df4d7-887a-40fe-9b09-b63394c656db_en?filename=241113-common-ground-taxonomy-instruction-report_en.pdf

International Resource Panel (2020). Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future. Nairobi, Kenya: International Resource Panel. United Nations Environment Programme. https://www.resourcepanel.org/reports/resource-efficiency-and-climate-change

International Solid Waste Association (2016). Waste Management Outlook for Mountain Regions - Sources and Solutions. https://www.iswa.org/closing-the-worlds-biggest-dumpsites-task-force/?v=518f4a738816

International Solid Waste Association (2021). The future of the waste management sector: Trends, opportunities and challenges for the decade 2021-2030. https://www.iswa.org/wp-content/uploads/2022/06/ISWA-Digital-Future-of-Waste-Management-Sector.pdf

INTERPOL (2020). INTERPOL report alerts to sharp rise in plastic waste crime. https://www.interpol.int/en/News-and-Events/News/2020/INTERPOL-report-alerts-to-sharp-rise-in-plastic-waste-crime

Interreg Europe (2024). Sustainable and circular construction. https://www.interregeurope.eu/find-policy-solutions/policy-briefs/sustainable-circular-construction

Intesa San Paolo (2022). Support to the Circular Economy. https://group.intesasanpaolo.com/en/sustainability/support-to-esg-transition/support-to-circular-economy.

Iranmanesh, M., Maroufkhani, P., Asadi, S., Ghobakhloo, M., Dwivedi, Y.K. and Tseng, M.L. (2023). Effects of supply chain transparency, alignment, adaptability, and agility on blockchain adoption in supply chain among SMEs. Computers and Industrial Engineering 176. https://doi.org/10.1016/j.cie.2022.108931

ISO (2022). Circular economy - The role of conformity assessment. https://www.iso.org/files/live/sites/isoorg/files/store/en/PUB100471.pdf

ISO (2024). Circular economy — Vocabulary, principles and guidance for implementation. https://www.iso.org/obp/ui/en/#iso:std:iso:59004:ed-1:v1:en

Jabbour, C.J.C., Fiorini, P.d.C., Wong, C.W.Y., Jugend, D., Jabbour, A.B.L.d.S., Seles, B.M.R.P. et al. (2020). First-mover firms in the transition towards the sharing economy in metallic natural resource-intensive industries: implications for the circular economy and emerging industry 4.0 technologies. Resources Policy 66, 1-13. https://doi.org/10.1016/j.resourpol.2020.101596

Jackson, T. (2009). Prosperity Without Growth? The Transition to a Sustainable Economy. https://www.sd-commission.org.uk/data/files/publications/prosperity_without_growth_report.pdf

Jaeger-Erben, M., Jensen, C., Hofmann, F. and Zwiers, J. (2021). There is no sustainable circular economy without a circular society. Resources, Conservation and Recycling 168, 105476. https://doi.org/10.1016/j.resconrec.2021.105476

Jaimes, W. and Maroufi, S. (2020). Sustainability in steelmaking. Current Opinion in Green and Sustainable Chemistry 24, 42-47. https://doi.org/10.1016/j.cogsc.2020.01.002

Jaureguiberry, P., Titeux, N., Wiemers, M., Bowler, D.E., Coscieme, L., Golden, A.S. et al. (2022). The direct drivers of recent global anthropogenic biodiversity loss. Science Advances 8(45), eabm9982. https://www.science.org/doi/abs/10.1126/sciadv.abm9982

Jawad, Z.N. and Balázs, V. (2024). Machine learning-driven optimization of enterprise resource planning (ERP) systems: a comprehensive review. Beni-Suef University Journal of Basic and Applied Sciences 13(1), 4. https://doi.org/10.1186/s43088-023-00460-y

Kaack, L.H., Donti, P.L., Strubell, E., Kamiya, G., Creutzig, F. and Rolnick, D. (2022). Aligning artificial intelligence with climate change mitigation. Nature Climate Change 12(6), 518-527. https://doi.org/10.1038/s41558-022-01377-7

Kaewunruen, S., Guo, Y., Jing, G. and Matsumoto, A. (2023). Circular economy implementation in railway systems beyond net zero. https://doi.org/10.3389/fbuil.2023.1239740

Kalra, R., Gaur, S. and Goel, M. (2021). Microalgae bioremediation: A perspective towards wastewater treatment along with industrial carotenoids production. Journal of Water Process Engineering 40, 101794. https://doi.org/10.1016/j.jwpe.2020.101794

Kamweru, G.N. (2023). An analogy of Indigenous and contemporary landscape urbanism in Kenya: Samburu settlements vs Swahili villas. https://www.ajlajournal.org/articles/an-analogy-of-indigenous-and-contemporary-landscape-urbanism-in-kenya Accessed: 22 October 2024.

Kasser, T. and Gonick, L. (2018). Hyper-capitalism: The modern economy, its values, and how to change them. https://thenewpress.com/books/hypercapitalism

Kasza, K.A., Hyland, A.J., Brown, A., Siahpush, M., Yong, H.-H., McNeill, A.D. et al. (2011). The Effectiveness of Tobacco Marketing Regulations on Reducing Smokers' Exposure to Advertising and Promotion: Findings from the International Tobacco Control (ITC) Four Country Survey. International Journal of Environmental Research and Public Health 2

Kaza, S., Yao, L.C., Bhada-Tata, P. and Van Woerden, F. (2018). What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Urban Development. https://datatopics.worldbank.org/what-a-waste/

Kennedy, E.H. and Givens, J.E. (2019). Eco-habitus or Eco-powerlessness? Examining Environmental Concern across Social Class. Sociological Perspectives 62(5), 646-667. https://doi.org/10.1177/0731121419836966

Khalid, M.Y., Arif, Z.U., Hossain, M. and Umer, R. (2023). Recycling of wind turbine blades through modern recycling technologies: A road to zero waste. Renewable Energy Focus 44, 373-389. https://doi.org/10.1016/j.ref.2023.02.001

Khan, S., Anjum, R., Raza, S.T., Ahmed Bazai, N. and Ihtisham, M. (2022). Technologies for municipal solid waste management: Current status, challenges, and future perspectives. Chemosphere 288, 132403. https://doi.org/10.1016/j.chemosphere.2021.132403

Khawer, M.U.B., Naqvi, S.R., Ali, I., Arshad, M., Juchelková, D., Anjum, M.W. et al. (2022). Anaerobic digestion of sewage sludge for biogas & biohydrogen production: State-of-the-art trends and prospects. Fuel 329, 125416. https://doi.org/10.1016/j.fuel.2022.125416

Kirchherr, J., Yang, N.-H.N., Schulze-Spüntrup, F., Heerink, M.J. and Hartley, K. (2023). Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions. Resources, Conservation and Recycling 194, 107001. https://doi.org/10.1016/j.resconrec.2023.107001

Kireeva, N., Zavyalov, D., Saginova, O. and Zavyalova, N. (2021). Car Sharing Market Development in Russia. Transportation Research Procedia 54, 123-128. https://doi.org/10.1016/j.trpro.2021.02.055

Knowledge Hub (2020). Cooperative El Álamo: Informal recyclers ('waste pickers') cooperative in Buenos Aires. https://knowledge-hub.circle-economy.com/article/7031?n=Cooperative-El-%C3%81lamo-Informal-recyclers-(%27waste-pickers%27)-cooperative-in-Buenos-Aires-

Korhonen, J., Honkasalo, A. and Seppälä, J. (2018). Circular Economy: The Concept and its Limitations. Ecological Economics 143, 37-46. https://doi.org/10.1016/j.ecolecon.2017.06.041

Korsunova, A., Horn, S. and Vainio, A. (2021). Understanding circular economy in everyday life: Perceptions of young adults in the Finnish context. Sustainable Production and Consumption 26, 759-769. https://doi.org/10.1016/j.spc.2020.12.038

Kossoff, D., Dubbin, W.E., Alfredsson, M., Edwards, S.J., Macklin, M.G. and Hudson-Edwards, K.A. (2014). Mine tailings dams: Characteristics, failure, environmental impacts, and remediation. Applied Geochemistry 51, 229-245. https://doi.org/10.1016/j.apgeochem.2014.09.010

Krstić, M., Agnusdei, G.P., Miglietta, P.P., Tadić, S. and Roso, V. (2022). Applicability of Industry 4.0 Technologies in the Reverse Logistics: A Circular Economy Approach Based on COmprehensive Distance Based RAnking (COBRA) Method. Sustainability 14(9). https://doi.org/10.3390/su14095632

Kunz, N., Mayers, K. and Van Wassenhove, L. (2018). Stakeholder Views on Extended Producer Responsibility and the Circular Economy. California Management Review 60, 000812561775269. https://journals.sagepub.com/doi/10.1177/0008125617752694

Labaran, Y.H., Mathur, V.S. and Farouq, M.M. (2021). The carbon footprint of construction industry: A review of direct and indirect emission. Journal of Sustainable Construction Materials and Technologies 6(3), 101-115. https://doi.org/10.29187/jscmt.2021.66

Lamont, D. (2021). Investing in natural capital: Benefits and barriers. https://mybrand.schroders.com/m/84e4ad2332bfc9bf/original/2021-Nov-Investing-in-natural-capital-DL.pdf

Landrigan, Philip J et al. (2025) The Lancet Countdown on health and plastics; The Lancet, Volume 0, Issue 0 . https://doi.org/10.1016/S0140-6736(25)01447-3

Laville, S. (2025). 'Thailand bans imports of plastic waste to curb toxic pollution'. The Guardian https://www.theguardian.com/environment/2025/jan/07/thailand-bans-imports-plastic-waste-curb-toxic-pollution

Lawlor, E. and Spratt, S. (2021). Circular investment: A review of global spending and barriers to increasing it. Chatham House. https://static.resourcetrade.earth/JE-07-Circular-Economy-Report-vf.pdf

Lee, R.P., Meyer, B., Huang, Q. and Voss, R. (2020). Sustainable waste management for zero waste cities in China: potential, challenges and opportunities. Clean Energy 4(3), 169-201. https://doi.org/10.1093/ce/zkaa013

Levkoe, C., Ray, L. and McLaughlin, J. (2019). The Indigenous Food Circle: Reconciliation and Resurgence through Food in Northwestern Ontario. Journal of Agriculture, Food Systems, and Community Development 9(B), 101-114. https://doi.org/10.5304/jafscd.2019.09B.008

Li, J., Zeng, X., Chen, M., Ogunseitan, O.A. and Stevels, A. (2015). "Control-Alt-Delete": Rebooting Solutions for the E-Waste Problem. Environmental Science & Technology 49(12), 7095-7108. https://doi.org/10.1021/acs.est.5b00449

Lifset, R., Kalimo, H., Jukka, A., Kautto, P. and Miettinen, M. (2023). Restoring the incentives for eco-design in extended producer responsibility: The challenges for eco-modulation. Waste Management 168, 189-201. https://doi.org/10.1016/j.wasman.2023.05.033

Lisiecki, M., Damgaard, A., Ragaert, K. and Astrup, T.F. (2023). Circular economy initiatives are no guarantee for increased plastic circularity: A framework for the systematic comparison of initiatives. Resources, Conservation and Recycling 197, 107072. https://doi.org/10.1016/j.resconrec.2023.107072

Lottermoser, B. (2010). Mine wastes: Characterization, treatment and environmental impacts. Berlin, Heidelberg, New York: Springer.

Lybæk, R., Christensen, T.B. and Thomsen, T.P. (2021). Enhancing policies for deployment of Industrial symbiosis – What are the obstacles, drivers and future way forward? Journal of Cleaner Production 280, 124351. https://doi.org/10.1016/j.jclepro.2020.124351

Maalouf, A. and Mavropoulos, A. (2022a). Re-assessing global municipal solid waste generation. Waste Management & Research 41, 936 - 947. https://doi.org/10.1177/0734242X221074116

Maalouf, A. and Mavropoulos, A. (2022b). Re-assessing global municipal solid waste generation. Waste Manag Res 41(4), 936-947. https://doi.org/10.1177/0734242X221074116

Mair, J., & Reilly, K. (2020). Artificial Intelligence and Machine Learning for Sustainable Finance: Advancing Circular Economy Metrics. Journal of Financial Innovation 12(4), 289-304.

Maiurova, A., Kurniawan, T.A., Kustikova, M., Bykovskaia, E., Othman, M.H.D., Singh, D. et al. (2022). Promoting digital transformation in waste collection service and waste recycling in Moscow (Russia): Applying a circular economy paradigm to mitigate climate change impacts on the environment. Journal of Cleaner Production 354, 131604. https://doi.org/10.1016/j.jclepro.2022.131604

Mallick, P.K., Salling, K.B., Pigosso, D.C.A. and McAloone, T.C. (2023). Closing the loop: Establishing reverse logistics for a circular economy, a systematic review. Journal of Environmental Management 328, 117017. https://doi.org/10.1016/j.jenvman.2022.117017

Mallick, P.K., Salling, K.B., Pigosso, D.C.A. and McAloone, T.C. (2024). Designing and operationalising extended producer responsibility under the EU Green Deal. Environmental Challenges 16, 100977. https://doi.org/10.1016/j.envc.2024.100977

Marchesi, M. and Tweed, C. (2021). Social innovation for a circular economy in social housing. Sustainable Cities and Society 71, 102925. https://doi.org/10.1016/j.scs.2021.102925

Marini, E. (2024). Recycled cotton: what it is and all the advantages of this fabric. https://rifo-lab.com/en/blogs/rifo-stories/recycled-cotton-what-it-is-and-all-the-advantages-of-this-fabric?srsltid=AfmBOopiOfwnFngKvqPUwMGnid2igoSi40XFmqZ_V6x8PunvWRWBXH-w Accessed: 6 October 2024

Marty, E., Bullock, R., Cashmore, M., Crane, T. and Eriksen, S. (2023). Adapting to climate change among transitioning Maasai pastoralists in southern Kenya: an intersectional analysis of differentiated abilities to benefit from diversification processes. The Journal of Peasant Studies 50(1), 136-161. https://doi.org/10.1080/03066150.2022.2121918

Mazzocchi, F. (2020). A deeper meaning of sustainability: Insights from Indigenous Knowledge. The Anthropocene Review 7(1), 77-93. https://doi.org/10.1177/2053019619898888

Mc Donough, W. and Braungart, M. (2002). Cradle to Cradle: Remaking the Way We Make Things. https://mcdonough.com/writings/cradle-cradle-remaking-way-make-things/

Mendez Alva, F., De Boever, R. and Van Eetvelde, G. (2021). Hubs for Circularity: Geo-Based Industrial Clustering towards Urban Symbiosis in Europe. Sustainability 13(24). https://doi.org/10.3390/su132413906

Menegaki, M. and Damigos, D. (2018). A review on current situation and challenges of construction and demolition waste management. Current Opinion in Green and Sustainable Chemistry 13, 8-15. https://doi.org/10.1016/j.cogsc.2018.02.010

Milios, L. (2021). Towards a Circular Economy Taxation Framework: Expectations and Challenges of Implementation. Circular Economy and Sustainability 1. https://doi.org/10.1007/s43615-020-00002-z

Miller, D. and Hansen, J. (2019). Why Fee and Dividend will Reduce Emissions Faster Than Other Carbon Pricing Policies. https://csas.earth.columbia.edu/sites/default/files/content/Fee-and-Dividend-Miller-Hansen-20191110-1.pdf

Minderoo Foundation (2024). The polymer premium: A free plastic pollution. https://cdn.minderoo.org/content/uploads/2024/04/21232940/The-Polymer-Premium-a-Fee-on-Plastic-Pollution.pdf

Ministerium of Transport Baden-Württemberg (2022). Roadmap ReFuels Baden-Württemberg. https://vm.baden-wuerttemberg.de/fileadmin/

redaktion/m-mvi/intern/Dateien/PDF/221215_ReFuels_BW_Broschuere_web.pdf

Ministry of Environment and Forest and Climate Change, Government of India (2011). Implementation of E-Waste Rules. https://cpcb.nic.in/displaypdf.php?id=aHdtZC9JbXBsaW1lbnRhdGlvbkUtV2FzdGUucGRm#:~:text=The%20E%2Dwaste%20(Management%20%26,higher%20pollution%20and%20less%20recovery%2C

Ministry of the Environment Japan (2014). History and current state of waste management in Japan. https://www.env.go.jp/content/900453392.pdf

Ministry of Environment, Rwanda and United Nations Development Programme (2022). Rwanda National Circular Economy Action Plan and Roadmap. https://www.environment.gov.rw/index.php?e ID=dumpFile&t=f&f=58556&token=1efafef04395aa568ceac5346426c5d29864bced

Mlambo, V., Dibakoane, S.R., Mashiloane, T., Mukwevho, L., Wokadala, O.C. and Mnisi, C.M. (2023). Rethinking food waste: Exploring a black soldier fly larvae-based upcycling strategy for sustainable poultry production. Resources, Conservation and Recycling 199, 107284. https://doi.org/10.1016/j.resconrec.2023.107284

Moalem, R. and Mosgaard, M. (2021a). A Critical Review of the Role of Repair Cafés in a Sustainable Circular Transition. Sustainability 13, 12351. https://doi.org/10.3390/su132212351

Moalem, R.M. and Mosgaard, M.A. (2021b). A Critical Review of the Role of Repair Cafés in a Sustainable Circular Transition. Sustainability 13(22). https://doi.org/10.3390/su132212351

Mohamad, N., Muthusamy, K., Embong, R., Kusbiantoro, A. and Hashim, M.H. (2022). Environmental impact of cement production and Solutions: A review. Materials Today: Proceedings 48, 741-746. https://doi.org/10.1016/j.matpr.2021.02.212.

Monteiro, J. and Roussanaly, S. (2022). CCUS scenarios for the cement industry: Is CO_2 utilization feasible? Journal of CO2 Utilization 61, 102015. https://doi.org/10.1016/j.jcou.2022.102015

Mor, S. and Ravindra, K. (2023). Municipal solid waste landfills in lower- and middle-income countries: Environmental impacts, challenges and sustainable management practices. Process Safety and Environmental Protection 174, 510-530. https://doi.org/10.1016/j.psep.2023.04.014

Moreno, M., De los Rios, C., Rowe, Z. and Charnley, F. (2016). A Conceptual Framework to Circular Design 8(9), 937. https://doi.org/10.3390/su8090937

Morseletto, P. (2020). Restorative and regenerative: Exploring the concepts in the circular economy. Journal of Industrial Ecology 24(4), 763-773. https://doi.org/10.1111/jiec.12987

Mortensen, L. and Kørnøv, L. (2019). Critical factors for industrial symbiosis emergence process. Journal of Cleaner Production 212, 56-69. https://doi.org/10.1016/j.jclepro.2018.11.222

Mundell, I. (n.d.) Materials as a service. https://www.imperial.ac.uk/Stories/materials-as-a-service/ Accessed: 21 March 2025

Muranko, Z., Andrews, D., Chaer, I. and Newton, E.J. (2019). Circular economy and behaviour change: Using persuasive communication to encourage pro-circular behaviours towards the purchase of remanufactured refrigeration equipment. Journal of Cleaner Production 222, 499-510. https://doi.org/10.1016/j.jclepro.2019.02.219.

Nature Positive Initiative (2025). A global goal for nature. https://www.naturepositive.org/

Neves, A., Godina, R., Azevedo, S.G. and Matias, J.C.O. (2020). A comprehensive review of industrial symbiosis. Journal of Cleaner Production 247, 119113. https://doi.org/10.1016/j.jclepro.2019.119113

Ni, Z., Chan, H.K. and Tan, Z. (2023). Systematic literature review of reverse logistics for e-waste: overview, analysis, and future research agenda. International Journal of Logistics Research and Applications 26(7), 843-871. https://doi.org/10.1080/13675567.2021.1993159

Niessen, L. and Bocken, N.M.P. (2021). How can businesses drive sufficiency? The business for sufficiency framework. Sustainable Production and Consumption 28, 1090-1103. https://doi.org/10.1016/j.spc.2021.07.030.

Nogueira, A., Ashton, W., Teixeira, C., Lyon, E. and Pereira, J. (2020). Infrastructuring the Circular Economy. Energies 13(7). https://doi.org/10.3390/en13071805

OECD (2001). Extended Producer Responsibility: A Guidance Manual for Governments. https://doi.org/10.1787/9789264189867-en

Ogunmakinde, O., Sher, W. and Egbelakin, T. (2021). Circular economy pillars: a semi-systematic review. Clean Technologies and Environmental Policy 23. https://doi.org/10.1007/s10098-020-02012-9

Ojha, V., Sharma, A., Ranjan, V.P., Rautela, R., Dhawral, A. and Kumar, S. (2024). Resource recovery from legacy waste dumpsites in India: A path towards sustainable waste management. Chemosphere 365, 143337. https://doi.org/10.1016/j.chemosphere.2024.143337

Olivetti, E.A. and Cullen, J.M. (2018). Toward a sustainable materials system. Science 360(6396), 1396-1398. https://www.science.org/doi/10.1126/science.aat6821

Opare, E.O., Struhs, E. and Mirkouei, A. (2021). A comparative state-of-technology review and future directions for rare earth element separation. Renewable and Sustainable Energy Reviews 143, 110917. https://doi.org/10.1016/j.rser.2021.110917

Organisation for Economic Cooperation and Development (2018). Tax policies for inclusive growth in a changing world. https://www.oecd.org/g20/Tax-policies-for-inclusive-growth-in-a-changing-world-OECD.pdf

Organisation for Economic Cooperation and Development (2019). Global Material Resources Outlook to 2060. https://www.oecd-ilibrary.org/content/publication/9789264307452-en

Organisation for Economic Cooperation and Development (2022a). Projections of plastic leakage to the environment to 2060 https://www.oecd-ilibrary.org/sites/aa1edf33-en/1/3/2/4/index.html?itemId =/content/publication/aa1edf33-en&_csp_=ca738cf5d4f327be3b6fec4af9ce5d12&itemIGO=oecd&itemContentType=book

Organization for Economic Cooperation and Development (2022b). Share of plastic waste that is recycled, 2000 to 2019. https://ourworldindata.org/grapher/share-plastic-waste-recycled

Organization for Economic Cooperation and Development (2024a). Monitoring Progress towards a Resource-Efficient and Circular Economy. https://www.oecd-ilibrary.org/content/publication/3b644b83-en

Organization for Economic Cooperation and Development (2024b). Green Public Procurement: An Overview of Green Reforms in Country Procurement Systems. https://openknowledge.worldbank.org/entities/publication/7bafc4b7-d785-5954-b71e-0c1a9ad0ab2c

Ottelin, J., Cetinay, H. and Behrens, P. (2020). Rebound effects may jeopardize the resource savings of circular consumption: evidence from household material footprints. Environmental Research Letters 15. https://doi.org/10.1088/1748-9326/abaa78.

Owen, J.R., Kemp, D., Lechner, A.M., Harris, J., Zhang, R. and Lèbre, É. (2023). Energy transition minerals and their intersection with land-connected peoples. Nature Sustainability 6(2), 203-211. https://doi.org/10.1038/s41893-022-00994-6

Padilla-Rivera, A., do Carmo, B.B.T., Arcese, G. and Merveille, N. (2021). Social circular economy indicators: Selection through fuzzy delphi method. Sustainable Production and Consumption 26, 101-110. https://doi.org/10.1016/j.spc.2020.09.015

Palansooriya, K.N., Dissanayake, P.D., Igalavithana, A.D., Tang, R., Cai, Y. and Chang, S.X. (2023). Converting food waste into soil amendments for improving soil sustainability and crop productivity: A review. Science of The Total Environment 881, 163311. https://doi.org/10.1016/j.scitotenv.2023.163311

Pan, S.-Y., Chen, Y.-H., Fan, L.-S., Kim, H., Gao, X., Ling, T.-C. et al. (2020). CO_2 mineralization and utilization by alkaline solid wastes for potential carbon reduction. Nature Sustainability 3(5), 399-405. https://doi.org/10.1038/s41893-020-0486-9

Papale, L.G., Guerrisi, G., De Santis, D., Schiavon, G. and Del Frate, F. (2023). Satellite Data Potentialities in Solid Waste Landfill Monitoring: Review and Case Studies. Sensors 23(8), 3917. https://doi.org/10.3390/s23083917

Park, I., Tabelin, C.B., Jeon, S., Li, X., Seno, K., Ito, M. et al. (2019). A review of recent strategies for acid mine drainage prevention and mine tailings recycling. Chemosphere 219, 588-606. https://doi.org/10.1016/j.chemosphere.2018.11.053

Partnership for Carbon Accounting Financials (2021). PCAF and the EU Taxonomy Regulation. https://carbonaccountingfinancials.com/files/2021-03/pcaf-and-the-eu-taxonomy-regulation.pdf?ff091b5526

Patel, A., Desai, S.S., Mariam, I., Enman, J., Rova, U., Christakopoulos, P. et al. (2024). Innovative biorefinery approaches for upcycling of post-consumer food waste in a circular bioeconomy context. Chemical Engineering Journal 494, 152990. https://doi.org/10.1016/j.cej.2024.152990

Pathak, G., Nichter, M., Hardon, A., Moyer, E., Latkar, A., Simbaya, J. et al. (2023). Plastic pollution and the open burning of plastic wastes. Global Environmental Change 80, 102648. https://doi.org/10.1016/j.gloenvcha.2023.102648

Patwa, N., Sivarajah, U., Seetharaman, A., Sarkar, S., Maiti, K. and Hingorani, K. (2021). Towards a circular economy: An emerging economies context. Journal of Business Research 122, 725-735. https://doi.org/10.1016/j.jbusres.2020.05.015

Pauliuk, S., Carrer, F., Heeren, N. and Hertwich, E.G. (2024). Scenario analysis of supply- and demand-side solutions for circular economy and climate change mitigation in the global building sector. J Ind Ecol 28(6), 1699-1715. https://doi.org/10.1111/jiec.13557

Pisani-Ferry, J. (2021). Climate policy is macroeconomic policy, and the implications will be significant. https://www.piie.com/publications/policy-briefs/climate-policy-macroeconomic-policy-and-implications-will-be-significant

Plank, B., Streeck, J., Virág, D., Krausmann, F., Haberl, H. and Wiedenhofer, D. (2022). From resource extraction to manufacturing and construction: flows of stock-building materials in 177 countries from 1900 to 2016. Resources, Conservation and Recycling 179, 106122. https://doi.org/10.1016/j.resconrec.2021.106122

Plantinga, A. and Scholtens, B. (2021). The financial impact of fossil fuel divestment. Climate Policy 21(1), 107-119. https://doi.org/10.1080/14693062.2020.1806020

Poppe, E., Wagner, E., Jaeger-Erben, M., Druschke, J. and Köhn, M. (2021). Is it a bug or a feature? The concept of software obsolescence. https://doi.org/10.31880/10344/10242

Potting, J., Hekkert, M., Worrell, E. and Heanemaaijer, A. (2017). Circular economy: Measuring innovation in the product chain. https://www.pbl.nl/uploads/default/downloads/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf

Pottinger, A.S., Geyer, R., Biyani, N., Martinez, C.C., Nathan, N., Morse, M.R. et al. (2024). Pathways to reduce global plastic waste mismanagement and greenhouse gas emissions by 2050. Science 386(6726), 1168-1173. https://doi.org/10.1126/science.adr3837

Pouikli, K. (2020). Concretising the role of extended producer responsibility in European Union waste law and policy through the lens of the circular economy. ERA Forum 20(4), 491-508. https://doi.org/10.1007/s12027-020-00596-9

Prakash, S., Dehoust, G., Gsell, M., Schleicher, T. and Stamminger, P.D.R. (2020). Influence of the service life of products in terms of their environmental impact: Establishing an information base and developing strategies against "obsolescence". https://www.umweltbundesamt.de/publikationen/influence-of-the-service-life-of-products-in-terms

Preston City Council (2019). How we built community wealth in Preston: Achievements and lessons. https://cles.org.uk/wp-content/uploads/2019/07/CLES_Preston-Document_WEB-AW.pdf

PWC (2024). Embracing a circular economy for a resilient tomorrow - Reinventing Asia Pacific. https://www.pwc.com/gx/en/issues/esg/esg-asia-pacific/reinventing-asia-pacific.html

Rahman, S.M.M. and Kim, J. (2020). Circular economy, proximity, and shipbreaking: A material flow and environmental impact analysis. Journal of Cleaner Production 259, 120681. https://doi.org/10.1016/j.jclepro.2020.120681

Rai, K.K. (2018). Indigenous Peoples and local communities. In 25 years of achievements on biodiversity conservation in Nepal. Kathmandu, Nepal. 71-73. https://www.cbd.int/api/v2013/documents/BD049A13-5D91-67D5-5B38-90108F6A4D29/attachments/204558/MOFE_IBD_2018_Final%20(1).pdf

Rai, K.K. (2023). Indigenism Munthum Biocultural for Restoration and Biodiversity Conservation Initiative in Landscape Approach - Nepal.

Ramboll, Fraunhofer and Institute, E. (2020). The decarbonisation benefits of sectoral circular economy actions. European Environment Agency. https://brandcentral.ramboll.com/share/Ntjri6mNKZonSD19BGCH

Reike, D., Hekkert, M.P. and Negro, S.O. (2023). Understanding circular economy transitions: The case of circular textiles. Business Strategy and the Environment 32(3), 1032-1058. https://doi.org/10.1002/bse.3114

Ren, Y., Wu, K.-J., Lim, M.K. and Tseng, M.-L. (2023). Technology transfer adoption to achieve a circular economy model under resource-based view: A high-tech firm. International Journal of Production Economics 264, 108983. https://doi.org/10.1016/j.ijpe.2023.108983

Reyna-Bensusan, N., Wilson, D.C., Davy, P.M., Fuller, G.W., Fowler, G.D. and Smith, S.R. (2019). Experimental measurements of black carbon emission factors to estimate the global impact of uncontrolled burning of waste. Atmospheric Environment 213, 629-639. https://doi.org/10.1016/j.atmosenv.2019.06.047

Rinkinen, J., Jalas, M. and Shove, E. (2015). Object Relations in Accounts of Everyday Life. Sociology 49(5), 870-885. https://doi.org/10.1177/0038038515577791

Rinkinen, J. and Shove, E. (2023). Material culture and the circular economy. Frontiers in Sustainability 4. https://doi.org/10.3389/frsus.2023.1158079

Rinkinen, J., Shove, E. and Marsden, G. (2020). Conceptualising Demand: A Distinctive Approach to Consumption and Practice. https://doi.org/10.4324/9781003029113

Robinson, S. (2022). Chapter 3 - A systems thinking perspective for the circular economy. Circular Economy and Sustainability 35-52. https://doi.org/10.1016/B978-0-12-819817-9.00034-X

Roci, M., Salehi, N., Amir, S., Shoaib-ul-Hasan, S., Asif, F.M.A., Mihelič, A. et al. (2022). Towards circular manufacturing systems implementation: A complex adaptive systems perspective using modelling and simulation as a quantitative analysis tool. Sustainable Production and Consumption 31, 97-112. https://doi.org/10.1016/j.spc.2022.01.033

Roman, M., Varga, H., Cvijanovic, V. and Reid, A. (2020). Quadruple Helix Models for Sustainable Regional Innovation: Engaging and Facilitating Civil Society Participation. Economies 8(2), 48. https://doi.org/10.3390/economies8020048

Rukwaro, R.W. and Mukono, K.M. (2001). Architecture of societies in transition — the case of the Maasai of Kenya. Habitat International 25(1), 81-98. https://doi.org/10.1016/S0197-3975(00)00030-8.

Ruokamo, E., Savolainen, H., Seppälä, J., Sironen, S., Räisänen, M. and Auvinen, A.-P. (2023). Exploring the potential of circular economy to mitigate pressures on biodiversity. Global Environmental Change 78, 102625. https://doi.org/10.1016/j.gloenvcha.2022.102625

Ryter, J., Fu, X., Bhuwalka, K., Roth, R. and Olivetti, E.A. (2021). Emission impacts of China's solid waste import ban and COVID-19 in the copper supply chain. Nature Communications 12(1), 3753. https://doi.org/10.1038/s41467-021-23874-7

Saavedra, Y.M.B., Iritani, D.R., Pavan, A.L.R. and Ometto, A.R. (2018). Theoretical contribution of industrial ecology to circular economy. Journal of Cleaner Production 170, 1514-1522. https://doi.org/10.1016/j.jclepro.2017.09.260

Said, Z., Sharma, P., Thi Bich Nhuong, Q., Bora, B.J., Lichtfouse, E., Khalid, H.M. et al. (2023). Intelligent approaches for sustainable management and valorisation of food waste. Bioresource Technology 377, 128952. https://doi.org/10.1016/j.biortech.2023.128952

Sánchez-García, E., Martínez-Falcó, J., Marco-Lajara, B. and Manresa-Marhuenda, E. (2024). Revolutionizing the circular economy through new technologies: A new era of sustainable progress. Environmental Technology & Innovation 33, 103509. https://doi.org/10.1016/j.eti.2023.103509

Scalabrino, C., Navarrete Salvador, A. and Oliva Martínez, J.M. (2022). A theoretical framework to address education for sustainability for an earlier transition to a just, low carbon and circular economy. Environmental Education Research 28(5), 735-766. https://doi.org/10.1080/13504622.2022.2031899

Schatzki, T. (2019). Social Change in a Material World. https://www.routledge.com/Social-Change-in-a-Material-World/Schatzki/p/book/9780367144531

Schirmeister, C.G. and Mülhaupt, R. (2022). Closing the Carbon Loop in the Circular Plastics Economy. Macromolecular Rapid Communications 43(13), 2200247. https://doi.org/10.1002/marc.202200247

Schröder, P. (2020). Promoting a Just Transition to an Inclusive Circular Economy. Chatham House Research Paper. https://www.chathamhouse.org/2020/04/promoting-just-transition-inclusive-circular-economy

Schröder, P., Lemille, A. and Desmond, P. (2020). Making the circular economy work for human development. Resources, Conservation and Recycling 156, 104686. https://doi.org/10.1016/j.resconrec.2020.104686

Schröder, P. and Raes, J. (2021). Financing an inclusive circular economy: De-risking investments for circular business models and the SDGs. Chatham House. https://www.chathamhouse.org/sites/default/files/2021-07/2021-07-16-inclusive-circular-economy-schroder-raes.pdf

Schroeder, P., Anggraeni, K. and Weber, U. (2019). The Relevance of Circular Economy Practices to the Sustainable Development Goals. Journal of Industrial Ecology 23(1), 77-95. https://doi.org/10.1111/jiec.12732

Seif, R., Salem, F.Z. and Allam, N.K. (2024). E-waste recycled materials as efficient catalysts for renewable energy technologies and better environmental sustainability. Environment, Development and Sustainability 26(3), 5473-5508. https://doi.org/10.1007/s10668-023-02925-7

Serna-Guerrero, R., Ikonen, S., Kallela, O. and Hakanen, E. (2022). Overcoming data gaps for an efficient circular economy: A case study on the battery materials ecosystem. Journal of Cleaner Production 374, 133984. https://doi.org/10.1016/j.jclepro.2022.133984

Shevchenko, T., Saidani, M., Ranjbari, M., Kronenberg, J., Danko, Y. and Laitala, K. (2023). Consumer behavior in the circular economy: Developing a product-centric framework. Journal of Cleaner Production 384, 135568. https://doi.org/10.1016/j.jclepro.2022.135568

Silverman, D. (2024). Companies pioneer 'materials as a service' using techniques created at Imperial. Imperial College. London.

Simas, M., Aponte, F. and Wiebe, K. (2022). The Future is Circular: Circular Economy and Critical Minerals for the Green Transition. https://hdl.handle.net/11250/3032049

Sizirici, B., Fseha, Y., Cho, C.-S., Yildiz, I. and Byon, Y.-J. (2021). A Review of Carbon Footprint Reduction in Construction Industry, from Design to Operation. Materials 14(20), 6094. https://doi.org/10.3390/ma14206094

Spangenberg, J.H. and Lorek, S. (2019). Sufficiency and consumer behaviour: From theory to policy. Energy Policy 129, 1070-1079. https://doi.org/10.1016/j.enpol.2019.03.013

Stahel, W.R. (2019). The Circular Economy: A User's Guide. https://doi.org/10.4324/9780429259203

Stahel, W.R. and Clift, R. (2016). Stocks and Flows in the Performance Economy. In Taking Stock of Industrial Ecology. Clift, R. and Druckman, A. (eds.). Cham: Springer International Publishing. 137-158. https://doi.org/10.1007/978-3-319-20571-7_7

Stegmann, P., Daioglou, V., Londo, M., van Vuuren, D.P. and Junginger, M. (2022). Plastic futures and their $CO_{(2)}$ emissions. Nature 612(7939), 272-276. https://doi.org/10.1038/s41586-022-05422-5

Steinberger, J.K. and Roberts, J.T. (2010). From constraint to sufficiency: The decoupling of energy and carbon from human needs, 1975–2005. Ecological Economics 70(2), 425-433. https://doi.org/10.1016/j.ecolecon.2010.09.014

Stracqualursi, A. and Andreucci, M.B. (2023). Water Resources Management in a Regenerative Design Approach. https://link.springer.com/chapter/10.1007/978-3-031-36554-6_39#citeas

Sumo, P.D., Arhin, I., Danquah, R., Nelson, S.K., Achaa, L.O., Nweze, C.N. et al. (2023). An assessment of Africa's second-hand clothing value chain: a systematic review and research opportunities. Textile Research Journal 93(19-20). https://doi.org/10.1177/00405175231175057

Sun, B., Schnoor, J.L. and Zeng, E.Y. (2022). Decadal Journey of E-Waste Recycling: What Has It Achieved? Environ Sci Technol 56(18), 12785-12792. https://doi.org/10.1021/acs.est.2c01474

Supriya, Chaudhury, R., Sharma, U., Thapliyal, P.C. and Singh, L.P. (2023). Low-CO_2 emission strategies to achieve net zero target in cement sector. Journal of Cleaner Production 417, 137466. https://doi.org/10.1016/j.jclepro.2023.137466

Syberg, K., Nielsen, M.B., Westergaard Clausen, L.P., van Calster, G., van Wezel, A., Rochman, C. et al. (2021). Regulation of plastic from a circular economy perspective. Current Opinion in Green and Sustainable Chemistry 29, 100462. https://doi.org/10.1016/j.cogsc.2021.100462

Systemiq (2022). Critical raw materials for the energy transition in The EU: How circular economy approaches can increase supply security for critical raw materials. https://www.systemiq.earth/wp-content/uploads/2022/11/Systemiq-2022.-Circular-Economy-Critical-Raw-Materials-factsheets_final.pdf

Systemiq (2023). Mobilizing blended finance for circular waste collection and sortation infraestructure. https://www.stopoceanplastics.com/wp-content/uploads/2023/06/Systemiq_Mobilizing-Blended-Finance-for-Waste-Management_EN_final-1-compressed.pdf

Talens Peiró, L., Ardente, F. and Mathieux, F. (2017). Design for Disassembly Criteria in EU Product Policies for a More Circular Economy: A Method for Analyzing Battery Packs in PC-Tablets and Subnotebooks. Journal of Industrial Ecology 21. https://onlinelibrary.wiley.com/doi/10.1111/jiec.12608

Tan, J., Jia, S. and Ramakrishna, S. (2023). Accelerating Plastic Circularity: A Critical Assessment of the Pathways and Processes to Circular Plastics. Processes 5. https://www.mdpi.com/2227-9717/11/5/1457; https://www.sciencedirect.com/science/article/pii/S0921344923002082

Tan, Q., Duan, H., Liu, L., Yang, J. and Li, J. (2018). Rethinking residential consumers' behavior in discarding obsolete mobile phones in China. Journal of Cleaner Production 195, 1228-1236. https://doi.org/10.1016/j.jclepro.2018.05.244

Tembo, P.M., Dyer, C. and Subramanian, V. (2024). Lithium-ion battery recycling—a review of the material supply and policy infrastructure. NPG Asia Materials 16(1), 43. https://doi.org/10.1038/s41427-024-00562-8

The Ministry of the Environment Japan (2025). Revision of Green Bond and Green Loan Guidelines Annex 1 (Green List). https://www.env.go.jp/en/press/press_04394.html

Trinomics (2018). Behavioural Study on Consumers' Engagement in the Circular Economy. https://data.europa.eu/doi/10.2818/921596

Turner, C. (2024). Towards a circular economy in space. https://blogs.esa.int/cleanspace/2024/12/10/towards-a-circular-economy-in-space/ Accessed: 24 March 2025

UNEP (2019). Global chemicals outlook II. https://www.unep.org/topics/chemicals-and-pollution-action/chemicals-management/global-chemicals-outlook

United Nations (2024). Resoucing the energy transition: Principles to guide critical energy transition minerals towards equity and justice. https://www.un.org/sites/un2.un.org/files/report_sg_panel_on_critical_energy_transition_minerals_11_sept_2024.pdf

United Nations Development Programme (2024). Circular Economy as an Enabler for Responsible Banking: Leveraging the Nexus between Circularity and Sustainability Impact. https://www.unepfi.org/industries/banking/circular-economy-enabling-responsible-banking/

United Nations Economic Commission for Europe (2022). Reform of Harmonized System codes needed to support circular economy transition. https://unece.org/circular-economy/news/reform-harmonized-system-codes-needed-support-circular-economy-transition#:~:text=The%20transition%20from%20linear%20to%20circular%20economies%20-requires,considerations%20were%20not%20prominent%20in%20economic%20policy%20debates Accessed: 25 August 2023

United Nations Economic Commission for Europe (2023a). UN-ENERGY POLICY BRIEF Aligning Critical Raw Materials Development with sustainable development https://unece.org/sites/default/files/2023-07/2023_UN%20Energy%20Policy%20Brief%20Aligning%20CRMs-062723.pdf.United Nations Economic Commission for Europe (2023b). Traceability for Sustainable Garment and Footwear. https://unece.org/trade/traceability-sustainable-garment-and-footwear

United Nations Economic Commission for Europe (2024). Guidelines for Measuring Circular Economy. https://unece.org/sites/default/files/2024-02/ECECESSTAT20235_WEB.pdf

United Nations Environment Programme (2018a). Africa Waste Management Outlook. https://www.unep.org/ietc/resources/publication/africa-waste-management-outlook

United Nations Environment Programme (2018b). Building circularity into our economies through sustainable procurement. https://circularprocurement.ca/wp-content/uploads/2021/02/Building-Circularity-into-Economies-through-Procurement.pdf

United Nations Environment Programme (2019a). Global Resources Outlook 2019: Natural Resources for the Future We Want. Nairobi, Kenya: United Nations Environment Programme. https://wedocs.unep.org/20.500.11822/27517

United Nations Environment Programme (2019b). Undersatanding Circularity. https://buildingcircularity.org/

United Nations Environment Programme (2020a). Financing Circularity: Demystifying Finance for the Circular Economy. https://www.unepfi.org/publications/financing-circularity/

United Nations Environment Programme (2020b). Waste Force. https://www.unep.org/resources/assessment/wasteforce

United Nations Environment Programme (2022). Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi. https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction

United Nations Environment Programme (2023a). Turning off the Tap. How the world can end plastic pollution and create a circular economy. https://www.unep.org/resources/turning-off-tap-end-plastic-pollution-create-circular-economy

United Nations Environment Programme (2023b). Developing Metrics for Transition Finance Discussion Paper. https://www.unepfi.org/wordpress/wp-content/uploads/2023/12/Developing-Metrics-for-Transition-Finance.pdf

United Nations Environment Programme (2023c). Chemicals in plastics - A technical report. https://www.unep.org/resources/report/chemicals-plastics-technical-report

United Nations Environment Programme (2023d). Sustainability and Circularity in the Textile Value Chain - A Global Roadmap. https://www.oneplanetnetwork.org/sites/default/files/2023-10/Full%20Report%20-%20UNEP%20Sustainability%20and%20Circularity%20in%20the%20Textile%20Value%20Chain%20A%20Global%20Roadmap.pdf

United Nations Environment Programme (2024a). Global Resources Outlook 2024 - Bend the tend. https://www.unep.org/resources/Global-Resource-Outlook-2024

United Nations Environment Programme (2024b). Circular Economy: From indicators and data to policy-making. https://www.unep.org/resources/report/circular-economy-indicators-and-data-policy-making

United Nations Environment Programme (2024c). Global Waste Management Outlook 2024 - Beyond an age of waste. https://www.unep.org/resources/global-waste-management-outlook-2024

United Nations Environment Programme and International Solid Waste Association (2015). Global Waste Management Outlook. https://www.unep.org/resources/report/global-waste-management-outlook

United Nations Institute for Training and Research (2022). Global Transboundary E-waste Flows Monitor 2022. https://ewastemonitor.info/gtf-2022/

United Nations Office on Drugs and Crime (2022). Combating waste trafficking: A guide to good legislative practices. https://sherloc.unodc.org/cld/uploads/pdf/Combating_Waste_Trafficking_-_Guide_on_Good_Legislative_Practices_-_EN.pdf

United Nations Office on Drugs and Crime (2024). Legal Frameworks to Address Waste Trafficking in the ASEAN Region – Review and Gap Analysis. https://doi.org/10.18356/9789211065343

United Natios Institute for Training and Research (2024). Global e-waste monitor 2024: Eletronic waste rising five times faster than documented e-waste recycling. https://unitar.org/about/news-stories/press/global-e-waste-monitor-2024-electronic-waste-rising-five-times-faster-documented-e-waste-recycling

University of Cambridge Institute for Sustainability Leadership and The Wuppertal Institute (2023). Embracing circularity: A pathway for strengthening the Critical Raw Materials Act. https://www.corporateleadersgroup.com/files/cisl_embracing_circularity_report_v5.pdf

Van Niekerk, A.J. (2022). The Inclusive Economy: Criteria, Principles and Ubuntu. Auckland Park, South Africa: UJ Press.

Vaughn, R.A. (2000). How Advertising Works: A Planning Model. .. putting it all together. Advertising & Society Review 1(1). http://dx.doi.org/10.1353/asr.2000.0015

Velenturf, A.P.M. and Purnell, P. (2021). Principles for a sustainable circular economy. Sustainable Production and Consumption 27, 1437-1457. https://doi.org/10.1016/j.spc.2021.02.018

Vence, X. and López Pérez, S.D. (2021). Taxation for a Circular Economy: New Instruments, Reforms, and Architectural Changes in the Fiscal System. Sustainability 13(8). https://doi.org/10.3390/su13084581

Villalba-Eguiluz, U., Sahakian, M., González-Jamett, C. and Etxezarreta, E. (2023). Social and solidarity economy insights for the circular economy: Limited-profit and sufficiency. Journal of Cleaner Production 418, 138050. https://doi.org/10.1016/j.jclepro.2023.138050

Villamagna, A.M., Angermeier, P.L. and Bennett, E.M. (2013). Capacity, pressure, demand, and flow: A conceptual framework for analyzing ecosystem service provision and delivery. Ecological Complexity 15, 114-121. https://doi.org/10.1016/j.ecocom.2013.07.004

Vittuari, M., Garcia Herrero, L., Masotti, M., Iori, E., Caldeira, C., Qian, Z. et al. (2023). How to reduce consumer food waste at household level: A literature review on drivers and levers for behavioural change. Sustainable Production and Consumption 38, 104-114. https://doi.org/10.1016/j.spc.2023.03.023

Von Bertalanffy, L. (1968). General system theory: Foundations, development, application. IEEE Transactions on Systems, Man and Cybernetics 4(6). https://doi.org/10.1109/TSMC.1974.4309376

Wagner, M., Monclús, L., Arp, H.P.H., Groh, K.J., Loseth, M.E., Muncke, J. et al. (2024). State of the science on plastic chemicals - Identifying and addressing chemicals and polymers of concern. PlastChem 1. http://dx.doi.org/10.5281/zenodo.10701706

Wagner, T.P. and Raymond, T. (2015). Landfill mining: Case study of a successful metals recovery project. Waste Management 45, 448-457. https://doi.org/10.1016/j.wasman.2015.06.034

Walden, J., Steinbrecher, A. and Marinkovic, M. (2021). Digital Product Passports as Enabler of the Circular Economy. Chemie Ingenieur Technik 93(11), 1717-1727. https://doi.org/10.1002/cite.202100121

Wang, K., Costanza-van den Belt, M., Heath, G., Walzberg, J., Curtis, T., Barrie, P. et al. (2022). Circular economy as a climate strategy: current knowledge and calls to action. World Resources Institute. https://www.nrel.gov/docs/fy23osti/84141.pdf

Wang, P., Zhang, L.-Y., Tzachor, A. and Chen, W.-Q. (2024). E-waste challenges of generative artificial intelligence. Nature Computational Science 4(11), 818-823. https://doi.org/10.1038/s43588-024-00712-6

Warde, A. (2005). Consumption and Theories of Practice. Journal of Consumer Culture 5(2), 131-153. https://doi.org/10.1177/1469540505053090.

Wastling, T., Charnley, F. and Moreno, M. (2018). Design for Circular Behaviour: Considering Users in a Circular Economy. Sustainability 10(6), 1743. https://doi.org/10.3390/su10061743

Watson, A., Zochowski, T. and McGarvey, R. (2021). Constrained by Accounting: Examining How Current Accounting Practice is Constraining the Net Zero Transition. http://dx.doi.org/10.2139/ssrn.3811577

Watson, A.H., Corser, P.G., Garces Pardo, E.E., Lopez Christian, T.E. and Vandekeybus, J. (2010). A comparison of alternative tailings disposal methods — the promises and realities. Mine Waste 2010: First International Seminar on the Reduction of Risk in the Management of Tailings and Mine Waste. Perth: Australian Centre for Geomechanics. 499-514. https://doi.org/10.36487/ACG_rep/1008_41_Watson

Watson, M. and Pantzar, M. (2012). The Dynamics of Social Practice : Everyday Life and how it Changes. London: Sage. http://digital.casalini.it/9781446258170

Wayman, E. (2023). Recycling rare earth elements is hard. Science is trying to make it easier. https://www.sciencenews.org/article/recycling-rare-earth-elements-hard-new-methods

Webster, K. (2021). A Circular Economy Is About the Economy. Circular Economy and Sustainability 1(1), 115-126. https://doi.org/10.1007/s43615-021-00034-z

Webster, K. (2022). The long road to a social dividend. Earth4All Deep-dive Paper 05, The Club of Rome.

White, O. (2023). Climate and Nature-based Interventions in Livestock. https://www.fairr.org/news-events/insights/seaweed-and-regenerative-aquaculture-need-more-investment-to-overcome Accessed: 21 March 2025

Wiedenhofer, D., Fishman, T., Plank, B., Miatto, A., Lauk, C., Haas, W. et al. (2021). Prospects for a saturation of humanity's resource use? An analysis of material stocks and flows in nine world regions from 1900 to 2035. Global Environmental Change 71, 102410. https://doi.org/10.1016/j.gloenvcha.2021.102410.

Wiedinmyer, C., Yokelson, R. J. & Gullett, B. K. (2014) Global emissions of trace gases, particulate matter, and hazardous air pollutants from open burning of domestic waste. Environ. Sci. Technol 48, 9523–9530. https://pubs.acs.org/doi/10.1021/es502250z

Williams, M., Gower, R., Green, J., , Whitebread, E., Lenkiewicz, Z. and Schröder, P. (2019). No time to waste: Tackling the Plastic Pollution Crisis Before It's Too Late. https://learn.tearfund.org/en/resources/policy-reports/no-time-to-waste

World Bank (2021). Green Public Procurement: An Overview of Green Reforms in Country Procurement Systems. https://hdl.handle.net/10986/36508.

World Bank (2023). Behavior change in solid waste management: A compendium of cases. https://documents1.worldbank.org/curated/en/099091423124016666/pdf/P1773441302811082184c8156db86923f14.pdf

World Business Council for Sustainable Development (2023). The roadmap to nature positive: Foundations for the built environment system. https://www.wbcsd.org/resources/the-roadmap-to-nature-positive-foundations-for-the-built-environment-system/

World Customs Organization (2022). Transboundary trafficking in waste and ozone depleting substances tackled through Operation DEMETER VIII. https://www.wcoomd.org/en/media/newsroom/2022/december/operation-demeter-viii.aspx Accessed: 25 August 2023

World Economic Forum (2023). Digital Battery Passports: An Enabler for Sustainable and Circular Battery Management. https://www3.weforum.org/docs/WEF_Digital_Battery_Passport_2023.pdf#:~:text=In%202018%2C%20China%20passed%20the%20Interim%20Provisions,development%20of%20a%20Chinese%20digital%20battery%20passport

World Health Organization (2024). Electronic waste: Digital dumpsites and children's health. https://www.who.int/news-room/questions-and-answers/item/children-and-digital-dumpsites-e-waste-and-health Accessed: 21 March 2025

WTO (2025). Trade and environmental sustainability structured discussions. https://www.wto.org/english/tratop_e/tessd_e/TESSD_overview_eng.pdf

Wu, H., Zuo, J., Zillante, G., Wang, J. and Yuan, H. (2019). Status quo and future directions of construction and demolition waste research: A critical review. Journal of Cleaner Production 240, 118163. https://doi.org/10.1016/j.jclepro.2019.118163

WWF (2024). Artic Clean-UP: Turning the tide. https://www.arcticwwf.org/magazine-issues/2024/arctic-clean-up-turning-the-tide/

Yamaguchi, S. (2021). International trade and circular economy - Policy alignment. https://doi.org/10.1787/ae4a2176-en

Yang, M., Chen, L., Wang, J., Msigwa, G., Osman, A.I., Fawzy, S. et al. (2023). Circular economy strategies for combating climate change and other environmental issues. Environmental Chemistry Letters 21(1), 55-80. https://doi.org/10.1007/s10311-022-01499-6

Zante, G., Elgar, C.E., Hartley, J.M., Mukherjee, R., Kettle, J., Horsfall, L.E. et al. (2024). A toolbox for improved recycling of critical metals and materials in low-carbon technologies. RSC Sustainability 2(2), 320-347. https://doi.org/10.1039/D3SU00390F

Zara, C., Bellardini, L. and Gobbi, M. (2021). Circular Economy, Stock Volatility and Resilience to the COVID-19 Shock: Evidence from European Companies. https://dx.doi.org/10.2139/ssrn.3947722

Zeng, X., Duan, H., Wang, F. and Li, J. (2017). Examining environmental management of e-waste: China's experience and lessons. Renewable and Sustainable Energy Reviews 72, 1076-1082

Zeng, X. and Li, J. (2021). Emerging anthropogenic circularity science: principles, practices, and challenges. iScience 24(3), 102237. https://doi.org/10.1016/j.isci.2021.102237

Zhai, X., Li, Z., Huang, B., Luo, N., Huang, M., Zhang, Q. et al. (2018). Remediation of multiple heavy metal-contaminated soil through the combination of soil washing and in situ immobilization. Science of The Total Environment 635, 92-99. https://doi.org/10.1016/j.scitotenv.2018.04.119

Zhang, A. and Seuring, S. (2024). Digital product passport for sustainable and circular supply chain management: a structured review of use cases. International Journal of Logistics Research and Applications 1-28. https://doi.org/10.1080/13675567.2024.2374256

Zhang, L., Wang, X., & Li, X. (2020). Advances in Resource Recovery from Wastewater.

Zheng, J. and Suh, S. (2019). Strategies to reduce the global carbon footprint of plastics. Nature Climate Change 9(5), 374-378. https://doi.org/10.1038/s41558-019-0459-z

Zhu, F., Cakmak, E.K. and Cetecioglu, Z. (2023). Phosphorus recovery for circular Economy: Application potential of feasible resources and engineering processes in Europe. Chemical Engineering Journal 454, 140153. https://doi.org/10.1016/j.cej.2022.140153

Zaw Oo, P., Prapaspongsa, T., Strezov, V., Huda, N., Oshita, K., Takaoka et al. (2024). The role of global waste management and circular economy towards carbon neutrality. Sustainable Production and Consumption 52, 2352-5509. https://doi.org/10.1016/j.spc.2024.11.021

Zink, T. and Geyer, R. (2017). Circular Economy Rebound. Journal of Industrial Ecology 21(3), 593-602. https://doi.org/10.1111/jiec.12545

16 Energy System Transformation Pathways

Coordinating Lead Authors: Debora Ley (United Nations Economic Commission for Latin America and the Caribbean, ECLAC, Ministry of Environment and Natural Resources of Guatemala), Kevin Nnanye Nwaigwe (University of Botswana, Clean Energy Research Centre)

Lead Authors: Janelle Baker (Athabasca University), Sybil Derrible (University of Illinois Chicago), Elisabeth Gilmore (Carleton University), Peter King (late), Nandakumar Janardhanan (Institute for Global Environmental Strategies), Maria Virginia Vilariño (Argentine Business Council for Sustainable Development), Loïc De Weerdt (University of Antwerp)

Contributing Authors: Adedoyin Adeleke (Green Growth Africa Sustainability Network), Sabine Fuss (Potsdam Institute for Climate Impact Research), Chenmin He (Zhejiang University of Technology), Daniel Alejandro Pacheco Rojas (Universidad Nacional Autónoma de México), Ruben Prütz (Potsdam Institute for Climate Impact Research), Hareenanden Ramasawmy (University of Mauritius)

Fellows: Aseel Ibrahim Mohammed Abo-Taleb (Global Youth and Sustainability Organization), Ayodeji Stephen Adekanbi (HydroGEM Energy Advisory)

Credit: leungchopan/Envato

Chapter summary

Credit: mypics/Envato

Identifying and leveraging synergies between the energy transition and other systems can accelerate change by achieving multiple policy goals and improving cost-effectiveness *(very well established)*. The costs of inaction are higher than the costs of mitigation for pathways that limit global warming to 2°C over pre-industrial levels by the end of the century. While the current Nationally Determined Contributions fall short of meeting the Paris Agreement temperature target, aligning climate action with the Sustainable Development Goals (SDGs) can provide substantial co-benefits. For example, climate mitigation policies that also reduce air pollution could limit global warming levels by 0.5°C and save 2.4 million lives annually {16.2.3; 16.3; 16.5}.

Equitably sharing costs and benefits of the energy transition can build political and public support for climate and renewable energy policies, among others *(very well established)*. Combining subsidies for lower-income groups with training and capacity-building can address shifts in employment and livelihoods and improve distributional outcomes in national and subnational energy and climate policies. Actions, including access to and availability of finance, that recognize historical and current inequities and injustices between countries can enhance international cooperation *(well established)*. Equitable benefit-sharing together with participatory and inclusive decision-making for disadvantaged and marginalized groups, including Indigenous Peoples, can help prevent new energy developments from perpetuating harms and injustices *(well established)* {16.2.1; 16.2.2; 16.3; Box 16.1}.

Reforming economic incentives and phasing out subsidies for fossil-fuel production and consumption can improve the competitiveness of decarbonization efforts *(well established)*. Globally, fossil-fuel subsidies are estimated at 7 trillion (2022 US$) or 7.1 per cent of GDP. While politically challenging, subsidy reform could reduce emissions by approximately 36 per cent by 2025, prevent nearly one million premature deaths annually through improved air quality and generate substantial fiscal revenues. Carbon pricing mechanisms, carbon markets, taxing, and the application of the social cost of carbon can further support decarbonization efforts {16.2.3; 16.3}.

Closing the energy poverty gap requires coverage and access to modern and affordable electricity and clean cooking fuels at the household and community levels *(very well established)*. Achieving SDG 7.1, which aims

for universal energy access for all by 2030, is estimated to cost US$45 billion annually, representing less than 2 per cent of overall clean energy spending. Universal energy access supports multiple SDGs by improving basic services and infrastructure, health, education, and livelihood opportunities. Stand-alone systems, as well as mini and microgrids, can provide reliable and adequate electricity where grid expansion is not feasible. Including social and cultural considerations improves the adoption of clean electricity and modern fuels *(well established)* {16.2.1}.

Leveraging public finance to de-risk investment and reduce the cost of capital can mobilize private investment and support the energy transition in lower- and middle-income countries *(well established)*. Targeted subsidies and concessional financing can facilitate universal energy access, particularly to the lower-income countries and among Indigenous Peoples. Guarantee agencies have proven to be effective in attracting private investments in these countries *(established)*. Development banks can act as intermediaries between financial markets and borrowers, helping to reduce real and perceived risks, lower capital costs, and enhance financial flows and investment. *(well established)* {16.2.1; 16.3.3}.

Improving energy efficiency through higher-efficiency appliances, compact urban development, and public and active transportation can reduce energy demand, while delivering health and environmental co-benefits *(very well established)*. Stricter minimum energy performance standards, retrofit programmes, and passive building designs, implemented by local and national governments, lower energy use in buildings. Heat pumps for space and water heating can further reduce energy consumption, and their installations can be supported through subsidies and regulations *(virtually certain)*. Policies and funding mechanisms that promote mixed land-use support public and active transport, avoid long-term carbon lock-in, and improve human well-being *(well established)*. Prioritizing low-income populations, including those in informal settlements or with disabilities, can ensure equitable access to lower energy-efficient options *(established)* {16.2.2; 16.4.1}.

Promoting behavioural change and collective action can reduce energy demand and help address inequality *(well established)*. Programmes can target various behaviours, including turning off equipment and recycling, as well as energy labelling, which can lower building energy demand by 5-30 per cent, depending on the building type and region. Renewable energy communities, in both urban and rural settings, can foster local ownership and align with user priorities. Social movements advocating for climate and energy justice, including those led by youth, Indigenous Peoples, women, labour, non-governmental organizations, and civil society, also play a crucial role in driving change {16.2.1; 16.2.2; 16.4.2}.

Limiting global warming to 1.5 °C by the end of the century requires a rapid decarbonization of the energy system, with 74–82 per cent of primary energy coming from low- or zero-carbon sources by 2050 *(very well established)*. By the middle of this century, 97–99 per cent of global electricity demand needs to be met by low- and zero-carbon sources. Replacing fossil fuels in hard-to-abate sectors requires developing markets for advanced biofuels, green hydrogen, green ammonia, and green methane *(well established)*. Electrifying energy-intensive sectors, such as transportation and industry, combined with clean electricity generation, is key to driving energy system decarbonization. Investment in grid infrastructure needs to at least double to around US$600 billion annually by 2030, to stay on track for the net-zero emissions by 2050 *(well established)* {16.2.3}.

Atmospheric carbon dioxide removal, including bioenergy with carbon capture and storage, is crucial for achieving net-zero carbon dioxide emissions by mid-century and limiting warming to 1.5 °C by the end of the century *(well established)*. Carbon dioxide removal can help offset residual emissions in hard-to-abate sectors. Bioenergy with carbon capture and storage (BECCS) and biochar could generate net energy, unlike direct air capture with carbon capture and storage and enhanced weathering, which require additional energy. However, biomass-based carbon dioxide removal (CDR) options, such as BECCS, face substantial sustainability challenges. Managing the trade-off between various CDR options requires a portfolio approach that accounts for environmental impacts and implications for economic prosperity and well-being {16.2.3}.

Developing new oil and gas fields is incompatible with the goal of limiting the warming to 1.5°C by the end of the century *(very well established)*. Oil and gas demand needs to decline by around 20 per cent by 2030, with

a global reduction in fossil-fuel use of 55-70 per cent by 2050. Expanding renewable energy reduces the need for new fossil-fuel production facilities. Phasing out fossil fuels from energy systems is achievable at a relatively low cost over the next decade *(well established)*. Investing in training and capacity-building is essential to ensure a just transition and prevent economic disruption *(well established)* {162.3; 16.3}.

Improving circularity in critical energy transition metal value chains can help reduce negative environmental and social impacts *(well established)*. The demand for critical energy transition metals is expected to increase fivefold between 2018 and 2050. Strengthening regulations and international coordination is necessary to enhance efficiency, minimize waste, and enhance governance throughout the value chain. Innovation, including the integration of advanced technologies, can enhance trust and traceability. A substantial proportion of critical mineral deposits are situated within or in close proximity to biodiversity hotspots and regions experiencing water stress. Where trade-offs arise, such as biodiversity loss and water and land degradation, the use of participatory and rights-based approaches is essential to address inequities, especially for Indigenous Peoples and marginalized groups *(well established)* {16.2; 16.5; Box 16.1}.

Energy sovereignty is essential for ensuring access to clean and affordable energy for Indigenous Peoples, including through demand reduction *(established but incomplete)*. At least 54 per cent of energy transition minerals are located on or near Indigenous Peoples' territories. Therefore, upholding Indigenous Peoples' right to self-determination, guided by the principles of free, prior, and informed consent, must be respected to ensure equitable benefit-sharing from mining and land use. Policies that respect Indigenous territorial rights and legal orders, support self-management of resources, enable community-led environmental monitoring, protect labour rights, and ensure fair revenue distribution can reduce inequities in the mineral value chain {16.2.4; 16.3}.

Sustainable and just energy transitions can support climate change adaptation and enhance nature and biodiversity *(well established)*. Indigenous Peoples and local communities play a crucial role in biodiversity conservation, but energy projects and infrastructure often threaten biocultural diversity by continued rights violations and environmental injustices to Indigenous Peoples and their territories. Promoting biocultural diversity and Indigenous rights can decrease the damages of energy systems to biodiversity *(established but incomplete)*. Expanding energy access and closing the energy poverty gap increase the resilience of vulnerable populations, for example, by powering early warning systems *(very well established)* {Box 16.1}.

Breaking down silos between policy domains improves coordination of energy transition and sustainable development *(virtually certain)*. Integrating robust circularity practices in critical energy transition metal value chains can reduce material demand and minimize adverse environmental and social impacts *(well established)*. Innovative energy solutions, such as agrivoltaics, which combine energy production and agriculture, can be effective in reducing energy and land-use challenges *(well established)*. Policies supporting integrated watershed management, including mini and microhydroelectric plants, can boost electricity generation, restore forests and benefit communities *(well established)*. Subsidies, government loans, and research and development are key to advancing emerging technologies *(well established)* {16.3; 16.5}.

16.1 Introduction

Transforming energy systems requires rapid and significant changes in both developed and developing countries to align with the Paris Agreement's long-term temperature goals – limiting global average temperature to well below 2°C and striving to keep it to below 1.5°C above pre-industrial levels - while also supporting the achievement of the the Sustainable Development Goal 7: ensuring access to affordable, reliable, sustainable and modern energy for all.

Of the 620 exajoules of primary energy used worldwide in 2023, 81.5 per cent originated from fossil fuels and 14.6 per cent from renewables. In 2023, renewables accounted for 13.5 per cent of total final energy consumption, a key indicator used to monitor Sustainable Development Goal 7, and are projected to reach 20.9 per cent by 2030 (International Energy Agency [IEA] 2025a). Wind and solar energy contributed 13.25 per cent in 2023 for electricity, with growth rates of 10.3 per cent and 24.2 per cent, respectively, (Energy Institute 2024).

Energy consumption supports the needs of the global population, but generates pollution, with carbon dioxide (CO_2) being the most prevalent greenhouse gas. There is a near-linear relationship between cumulative CO_2 emissions and global warming (Intergovernmental Panel on Climate Change [IPCC] 2021). Given the direct effect of fossil fuel production and consumption on rising global temperatures, it is crucial to rapidly decarbonize the global energy system to align with the targets of the Paris Agreement.

However, nearly 20 per cent of the world's population lives in countries at risk of not achieving a socially responsible energy transition with equitable, just and inclusive outcomes (World Economic Forum [WEF] 2024). Nationally determined contributions are not on track to meet the Paris Agreement temperature goals.

Emission reductions across all sectors are estimated to require a 42 per cent cut by 2030 and 57 per cent by 2035 to stay aligned with a 1.5°C target by the end of the century (United Nations Environment Programme [UNEP] 2024a).

To address the challenges outlined above, this chapter identifies four critical solution pathways:

- energy access for all – ensuring that everyone has access to modern, reliable, affordable, and clean energy supplies
- energy-demand management through energy efficiency, land-use planning, and behavioural change
- decarbonization and transition away from fossil fuels, including diversification and decentralization of the grid
- reducing damages in the shift to new technologies by achieving environmental sustainability in the critical energy transition mineral value chain

To enable these pathways, this chapter considers regulatory certainty and expectations of increasing stringency, improved access to finance and governance that balances trade-offs without worsening existing inequities, and alignment with a just transition. Research and development and technological advancements also play a crucial role in reaching these objectives.

The chapter advances the assessment of energy transformation actions highlighted in the IPCC Sixth Assessment Cycle (IPCC 2023a). These include significant reductions in overall fossil-fuel use, minimal reliance on unabated fossil fuels, and the application of point-source carbon capture and storage in remaining fossil-fuel systems. Further transformations such as electricity systems that produce no net CO_2 emissions, widespread electrification, and alternative energy carriers in sectors less suited to electrification are also covered, as well as energy conservation and efficiency.

The chapter also assesses the feasibility of adaptation options, recognizing the dual role of energy as a means for adaptation and the vulnerability of energy infrastructure worldwide. Diversifying energy generation sources such as wind, solar, small-scale hydropower and managing demand through storage and energy efficiency improvements can boost energy reliability and reduce vulnerabilities to climate change.

The energy transition must incorporate infrastructure resilience, particularly to extreme weather events, reliable power systems, and efficient water use for existing and new energy generation systems (IPCC 2022a).

Credit: siwabudv/Envato

16.2 Solution pathways for energy system transformation

An overarching goal of a transformed energy system is that it is sustainable, affordable, reliable, and equitable, ensuring no one is left behind. While achieving these goals is technically possible and often cost-effective, deploying all these solutions at scale requires overcoming a range of challenges, including geophysical, environmental, economic, technological, sociocultural, and institutional barriers (IPCC 2022b). Political support and international cooperation are key to enabling energy transitions across developed and developing countries. At the same time, subnational governments, private sector entities, civil society, communities, and individuals all play an important role by implementing policies and embracing behavioural changes.

Aligned with the theme of GEO-7 to find solutions for the global environmental crises of climate change, biodiversity loss and land degradation, and pollution, this section focuses on four specific energy system goals. It proposes a variety of solutions and actions to support these goals, suggests specific levers to implement them, and identifies the actors and institutions responsible for their execution (**Figure 16.1**).

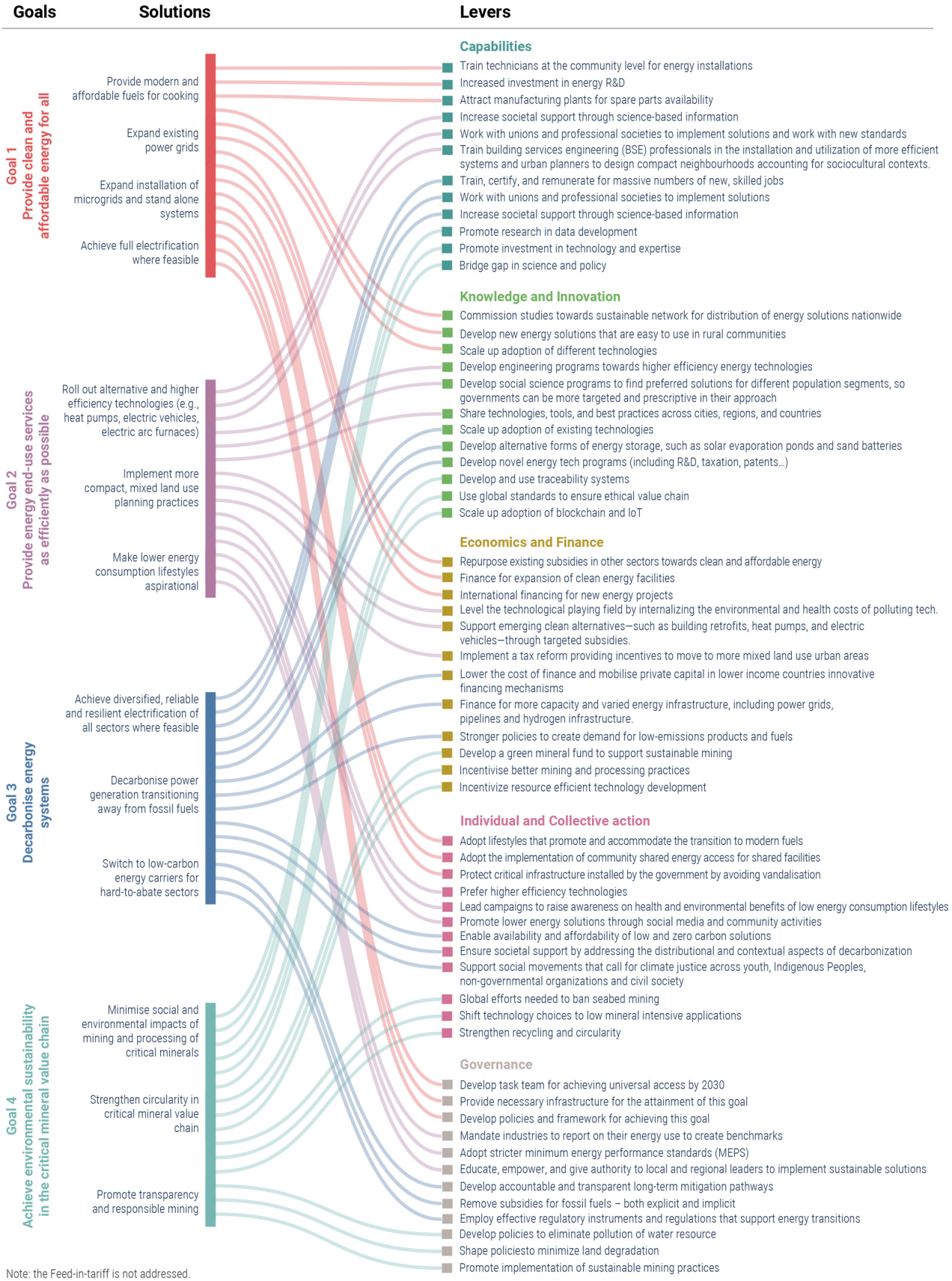
16.2.1 Solution pathway 1: Provide environmentally sustainable, safe, reliable, and affordable energy access and clean cooking, and eliminate energy poverty for all

There are three main technological options for bridging the electricity access gap, including stand-alone solar photovoltaic systems, mini-grids or distributed generation systems that utilize various renewable energy sources, and grid extension.

For clean cooking, diversifying fuel sources is essential. While eliminating the use of fuelwood is not yet viable for many rural families, options such as using efficient stoves as a transitional step towards switching to modern fuels or electrification, where feasible, are available.

Achieving universal access to electricity and clean cooking fuels by 2030 is estimated to cost US$45 billion annually. This amount represents less than 2 per cent of total projected spending on clean energy (United Nations 2023). Technically feasible pathways exist, although prioritizing community participation, acceptance, and adoption is essential, alongside significant needs for institutional strength and diverse financial mechanisms.

Figure 16.1: Representative Goals-Solutions-Levers (GSL) Diagram of the Solution Pathways for transformation of Energy Systems



Note: the Feed-in-tariff is not addressed.

Figure 16.2: **Solution Pathways for Energy Transformation**

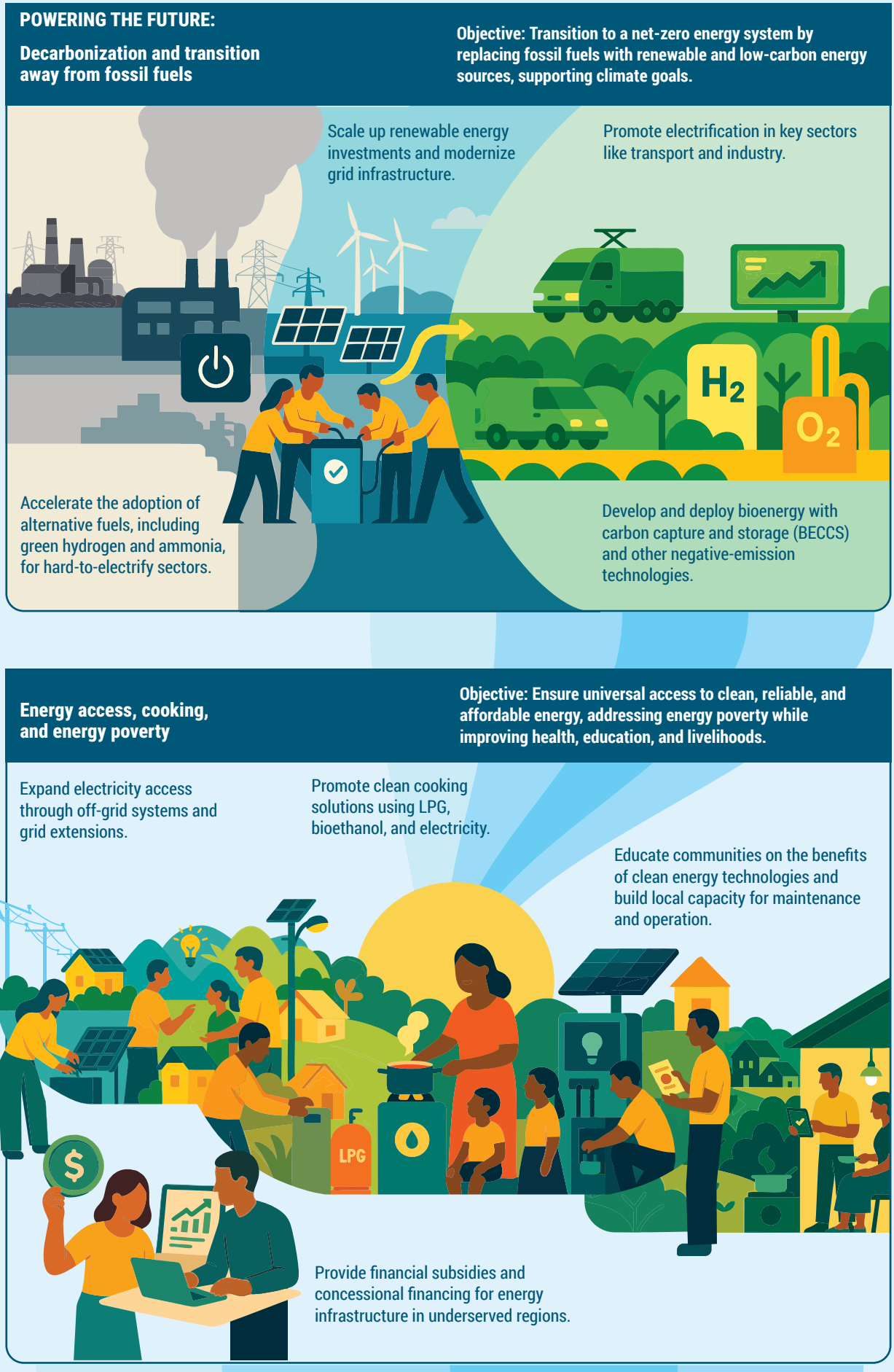


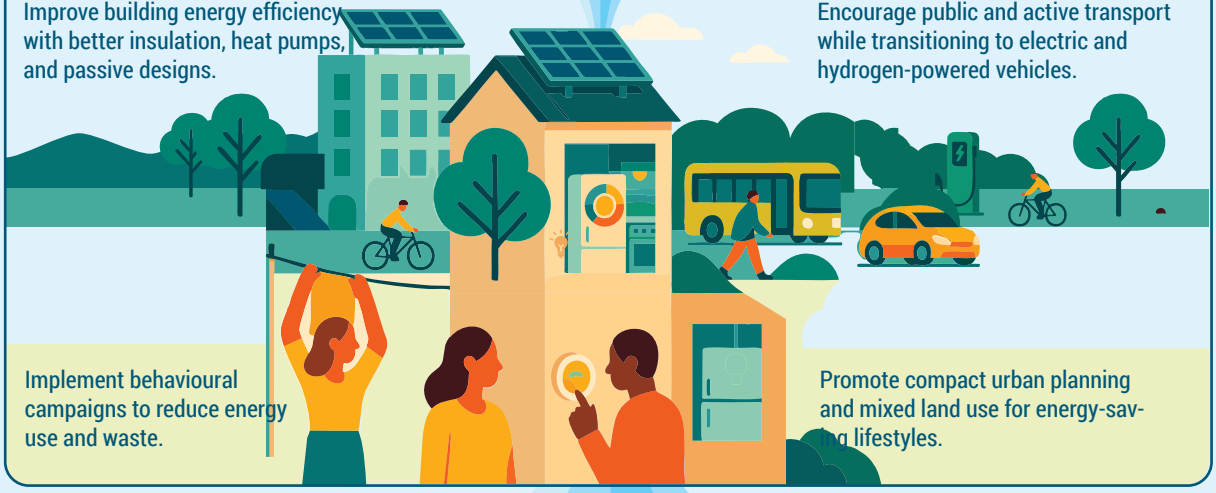
Figure 16.2: **Solution Pathways for Energy Transformation (cont.)**

Energy demand management

Objective: Reduce energy demand through efficiency, behavioural change, and land-use planning, lowering emissions and increasing resource efficiency.

Improve building energy efficiency with better insulation, heat pumps, and passive designs.

Encourage public and active transport while transitioning to electric and hydrogen-powered vehicles.



Implement behavioural campaigns to reduce energy use and waste.

Promote compact urban planning and mixed land use for energy-saving lifestyles.

Sustainable critical energy transition minerals value chains

Objective: Ensure responsible sourcing, production, and use of critical energy transition minerals to support the energy transformation while minimizing environmental and social harm.

Engage local communities and uphold Indigenous rights in mineral development.

Adopt sustainability standards for mining and processing CETMs.

Promote circular economy practices to reduce primary mineral demand.

Foster international cooperation for ethical and sustainable supply chains.

Achieving transformation through synergy

The four pathways must be pursued together to create an equitable, sustainable energy system. Combining these pathways enables co-benefits, reduces trade-offs, and accelerates the energy transition. By addressing systemic challenges and prioritizing inclusivity, these solutions contribute to meeting climate goals, advancing sustainable development, and enhancing global resilience.

Cultural and social factors, including different values and worldviews, as well as consultations and engagement in decision-making, are also crucial for the success of these efforts, especially concerning Indigenous Peoples and women. For example, practitioners are integrating the Mayan Cosmovision, their worldview, into the development of stand-alone solar photovoltaic systems in Indigenous communities in Guatemala. Another example is the need to provide targeted solutions that respond to the context of rural communities in Africa, Latin America and Asia to increase use of different types of efficient cookstoves while highlighting the dangers of relying on fuelwood for cooking (Bharadwaj et al. 2021; Tornel-Vázquez, Iglesias and Loureir 2024).

16.2.1.1 Current landscape

Universal energy access and elimination of energy poverty are critically needed for the growing global population. Efforts focus on expanding energy access through solar home systems, grid expansion, and providing clean cooking solutions. About 13 per cent of the world's population (roughly 940 million people) lacks access to electricity, while 40 per cent of the global population (around 3 billion people) does not have access to clean cooking fuels. (Ritchie et al. 2022). According to the World Energy Outlook 2023, the number of people without access to clean cooking is expected to decline by just over 15 per cent by 2030 (IEA 2023a). However, progress remains slow. Sub-Saharan Africa has seen only 5 per cent growth in access rates, while Latin America, including Mexico and Central and South American countries, has experienced around 4 per cent growth. Accelerated and sustained efforts are essential to meet the SDGs.

In 2019 the global electricity access rate was 90 per cent (Sustainable Energy for All [SEforALL] 2020). However, in the 95 countries with limited access, primarily concentrated in sub-Saharan Africa, only 82 per cent of people have access to electricity (United Nations 2020). Access rates are even lower in specific groups: 53 per cent in the least developed countries, 58 per cent in landlocked developing countries, 83 per cent in small island developing states (United Nations Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States 2021), and less than 10 per cent among displaced populations (NORCAP 2020). About 85 per cent of those without electricity live in rural communities.

Although the world is more than halfway towards achieving universal access to clean cooking worldwide by 2030, the number of people without access to environmentally sustainable, affordable, safe cooking energy is still increasing, especially in developing regions where population growth exceeds progress (IEA 2023a). Lack of access leads to millions of premature deaths each year, with women and children disproportionately affected due to their traditional roles in cooking and gathering fuelwood. Strategies to address this include targeted interventions for women, such as training programmes on the use of clean cooking technologies and financial support for women-led households to adopt these technologies (IEA 2023a). Additionally, women and children often face harassment and injuries when collecting fuelwood, especially during extreme weather events.

16.2.1.2 Solutions for clean electricity for all

Addressing this gap requires understanding the difference between electricity access and coverage, as well as the principles of energy poverty. For example, having access to the grid does not necessarily mean that a family or community can afford the connection or that the quality of service is adequate. Closing both the access and coverage gap can be facilitated through on- and off-grid solutions, although effective social, cultural, institutional, financing, and policy mechanisms still pose significant barriers. Key elements for improving electrification can be summarized as follows (Echevarría et al. 2017; Elabbas, Vries and Correljé 2023; Olówósejéjé et al. 2020; Puig et al. 2021, UNEP 2024a):

- Scaling up off-grid and mini-grid solutions: Depending on the specific context and population density, stand-alone systems may be necessary in areas. However, the greatest potential lies in expanding of mini-grids and distributed generation systems, either through single or hybrid technologies. Mini-grids might also be interconnected, supported by clear regulations and tariff structures, although this may not always benefit end users. Performance-based subsidies can motivate private sector investment.

- Expanding regional power pools: Harmonizing regulations and pricing structures, including bilateral agreements between countries, can

encourage trading, improve investments and build capacity. Expanding renewables-driven transmission infrastructure can support a clean, lower-cost, and more reliable grid. Examples include Electricity Integration of Central America, linking six countries, from Guatemala to Panama with additional bilateral connections between Mexico and Guatemala and Panama and Colombia, and the Southern African Power Pool, spanning 12 countries. These pools provide additional capacity, support integration of intermittent renewable energy generation and improve grid stability.

- Strengthening international funding structures and oversight: Building international partnerships that facilitate compliance and provide checks and balances for financing bodies, while enabling more coordinated and capital-intensive investments. This includes mobilizing concessional finance from

- Establishing supply-side and demand-side standards and incentives to support markets and address the affordability gap: Blended finance, which leverages public or concessional finance to attract private buy-ins, can strengthen the business case for energy projects, especially when supported by risk guarantees to reduce premiums. Demand-side subsidies, targeted for low-income groups and carefully tailored to local conditions, can support both affordability and market development.

- Local capacity is critical for effective policies, projects, workforce and compliance: For example, stable and predictable electricity policies and regulatory environments can improve compliance and development. Aligning local requirements with domestic capabilities supports project outcomes and just transitions. Development and adherence to quality and safety codes, along with certification and training, can prevent failures, ensuring reliability, quality and affordability, while building a skilled workforce.

- Investing in innovative grid technologies and digitalization: Smart grids, smart meters and data systems can improve grid efficiency and stability, enabling lower-cost and more targeted energy delivery. Supporting research and development strategies and startups working with digital innovations and AI can unlock new opportunities for deployment and use.

While grid expansion frequently provides benefits that outweighs the costs, it is not always feasible in rural areas of developing countries. Solar home systems have demonstrated their viability as a reliable source of electricity for households. Since 2015, annual sales of solar home systems with capacities above 11 Watt-peak have increased more than sevenfold in the sub-Saharan region (IEA 2023a). Such systems can supply enough electricity for basic energy needs, including lighting, phone charging, and a radio, although only systems above 50 Watt-peak are regarded as providing essential access (Energy Sector Management Assistance Program (ESMAP), GOGLA, Dalberg 2024.). These systems have also been criticized for not delivering quality electricity to users and for maintaining significant disparities in access and availability in rural areas (Monyei, Adewumi and Jenkins 2018). Enhancing enablers and levers such as donor agendas, training, product guarantees, access to spare parts, and most importantly, the acceptance of end users—who are often not consulted—can improve these outcomes. The installation and expansion of micro and mini-grids are also viable solutions that can give end users greater capacity to operate more appliances. Similar to stand-alone systems, distributed generation can also help create markets and opportunities. When implementing mini-grids as a solution, the challenge of policy restrictions on the sale of excess electricity generated by households should be addressed through inclusive stakeholder engagement.

Community energy access can speed up the shift away from energy poverty. Shared resources, which is a common approach in the health-care sector, can be extended to other community priorities (United Nations 2020). Community systems, regardless of the energy source, can make energy more affordable, especially for solar power (United States of America, Department of Energy 2023). For example, micro, mini, and small-scale hydroelectric systems can enable multiple productive uses and community benefits and can be combined with irrigation schemes to provide additional advantages to the watershed. In the case of communal solar energy, it also enables energy users to subscribe to a shared solar panel system, often

situated within their community, and enjoy the benefits of solar power (United States of America, Department of Energy 2023). There is also the potential to install a community biogas digester, especially in rural areas. However, proper characterization, planning, and definition are necessary to effectively process locally available feedstock. This will ensure the digester's proper performance. Household wastes are common feedstock for biodigesters (16.4) (Nwaigwe, Agarwal and Anyanwu 2018).

16.2.1.3 Solutions for clean cooking for all

A household is considered to have "clean cooking access" when it reliably uses as their primary cooking means, fuels and equipment that significantly limit or avoid the release of pollutants harmful to human health (IEA 2023b). Therefore, a household is considered to have access to clean cooking when it consistently uses one or more clean cooking technologies as its primary cooking mode for most meals, such as stoves using natural gas, liquefied petroleum gas (LPG), bioethanol, biogas, or electricity, (IEA 2023b). A shift towards clean energy sources for cooking entails a significant reduction in particulate matter (PM2.5) and carbon monoxide (CO) levels indoors, thereby reducing health risks (Rosenthal et al. 2018; Shupler et al. 2020). Globally, 2.8 billion people lack access to clean cooking fuels and technologies, which means will continue to face harmful household air pollution (United Nations 2020).

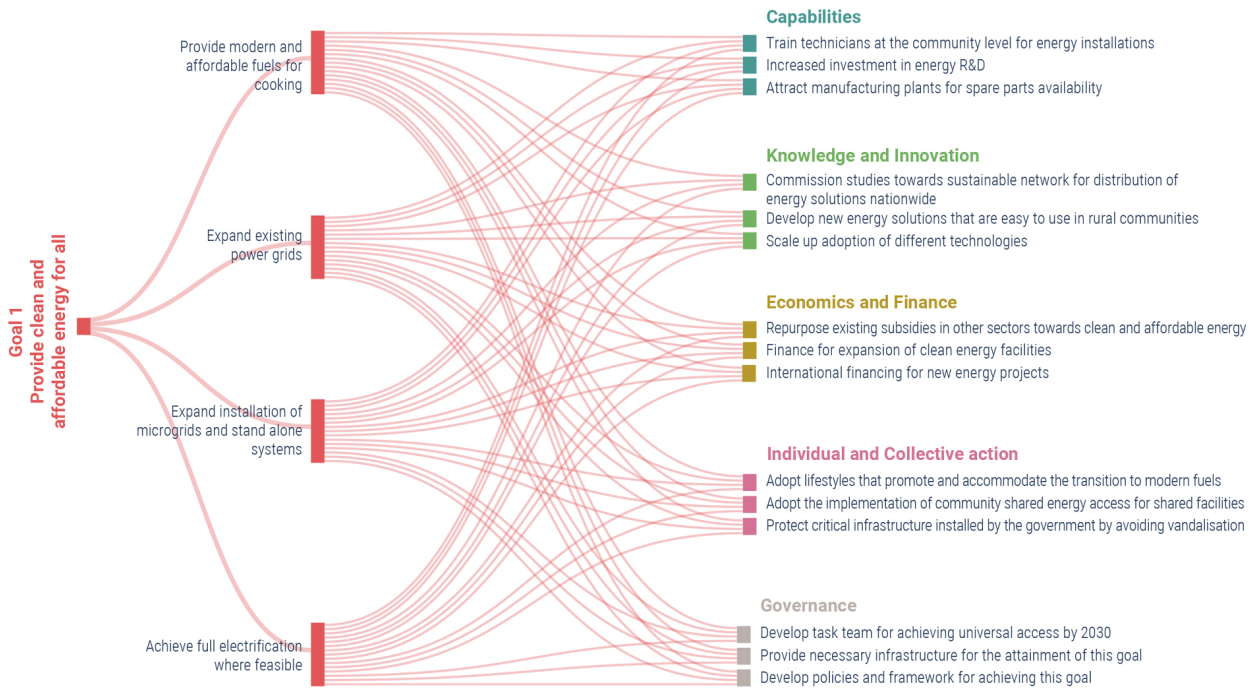
Reaching universal access to clean cooking fuels requires providing over 400 million people with access each year through the rest of the decade, with approximately half of them residing in sub-Saharan Africa. Today, fewer than 20 per cent of clean cooking plans are supported by clear financing schemes (IEA 2023b). The total investment in clean cooking access is significantly lower than what is needed to meet broader climate, health, and energy objectives. Currently, clean cooking investments are around US$2.5 billion annually and need to increase to US$8 billion annually from now until 2030, involving a cumulative investment of about US$60 billion (Coldrey, Lant and Ashworth 2023). Despite having the largest shortfall in clean cooking funding, only 7 per cent of the total investments made in clean cooking in the last five years have gone to Africa (Ritchie et al. 2021).

The expansion of existing power grids can also support clean cooking goals. However, as electrification is still under way, access to clean cooking also needs to be facilitated through modern fuels, specifically LPG for household cooking, and mainly through efficient cookstoves that still use fuelwood. It is crucial to consider the importance of cultural and social understanding and acceptance, which are not always guaranteed in rural communities. Therefore, all available options require proper introduction and acceptance before they can be adopted and used.

To achieve this solution, the following set of actions has proven successful in various contexts and is recommended to improve access to clean cooking (Gould et al. 2024; Kalli et al. 2022; Jeuland et al. 2023; Rochman, Kasim and Atmoko2023; Stritzke et al. 2021):

- Review subsidies: Governments should conduct a study to understand past challenges in cooking fuel subsidies, including implementation challenges that may hinder the provision of modern fuels to households.
- Track subsidized fuel purchases: Develop a database to monitor subsidized fuel purchases, limiting the quantity per person. Eligibility should be income-based, initially targeting the formal sector.
- Include informal communities: Local authorities should develop approaches for the distribution of cooking fuel via informal communities, considering living spaces and employment.
- Subsidize LPG: Governments should establish appropriately scaled financial subsidy for LPG.
- Support stove access with loans:Governments should consider providing financial subsidies and no-interest loans to low-income citizens for the purchase of safe, mechanically actuated LPG gas stove systems. The loan terms need to minimize financial burden for citizens, with disbursement facilitated through existing networks of commercial banks in coordination with governmental initiatives.
- Ensure safe infrastructure: Authorities need to mandate standards for safe LPG gas

Figure 16.3: Illustrative Goals-Solutions- Levers (GSL) diagram to show combination of solutions and levers to achieve goal 1



piping and regulators to connect the 12 kg size tanks to stoves.

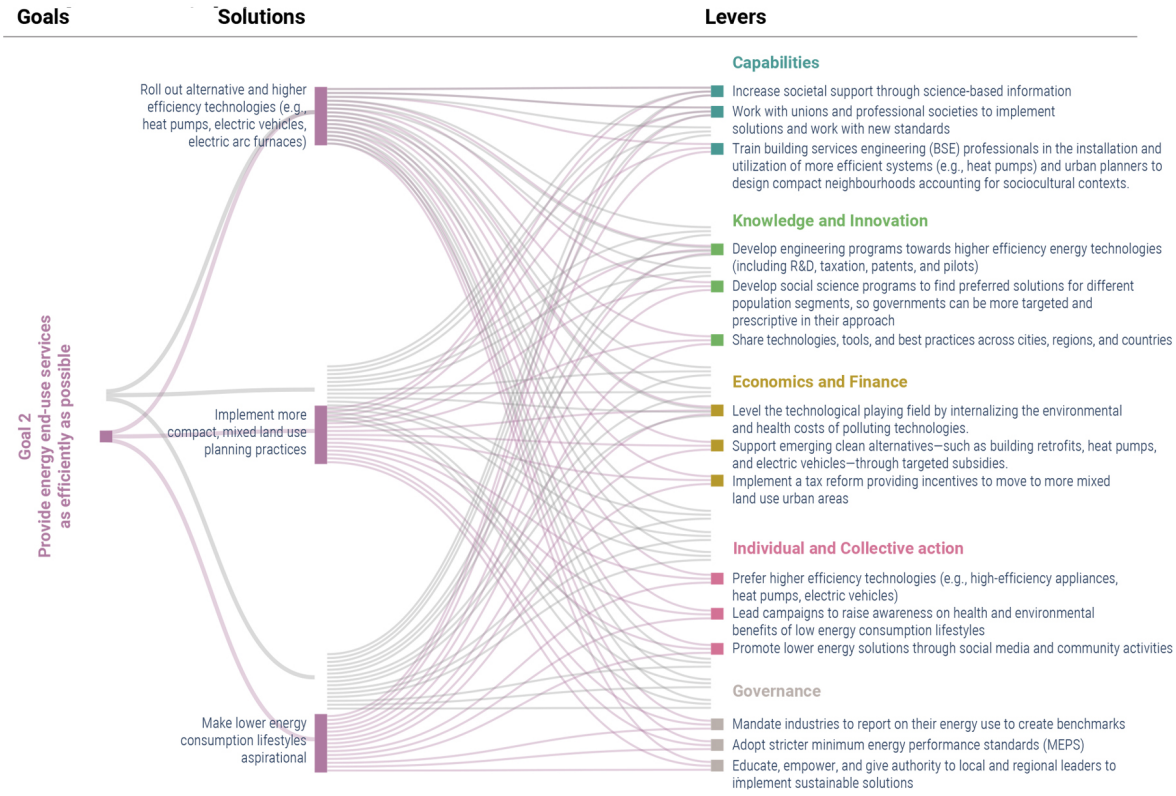
- Build community-level distribution networks: Establish local depots for subsidized LPG distribution to prevent monopolization. Tribal leaders should be involved in the distribution.
- Develop transport infrastructure: Create transport networks to supply remote and underserved communities.
- Certify and regulate: Implement state certification processes to ensure integrity of markets, components, products, installers, etc.
- Support adoption through capacity development: conduct education and training campaigns to introduce modern cooking technologies and address cultural barriers. Provide training on safe and effective use.
- Facilitate uptake through community demonstration initiatives: Launch demonstration initiatives at community-shared facilities to overcome the fear of new technologies.

There are social and behavioural consequences stemming from a lack of access to energy, and Indigenous Peoples are especially vulnerable. Each year, millions of premature deaths occur, with women and children being disproportionately affected, as one in three people in the poorest regions still cook over traditional open fire stoves, inhaling dangerous smoke daily (Malakar and Day 2020; IEA 2023b). In many rural communities, there is a cultural attachment to traditional cooking methods. Relevant government agencies must collaborate with local communities to transition to culturally appropriate, yet safe and efficient, cooking techniques.

Considering the negative effects of lack of energy access and energy poverty on large populations in developing countries, there is an urgent need to accelerate this transformation (Bonan, Pareglio and Tavoni 2017). To achieve the target set in SDG 7.1, it is recommended that the governments of developing countries establish and empower national task forces to ensure universal energy access by 2030 (United Nations 2020).

To achieve the necessary goal of providing clean and affordable energy for all, a summary of key solutions and actions is presented in **Figure 16.2**.

Figure 16.4: Illustrative GSL diagram to describe which combination of solutions and levers will achieve goal 2



16.2.2 Solution pathway 2: Improve energy management

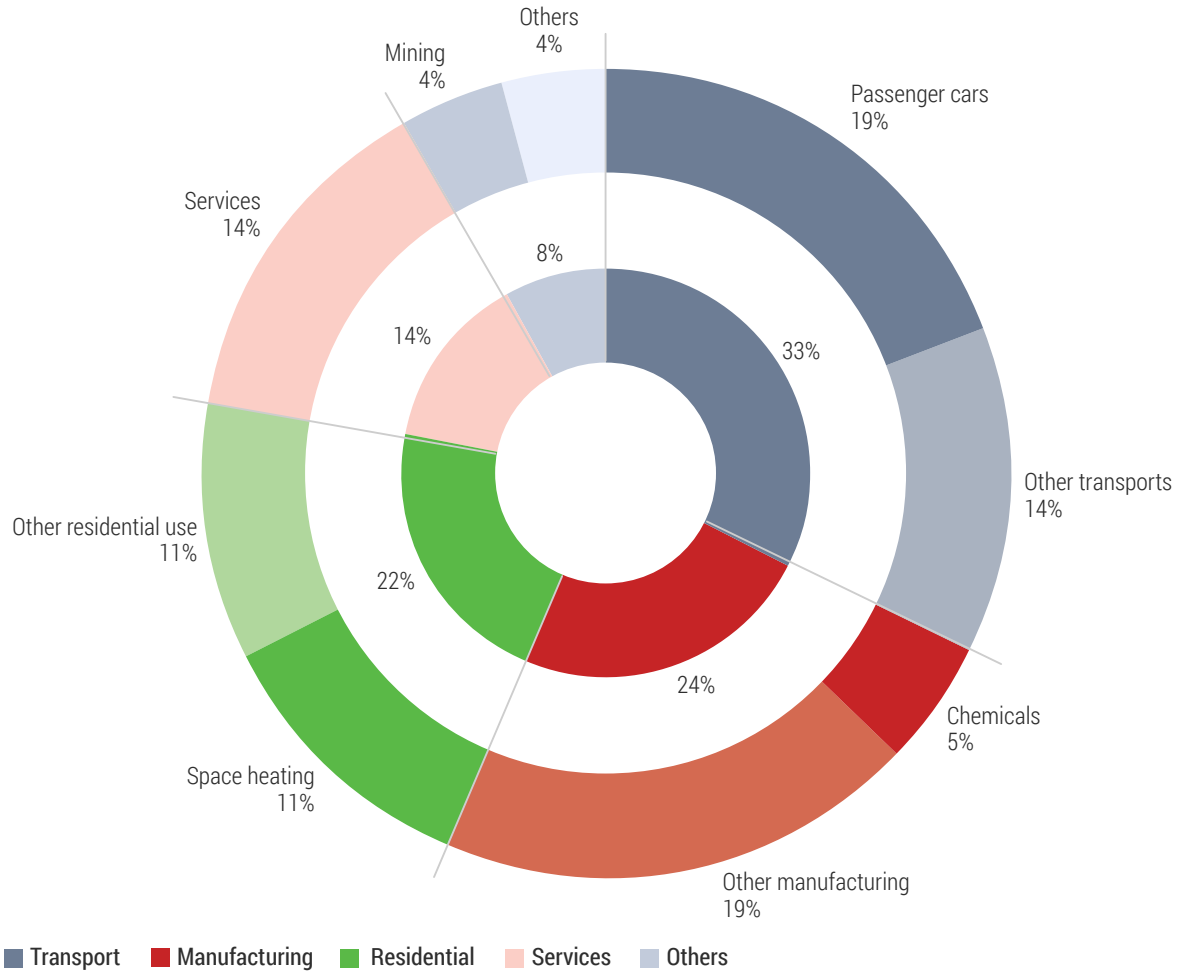
From buildings and transportation to electricity and stormwater, all infrastructure sectors require energy. Demand can be reduced through energy efficiency, land-use planning, and behavioural change. Energy efficiency solutions use better designs and technologies to replace or improve existing energy end-uses with a lower energy footprint, such as heat pumps instead of conventional furnaces. Land-use planning strategies promote practices that support lower energy consumption lifestyles and enhance human well-being – accessible jobs and grocery stores within a short distance of home – while safeguarding natural habitats. Behavioural change initiatives encourage people to reduce and conserve their energy use by adjusting their behaviour towards turning off equipment when not in use, switching travel modes, and recycling, for example.

Raising awareness and establishing the right regulatory and financial environments to encourage energy-demand reduction is crucial for gaining public acceptance and minimizing obstacles to implementation (Susskind et al. 2022; Ibrahim 2023; Carlander and Thollander 2023). Economic incentives such as subsidies for heat pumps and charging stations for electric vehicles, congestion pricing, or asymmetric property taxation could be introduced. Research and development programmes can be created to devise better energy-efficient technologies, to promote urban designs that are more sustainable, resilient and equitable, and to support more focused education campaigns that address the needs and concerns of various population segments.

16.2.2.1 Current landscape

The three largest energy end-uses are manufacturing, space heating, and passenger cars (**Figure 16.5**). The building sector accounts for 30 per cent of global energy consumption and 26 per cent of global energy-related emissions (IEA 2023c). Within buildings, space and water heating and cooling account for approximately 50 per cent of energy use (IEA 2023c), rising closer to 70 per cent in some regions (Derrible et al. 2021). The Buildings chapter of the IPCC's Sixth Assessment Report outlines many strategies to curb building energy demand (IPCC 2022b). Western cities generally expand with suburban areas that are less dense compared to their city centres. In contrast, residents of dense urban areas tend to consume less energy, have shorter or walkable commutes,

Figure 16.5: Energy use by sector in IEA countries in 2021



Source: IEA (2025)

and take public transport (Wiedenhofer, Lenzen and Steinberger 2013; Facchini et al. 2017).

16.2.2.2 Solutions for land-use planning

Energy consumption tends to be lower in mixed-use and more compact cities. Mixed land use as a combination of residential and commercial buildings leads to shorter distances to reach a destination. Denser street networks encourage walking and cycling. Smaller dwellings often require less energy (Estiri 2015; Bowley and Evins 2020).

In Europe, many cities densified in the 2010s, in part by leveraging real estate market mechanisms (Semprini et al. 2017; Cortinovis, Geneletti and Haase 2022). The fifteen-minute city concept can promote this densification by establishing most work, school, recreational and shopping amenities within a fifteen-minute walk, bike ride, or transit ride. This concept has been adopted and implemented in cities of all sizes and land-use patterns, from large, dense cities like Paris (World Resources Institute [WRI] 2023) to small, suburban communities like O'Fallon, Illinois, in the United States (O'Fallon Illinois 2022). When appropriately implemented with smooth sidewalks and no steps, the concept also has the potential to meet the needs of people with physical disabilities (Zivarts 2021; Buliung 2024). The C40 knowledge hub offers resources to implement this concept and showcases several case studies (C40 Cities Climate Leadership Group 2022).

Infrastructure, design, and maintenance practices need to be developed for both growing and shrinking cities (Zhai et al. 2022). In the United States, about half of the existing 30,000 towns are expected to lose population before 2100 (Sutradhar et al. 2024). Sethi et al. (2020) find that retrofitting existing urban areas and planning new compact urban areas can reduce GHG emissions by 50 and 23 per cent, respectively.

Land-use solutions are typically decided locally and encounter challenges such as high upfront costs and confusing, uncertain, or conflicting funding mechanisms (Khosla and Bhardwaj 2018). Local actions also require buy-in from both communities and land developers. Public campaigns, training sessions, and workshops help educate the public and local and regional actors, along with programmes that promote desirable and culturally sensitive land-use practices.

16.2.2.3 Solutions for more efficient technologies

New and more efficient technologies hold significant potential for reducing energy use. Even a non-exhaustive list of solutions by sector and their potential for energy reduction offers a wide selection of options (**Figure 16.6**). The effectiveness of these solutions is well established. The potential for reducing energy demand is provided as a general guideline, but it varies depending on the context. In particular, to adapt to climate change, further research is needed to better understand and manage the interdependencies and interrelationships between infrastructure systems (Movahedi and Derrible 2021; Movahedi et al. 2023).

16.2.2.3.1 Actions for buildings

Nearly net-zero energy, or low-energy, buildings are possible in most climate zones (IPCC 2022b; Reinhart 2025). Depending on local conditions including climate and technology availability, building retrofit efforts can reduce energy use by 13 to 36 per cent with shallow measures such as efficient lighting and appliances and 34 to 84 per cent with deep measures that involve better insulation and heat pumps, for instance (Ang et al. 2023).

Implementing heat pumps globally would reduce building energy demand. Heat pumps are three to five times more efficient than traditional technologies (IEA 2022a) and can be used for space heating, cooling, and water heating. As electrical devices, heat pumps increase electricity use, particularly during cold days in colder regions. Therefore, it is crucial to promote weatherization programmes, such as retrofitting buildings to suit the local climate, while also decarbonizing the electricity grid.

Heat pumps can also be strategically positioned. The Stockholm district heating network uses heat extracted from energy-intensive data centres to warm buildings. This could additionally support the information and communications technology sector, which consumes significant energy for cooling. (UNFCCC 2023a).

Passive designs that leverage natural shading and ventilation can reduce the energy needs for space heating, cooling, and lighting (Zhang et al. 2021; UNEP 2023). Positive-energy buildings can even produce more energy than they consume (Belleri et al. 2023).

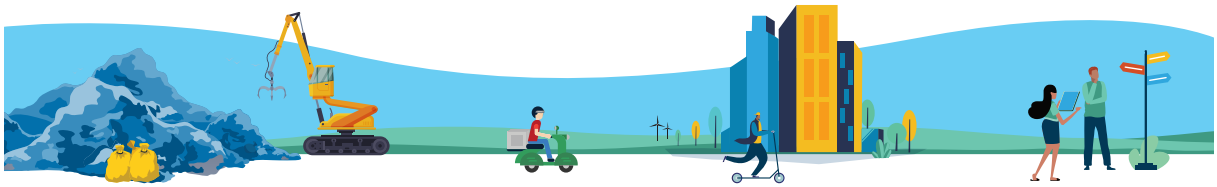
Green and energy-efficient buildings rely on the development of innovative, green-based, locally sourced materials to reduce heating loads in winter and cooling loads in summer. New materials, such as low-carbon alternatives to bricks and concrete blockwork, have been developed using natural fibres from agricultural waste and other low-cost materials (Goodhew et al. 2021, Touati et al. 2023). Green materials are also easier to dispose of. Solar-powered technologies such as solar water heaters can meet water heating needs.

Nature-based solutions such as green and blue infrastructure also offer many ecosystem services that can help reduce energy demand (Seidu et al. 2025). Rain gardens, bioswales, and sponge cities capture stormwater and prevent floods, reducing the need for pumping while also replenishing groundwater (McFarland et al. 2019). They can be implemented at various scales, from private homeowners to large building complexes and entire neighbourhoods, often supported through government programmes that educate the public about the practical and financial benefits of nature-based solutions (Dhakal and Chevalier 2017).

Energy-efficient equipment, such as smart thermostats, water heaters, and motion detectors for lighting can reduce energy waste. Smart meters allow real-time monitoring of energy use. Demand response strategies that encourage people to lower their consumption during peak periods can reduce the need for peaking power plants, which are often old and inefficiently powered by fossil fuels (Greening 2010; IEA 2024).

Stricter minimum energy performance standards can also encourage the adoption of new technologies, such as replacing conventional gas furnaces and boilers with heat pumps or enhancing building insulation. This can be further supported by international building labels and

Figure 16.6: Solutions by sector and their energy demand reduction potential



Solid waste

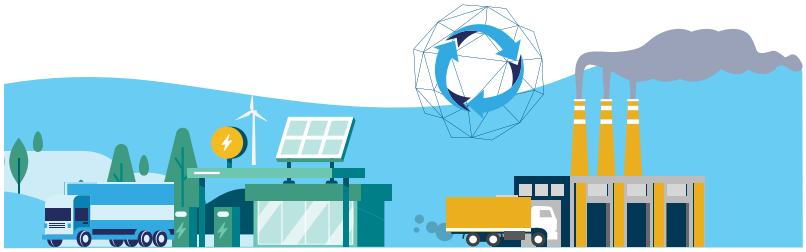
- Design products with recycling / elimination of waste in mind
- Organize recycling campaigns and programs
- Establish networks of industries for the recycling, repurpose, and remanufacturing of recyclable waste
- Reduce waste disposal
- Reuse products
- Recycle all waste that can be recycled
- Promote long-lasting product design
- Develop technologies to make more waste recyclable

Land use

- Medium to high densities of housing, jobs, and businesses
- Mixed land-use planning
- Denser street network/smaller blocks
- Transit-oriented development (TOD)
- Green and blue infrastructure

Buildings

- Air-source or ground-source heat pumps for space heating and cooling
- Right sizing (not too big)
- Compact buildings (minimize surface area exposed to outdoors
- Passive designs (natural shading and ventilation)
- Building insulation
- White-blue-green roofs
- Solar thermal systems (water heating)
- High efficiency air conditioners
- Adopt stricter minimum energy performance standards (MEPS)
- Building orientation
- Sealing leaks
- High efficiency windows (double or triple pane with low emissivity glass)
- Reflective (low-emission) materials for walls and roofs
- Smart buildings (Buildings Management Systems (BMS)
- Smart thermostat
- High efficiency appliances
- Dynamic demand (appliances partly controlled by utility provider such as refrigerators and EV charging)
- District heating and cooling networks for dense areas
- Solar panels (prosumerism)
- Phase out incandescent light bulbs universally
- Universal adoption of smart meters
- Regulate thermostat settings, especially in commercial buildings
- Turn equipment off or down when not needed
- Adjust water heater setting
- Adjust thermostat



Transport

- Shift fossil fuel-powered vehicles to electric and hydrogen
- Dense street network conducive to active and public transport use
- Adopt energy-efficient technologies for aviation and shipping
- Promote active and public transport use
- Reduce long-haul flights
- Ban short-haul flights and shift to train when possible
- Encourage people to walk and bike, and ride public transport
- Advance vehicle light-weighting
- Promote telework, telemedicine, distance learning
- Carpooling

Industries

- Electrify low-temperature heat applications
- Promote best available technologies (BAT) across the iron and steel sector, including scrap-based electric arc furnaces
- Replace old, inefficient equipment
- Use high efficiency electric motors
- Reuse and recycle construction and demolition waste from industries
- Promote and facilitate industrial symbiosis
- Promote and facilitate circular economy
- More efficient process designs

*The list is not exhaustive. Energy demand potential reduction offers a general indication and is context-dependent

Low-medium-high energy demand reduction potential

Solution type: Design; Technology; Institutional; Behaviour

certifications like Energy Performance Certificates in Europe and Leadership in Energy and Environmental Design and WELL Building Standard in the United States. Building energy labels have effectively stimulated private interest and investment in improving building energy efficiency (Gerassimenko, Defau and De Moor 2024; Khazal and Sønstebø 2023). These certificates provide a thorough energy assessment of a building, informing owners about possible efficiency upgrades and acting as an estimate for energy costs for prospective tenants or owners.

16.2.2.3.2 Actions for transport

Electricity- and green hydrogen-powered vehicles can help decarbonize the transport sector. Electricity is preferable for vehicles, hydrogen for aircraft, and hydrogen-based fuels for vessels (16.2.3.2). In some contexts, compressed biogas from the anaerobic digestion of organic waste such as post-harvest residue and manure offers potential as a short-term transport fuel (Xia, Cheng, and Murphy 2016; Nouni et al. 2021).

Various policies, programmes, and incentives exist, ranging from subsidizing the retrofit of existing vehicles to encouraging the purchase of new vehicles and building charging stations. Replacing one vehicle with another is not sustainable in areas that experience chronic traffic congestion. Traffic congestion affects energy consumption, economic growth, and human well-being. Travel demand management strategies can be implemented to reduce traffic congestion. These include promoting active and public transportation, incentivizing carpools through high-occupancy vehicle lanes and other tools, and encouraging remote work arrangements (Victoria Transport Policy Institute [VTPI] n.d.; IPCC 2022b).

Active and public travel modes are preferred. Insufficient investment in and promotion of public transport increases congestion and hampers economic development (Organisation for Economic Co-operation and Development [OECD] 2020). Active transport, such as walking and cycling, also offers health benefits (Mizdrak et al. 2023) and improves satisfaction (Schwanen 2021). To make active and public transport appealing, infrastructure must be in place, including sidewalks, bicycle routes, bicycle parking, transit-oriented development, integrated public transport routes, and denser street networks. (National Association of City Transportation Officials [NACTO] n.d.; Institute for Transportation & Development Policy [ITDP] n.d.; WRI 2021; Derrible 2025).

With air transport, short-haul flights have a higher emission factor per kilometre than medium and long-haul flights. Many regions offer lower-energy trains and buses to short-haul destinations. France has banned short-haul flights when a train alternative is available with a travel time of 2.5 hours or less. Many meetings can also be held online; a 50 per cent switch to online meetings with a careful selection of transport hubs to hold meetings is estimated to reduce carbon emissions by 60-70 per cent (Tao et al. 2021).

16.2.2.3.3 Actions for industry

Governments can require industries to report their energy consumption for benchmarking and use this data to analyse energy use patterns, which can lead to reduced energy demand. Maintaining and promptly replacing old equipment provides key opportunities to cut energy demand (IEA 2021a). When replacing equipment, industry can adopt best available techniques, such as using electric arc furnace technologies or hydrogen-based direct reduction processes (Kim et al. 2022). Bifacial and translucent solar technology that lets light in and generates electricity can be installed on roofs or covers of industrial warehouses, as well as agricultural and commercial roofs (Gupta, Kumar and Singh 2024). Many industries employ dedicated managers or work with energy consultants to monitor their energy consumption. Collaborating with these specialists offers opportunities to identify effective energy reduction strategies that consider local conditions. (Zierler, Wehrmeyer and Murphy 2017; Oksman et al. 2021; Succar et al. 2023).

The concept of industrial symbiosis also offers opportunities to create networks of industries located near one another that share or exchange goods (15.3). For example, several industries can collaborate on a district heating or cooling system. Kalundborg in Denmark provides a good example, involving 16 public and private companies (Chance et al. 2017). Creating networks for recycling, repurposing, remanufacturing, and reusing materials – especially metals, plastics, and glass – as well as reusing waste heat, presents important and often untapped opportunities to cut energy use. These solutions are usually carried out by networks of co-located industries, but they can also be encouraged or catalysed by governments.

16.2.2.3.4 Actions for solid waste

Figure 16.6 shows conventional solutions to reduce energy demand and emissions from the solid waste sector. According to the IPCC's Sixth Assessment Report, end-use strategies, including increasing the reusability, recyclability of products and materials, and adopting materials-efficient services, can reduce emissions in the industry sector by 29 per cent, 4.4 $GtCO_2$, by 2050 (IPCC 2022b). Further, applying circular economy strategies in the five key sectors of cement, aluminium, steel, plastics, and food can reduce 9.3 $GtCO_2$ equivalent in 2050, which is equivalent to all transport emissions (Ellen MacArthur Foundation and Material Economics 2021).

16.2.2.4 Solutions for behavioural interventions

Public support for extensive action to combat climate change is growing (United Nations Development Programme [UNDP] 2021; Dechezleprêtre et al. 2025). This can be leveraged to promote lower-energy lifestyles and compact living arrangements, focusing on benefits to human health and personal finances, not just the environmental impacts. Lower consumption will also require supporting infrastructure, such as adequate public transit systems or bicycle paths.

Programmes that target behaviour change have the potential to curb energy demand while being cost-effective and offering direct and indirect financial benefits (Kastner and Stern 2015). Zhang et. al (2018) estimate that behaviour change can lower energy demand between 10 per cent and 25 per cent for residential buildings and between 5 per cent and 30 per cent for commercial buildings. Many programmes, however, have limited success because they fail to reach their target audience. Research funding can be allocated to identify preferred solutions for different population segments and develop decision-making tools, enabling governments to be more targeted and prescriptive in their approach (Fontecha et al. 2022). In the European Union, programmes like Playing My Part have been successful in raising awareness and involving people more directly (IEA 2022b). A promising but underutilized strategy to align perceptions with objective realities (Bell and York 2010) is to hire social media influencers to convey positive and energy conservation messages to their followers (Bhukya and Paul 2023, Agarwal, Kumar, Gunasekaran 2024). For example, in mid-2024, the concept of "underconsumption core" trended on social media. The concept encouraged people to buy only what they needed (Fares and Lee 2024). The adoption of information-based tools such as energy labels on appliances has also gained popularity. While they may influence people's purchasing behaviour, the relationship is complex and often not sufficient (Zainudin et al. 2014; Beck and Özçaglar Toulouse 2023; Basiru et al. 2024).

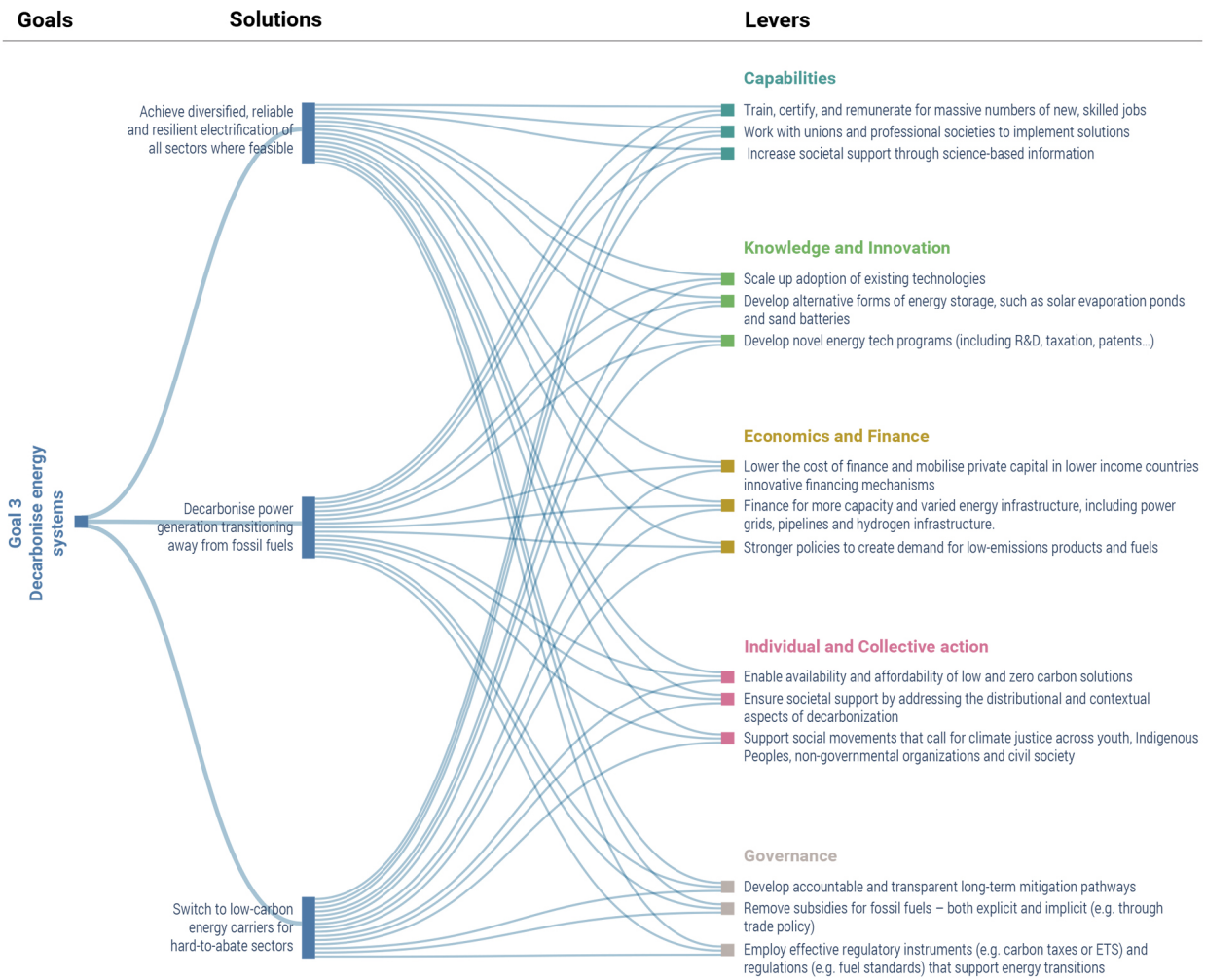
16.2.3 Solution pathway 3: Decarbonize and transition away from fossil fuels

While it remains technically feasible to reach the Paris temperature targets, comprehensive regulatory and economic approaches to support these pathways are essential. Affordable and reliable technologies, such as the rapid decrease in prices and effectiveness of solar and wind power, can support electrification. Diversifying energy systems requires regulatory and long-term certainty to drive adoption and develop new markets. Increasing and retraining the workforce can support just transitions, while implementation efforts should recognize that livelihoods are deeply tied to cultural and social ways of life.The experience of the Pavagada solar park in Karnataka, India illustrates this point, where landless agricultural labourers not only lost their primary income sources but also their connections to land-based traditions and community identities, underscoring the importance of more democratic ownership and governance of renewable energy initiatives (Ghosh, Bryant and Pillai 2023).

16.2.3.1 Current landscape

The costs of renewable energy, particularly solar photovoltaics, wind power and batteries, have fallen rapidly. Their cost reductions and faster adoption rates have surpassed those of other technologies such as fossil fuels combined with carbon capture and storage or bioenergy with carbon capture and storage (BECCS). (IPCC 2022b). Solar and wind energy registered record investment levels in 2022, with a growth of 266 gigawatts (GW) in generating capacity (Energy Institute 2023), including in developing countries (Nwaigwe 2022). Renewable energy production increased by 14 per cent in 2022, with notable increases in the Middle East at 19.9 per cent and Asia and the Pacific at 17.6 per cent. However, despite significant growth in renewable energy, around

Figure 16.7: Illustrative GSL diagram to describe which combination of solutions and levers will achieve Goal 3



four times more electricity was generated by coal, oil, and gas with 17,677 TWh than by renewable sources with 4,204 TWh in 2022 (Energy Institute 2023).

Global greenhouse gas emissions reached a record high of 53.0 $GtCO_2$ equivalent in 2023. Most of these emissions came from fossil CO_2, accounting for 73.7 per cent of the total, while methane contributed 18.9 per cent, nitrous oxide 4.7 per cent, and fluorinated gases 2.7 per cent (Crippa et al. 2024). The IEA Net Zero Roadmap can serve as a guide to the emissions from the energy sector (IEA 2023d).

16.2.3.2 Solutions for the electrification of all sectors

Limiting warming to 1.5°C by the end of the century requires a rapid increase in energy produced from low- or zero-carbon sources, reaching 74–82 per cent of primary energy in 2050, up from below 20 per cent in 2019 (IPCC 2022b). This transition needs to be supported by electrification of the most intense energy sectors, such as transportation, heating, and industry, powered by low- and zero-carbon energy.

Developing a diversified, reliable and resilient electrification of all end-uses and sectors, along with decarbonizing electricity generation, is a crucial near-term strategy for limiting warming (Clarke et al.2022). In scenarios that aim to limit warming to 1.5°C (>50 per cent with no or limited overshoot), low- and zero-carbon sources produce 97–99 per cent of global electricity in 2050. Even in scenarios that limit warming to 2°C (>67 per cent), 93–97 per cent of electricity still comes from low- and zero-carbon sources. By 2030, zero-carbon electricity generation should account for 62-92 per cent, alongside the phaseout of unabated

coal generation (Clarke et al.2022). Renewable electricity is growing exponentially rather than linearly, aligning with net-zero pathways by 2050 (WEF 2023a). However, land-use competition for renewable energy, such as solar and wind, and particularly bioenergy cropland in densely populated countries, may limit growth (van de Ven et al. 2021; Braun et al. 2025).

A major obstacle to expanding renewable energy is the existing grid system, which in many cases is outdated and lacks sufficient capacity, especially for the anticipated growth in renewable energy. Investment in grid infrastructure track with net-zero emissions by 2050 (IEA 2022c). Additionally, to balance the intermittent supply from solar and wind and stay on track to reach net zero by 2025. This can be supported by alternative energy storage methods, including hydrogen and other technologies that require further development, such as solar evaporation ponds, sand batteries, flow batteries, and gravity storage. Other barriers include the availability of critical energy minerals and expanding energy access to communities without electricity, as discussed in Sections 16.2.4 and 16.2.1, respectively.

16.2.3.3 Solutions for transitioning away from fossil fuels

The key to progressing on these pathways is transitioning away from fossil fuels. By 2030, demand for oil and gas needs to decline by approximately 20 per cent, which is consistent with the need to stop new conventional development of oil and gas (International Institute for Sustainable Development [IISD] 2022; IEA 2023a). Phasing out fossil fuels is technically feasible and is estimated to be relatively low in cost (IPCC 2022b).

Greater energy system integration across energy sources and regions is essential to enhance energy systems' flexibility and efficiency, optimize costs, and bridge regional energy disparities. System integration can also support aligning different policy objectives beyond energy supply, including sustainable development and carbon dioxide removal (CDR). Major contributions to emissions reductions at costs below US$20 per tCO_2-eq^{-1} come from solar and wind energy, energy efficiency upgrades, and reductions in methane emissions from coal mining, oil and gas, waste and other sources (IPCC 2023a).

Energy crops, biogenic waste and residues feature prominently in mitigation pathways that limit global warming to 1.5°C by the end of the century, either as feedstock for low-carbon bioenergy, or for carbon removal through BECCS or biochar, a carbon-rich, stable substance produced by heating biomass in a low-oxygen setting (IPCC 2018). By 2050, the IPCC's Sixth Assessment Report mitigation pathways with no or limited overshoot project a median annual delivery of 118 exajoules of primary energy via bioenergy and 3.8 gigatons CO_2 removed annually with BECCS deployment (Byers et al. 2022). However, large-scale deployment generates trade-offs related to land, water, and fertilizer demand with implications for food security and biodiversity conservation, which may substantially constrain sustainable expansion of bioenergy cropland with or without carbon capture and storage (IPCC 2023b; Deprez et al. 2024; Braun et al. 2025).

Rapid and deep decarbonization is required to preserve CDR methods for truly critical needs in hard-to-abate sectors (Buck et al. 2023; Shindell and Rogelj 2025). A portfolio approach is required to balance the diverse trade-offs of CDR options in terms of implementation challenges, environmental implications, and impacts on economic prosperity and well-being (Fuss et al. 2020; Prütz et al. 2024). However, CDR is needed in the context of net-zero CO_2 to balance any residual emissions from hard-to-abate sectors (Rogelj et al. 2018a; Luderer et al. 2018; Strefler et al. 2018; IPCC 2022b), such as aviation, shipping, or industry (IPCC 2022b). Beyond net-zero CO_2, CDR is also necessary to achieve net-negative CO_2 emissions, to reverse warming after a temporary temperature overshoot (Rogelj et al. 2018b). As mentioned previously, CDR remains unproven at scale and poses severe trade-offs related to land, water, energy, and fertilizer demand, with implications for biodiversity conservation and food security (Deprez et al. 2024; Prütz et al. 2024; Braun et al. 2025).

16.2.3.4 Solutions to switching to low-carbon energy carriers

Alternative fuels or energy carriers such as advanced biofuels, hydrogen, ammonia, or synthetic methane are needed to support decarbonization in

sectors that are harder to electrify (IPCC 2022b). These sectors include freight, aviation, shipping, and energy-intensive industries. Hydrogen and ammonia can also serve as replacements in fossil-fuel power plants, playing a crucial role in ensuring electricity security during clean energy transitions (IEA 2021b). Additionally, their growing importance as energy storage – converting surplus electricity into hydrogen through electrolysis and reconverting it into power, for example – highlights their significance in the clean energy transition. (Aneke and Wang 2016).

Green hydrogen is expected to contribute to 14 per cent of the final energy demand by 2050, helping meet the 1.5℃ by the end of the century (International Renewable Energy Agency [IRENA] 2023). This entails an expected installed capacity of 5,700 GW by 2050, a fivefold increase from 2020 (World Trade Organization [WTO] and IRENA 2023). Shifting from hydrogen, currently a net emitter, to green hydrogen requires producing it from zero-carbon or extremely low-carbon energy sources. The cost-effectiveness of green hydrogen is supported by increasing renewable capacity and decreasing the costs of electrolysers. The development of green hydrogen supply has been hindered by the current lack of demand. However, credible decarbonization policies and transitions for fossil fuels should boost demand.

Green hydrogen is considered one of the leading decarbonization pathways for the steel and chemical sectors. It can be used in a variety of industrial processes, such as replacing coal as a reducing agent in the steel production, substituting oil as raw material in the chemical industry, and for heating in industrial furnaces for the glass, cement and steel industries (United Nations Industrial Development Organization [UNIDO] 2022). If green hydrogen can be used at scale to process iron ore, steel production can be carbon-neutral (IPCC 2022b). As for the chemical sector, about 28 per cent of emissions reduction from the sector can be achieved using electrolytic hydrogen by 2050 (IEA 2023d).

With electric aviation still in its early stages and limited to smaller electric aircraft (Schwab et al. 2021), alternative fuels are a key to decarbonizing aviation. Renewable jet fuel only accounts for less than 0.1 per cent of the current global jet fuel demand. Eventually, hydrogen-fuelled aviation could be cheaper than using kerosene, although it would require approximately four times more fuel by volume (Yusaf et al. 2024).

16.2.4 Solution pathway 4: Shift to a responsible and sustainable Critical Energy Transition Mineral Value Chain

The shift to clean energy is mineral intensive. Approximately 30 to 50 minerals, including rare earth elements, remain critical for energy system transformation. The list of these critical energy transition minerals (CETM) varies across different countries, depending on their availability and accessibility (e.g., Government of Canada 2022).

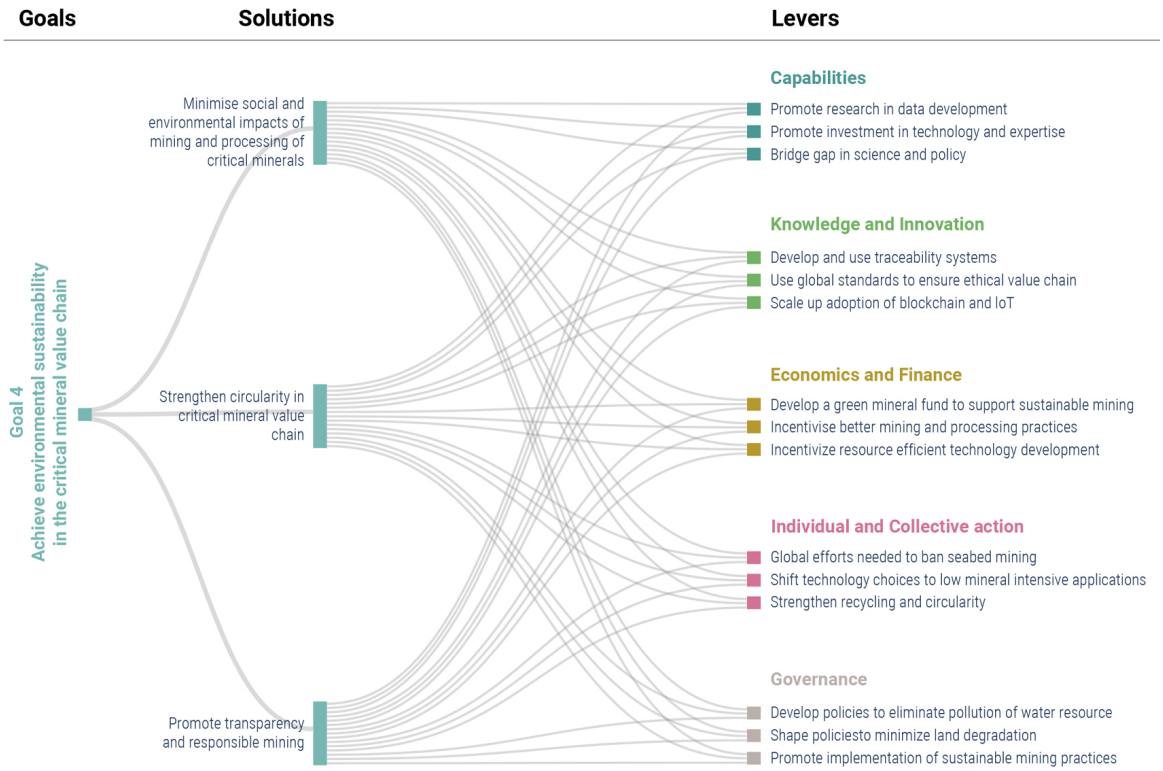
The three main strategies for the CETM value chain are to reduce social and environmental impacts, enhance circularity and resource efficiency, and establish a just and responsible value chain with benefit-sharing mechanisms. Eliminating water pollution is essential for all stakeholders, which requires strict regulations on the contamination of surface and groundwater sources. Similarly, attention must be given to reducing land degradation, as it can threaten food systems and biodiversity if neglected. The rights of Indigenous Peoples and CETM value chain workers must also be protected, and any harm to their livelihoods, as well as the livelihoods of surrounding communities, needs to be addressed.

16.2.4.1 Current landscape

The total mining production including that of mineral fuels grew from 11.3 billion metric tons in the 2000 to 17.9 billion metric tons in 2021 (Austria, Federal Ministry of Finance and International Organizing Committee for the World Mining Congress 2023). Demand for CETMs could surge significantly in the coming years (United Nations 2024). Minerals such as graphite, lithium, and cobalt could see a nearly 500 per cent increase by 2050 compared to 2018 (Hund et al. 2020). The COP28 goal to triple the renewable energy capacity worldwide could significantly increase demand for CETM supplies. The CETM production grew by 30 per cent in 2022, compared to the previous year (IEA 2023g). Over the last decade, reserves of lithium and copper grew by 40 per cent and 30 per cent, respectively (IEA 2022d).

Over 23 million people worldwide are estimated to be negatively affected by toxic pollution in land and

Figure 16.8: Illustrative GSL diagram to show combination of solutions and levers to achieve Goal 4



water resources caused by past and current mining activities. (Macklin et al. 2023). An increase in mining and processing activities is raising concerns about the unintended environmental, social, and economic consequences that can potentially jeopardize the equitable benefits of the energy transition across countries. Mining and processing activities pose serious threats to ecosystems and biodiversity in several regions. In 2019, about 80 per cent of global metal extraction occurred in most species-rich biomes (Sonter et al. 2020; Luckeneder et al. 2021), causing irreparable ecological damage and biodiversity loss. For example, in Eastern Brazil, over 30 per cent of the habitat for bird or frog species is directly or indirectly affected by mining (de Castro Pena et al. 2017), with a potential ripple effect on the region's biodiversity. In Brazil and Colombia, significant loss in biodiversity has been observed (Siqueira-Gay et. Al. 2020; Ruiz-Agudelo et. al. 2025). Globally, at least 54 per cent per cent of energy transition minerals projects – involving upstream and midstream activities – are located on or near Indigenous Peoples' territories. (Salvador et al. 2020; Owen et al. 2023). Indigenous Peoples, as well as local communities play a significant role in global biodiversity conservation, while mining projects and infrastructure threaten their biocultural diversity through ongoing rights infringements and environmental injustices that affect their populations and their territories (United Nations, 1948; United Nations 2007; Owen et al. 2023).

Mining and processing activities are very water-intensive, leading to irreparable damage to freshwater resources. Many mines around the world are also situated in or near areas facing severe water stress (Kunz 2020). The effluents from mining and processing facilities frequently pollute water sources, posing significant risks to the environment and human health (IEA 2022d). In numerous other regions, mining activities have caused surface and groundwater depletion, contamination, and land degradation. For example, in the Loess Plateau mining area of China, data from 2017 and 2019 indicate an average decrease of 8.66 g of soil organic matter per kilogram of soil (Wang et al. 2021), which is crucial for biological functions in agricultural lands (Zhang et al. 2023).

The mining and processing activities are also energy-intensive, relying heavily on fossil fuels. The mining sector alone accounts for approximately 1.7 per cent of global final energy consumption (Aramendia et al. 2023). Fossil fuels have accounted for 70 per cent of the energy used in the sector's operations (United States Department of Energy 2007), with average CO_2 equivalent emissions from the industry ranging from 4.6 tons per ton of copper to 75.8 tons per ton of neodymium oxide (IEA 2023e). Among

the top 10 countries with the largest GHG emissions from their mineral material sector, China tops the list (Zheng et al. 2023).

16.2.4.2 Solutions for improving the circularity of the critical energy transition metal sector

In the CETM sector, the inefficient use of materials and unregulated waste disposal exacerbate the challenges and damage the environment (UNDP 2016; IEA 2022d). Integrating circularity into CETM industry practices can reduce the emissions related to the extraction of various minerals (Babbitt et al. 2021; Safarzynska, Di Domenico and Raberto 2023; Toledano, Brauch and Arnold 2023; UNEP 2024b). Circularity needs to be built into every aspect of the value chain, from material energy requirements for mining to waste processing, requiring careful planning. Examples such as the European Union initiatives on battery recycling (European Commission 2023a) and the OECD Due Diligence Guidance (2018) illustrate promising approaches. Additionally, as technology evolves, emerging technologies are also likely to be less mineral intensive.

Another effective way to reduce the environmental footprint of the CETM sector is to promote urban mining and maximize recycling of minerals. While the current recycling rate for several minerals is very low, recycling can help meet a significant portion of the demand. Efficient recycling methods could supply up to 20 per cent of the total mineral demand between 2022 and 2050. (WWF 2022).

New and advanced technologies are needed to enhance the circularity of the CETM sector. While some industry players are adopting several technology changes, including electrification and energy-efficient practices (Mining Technology 2022), broader implementation is needed. Further, to track circularity and sustainability practices in the CETM value chain, advanced digital technologies, such as blockchain (Calvão and Archer 2021; IEA 2023f; Meier, Gruchmann, and Ivanov 2023), can play a crucial role. Blockchain can provide transparency, ensuring adherence to sustainability and equity standards and helps prevent black market activities (Calvão and Archer 2021). Additionally, standardizing national databases for the exchange of information across the value chain is essential for informing policy decisions.

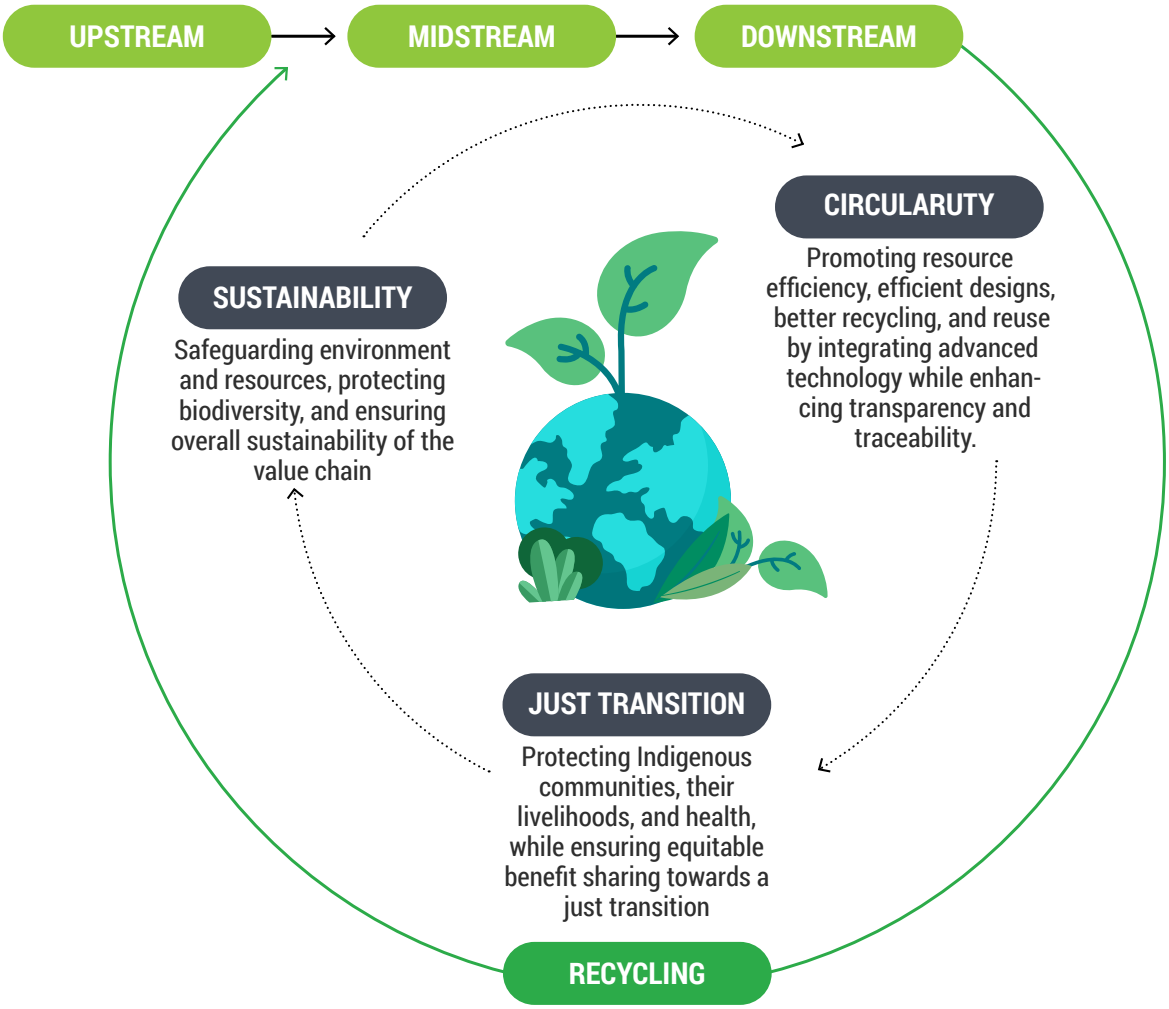
Finally, promoting circularity will also foster innovation in advanced technologies, which can help develop applications that are less mineral intensive. As the clean energy transition accelerates, there may be substantial demand for opening new mining and processing sites. Mining in unexplored and sensitive areas, especially ocean ecosystems, can have far-reaching and negative consequences. (Levin, Amon, Lily 2020). In 2024, Norway approved commercial deep-sea mining despite concerns from the international community about its potential unintended consequences (Nature 2024). Global mechanisms, including the United Nations Convention on the Law of the Sea, can present a negotiating space through which these mining initiatives can be litigated and potentially banned.

16.2.4.3 Solutions to reduce the environmental aspects of the critical energy transition minerals sector

Responsible mining and processing activities, along with effective waste management, are crucial for reducing environmental damage. Programmes such as the Climate Smart Mining Initiative (Hund et al. 2020) can assist mineral-rich countries in minimizing social, environmental, and climate impacts. For instance, policies could be implemented to strictly regulate mining and processing activities in medium-high to extreme water-stressed areas. Existing and new mining could also be heavily restricted in regions of high biodiversity or cultural value. For example, governments could restrict mining within any of the categories of land areas classified by the International Union for Conservation of Nature as in most need of conservation (International Union for Conservation of Nature [IUCN] 2013) or protected under any international institutions' directives, such as heritage sites (Turner 2012).

Since mining is energy-intensive, the CETM industry could be encouraged to adopt renewable energy sources. Integrating renewable energy at their sites could help improve energy access for rural populations, Indigenous Peoples, as well as local communities. In some cases, stricter environmental regulations can also enhance the financial performance of mining and processing companies by reducing the risk of lawsuits, fines and costly remediation. In 2018, the sector faced over US$20 billion in financial impacts due to litigation, development of new water sources,

Figure 16.9: Core Principles of a responsible CETM value chain



contamination management, and other issues (Carbon Disclosure Project 2018).

16.2.4.4 Solutions to promote transparency and improve governance

Mining causes disruption, especially for Indigenous Peoples and local communities (Janardhanan et al. 2023; Bebbington and Humphreys 2018). Human rights-based solutions can play a critical role in protecting communities, especially in high-risk situations (Lèbre et al. 2020). Recognizing the rights and sovereignty of Indigenous Peoples can also improve outcomes through more equitable engagement in negotiations, assessments and increased agency in whether and when to engage with mining companies (Horowitz et al. 2018). Protecting Indigenous Peoples' well-being, including their cultural identities, is supported by adhering to the right to free, prior, and informed consent (Owen et al. 2022; Burton et al. 2024) (well established).

Adequate finances are necessary to promote and incentivize sustainable mining and processing practices, with developed countries playing a leading role through the creation of a "green mineral fund". A global fund with a dedicated dividend mechanism could help to scale these efforts (Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development 2024). Such a fund could provide compensation to communities in resource-rich developing countries while encouraging sustainable practices. Governments and industries can jointly agree on the fund's design under the oversight of a multilateral institution. Examples of such funds include the Alaska Permanent Fund (International Labour Organization [ILO] 2002) and Mongolia's Sovereign Wealth Fund (World Bank 2021). Resources for a Green Mineral Fund can be generated from

Credit: FastSpeedsImagery/Envato

the private sector, end-user companies, or through a tax on advanced technology-based equipment or machinery exceeding a certain price threshold. These funds can then be used to finance sustainable mining in developing countries or support communities displaced or affected by mining. However, to prevent such a premium from hindering the energy transition, multiple tax bands can also be introduced based on technologies, ranging from essential to luxury. Elements such as product traceability, recyclability, and transparency can also be considered for categorizing into tax bands. This approach can further promote benefit-sharing (UNEP 2024b), especially through active participation and compensation of Indigenous Peoples (Government of Canada 2022).

Promoting transparency and strengthening governance in CETM value chain requires strong standards and effective traceability systems. Traceability involves the physical tracking of mineral resources at each point of trade (OECD 2016), supporting circularity and preventing illegal mineral flows. Certification and tracking methods will increase transparency and address due diligence concerns within the global market.

Several existing examples, such as Canada's Critical Mineral Traceability Project, Conflict-Free Sourcing Initiative, Alliance for Responsible Miners, and OECD due diligence guidance for responsible mineral value chains, are some of the notable initiatives. Adoption and strict adherence to Environmental, Social, and Governance criteria for licensing companies to operate would also increase their willingness to invest in and adopt these technologies. Additionally, developing a comprehensive global database that covers all activities, promoting the research and development of technologies, and establishing an international governing system.

Box 16.1 Equity and justice in the energy transition

Furthermore, paying closer attention to gendered experiences and values could lower risks for women during the energy transitions (Dudka 2024). Incorporating gender analysis can enhance the development of alternative pathways for health, safety, community development, and energy systems, ensuring gender-inclusive representation and benefit distribution (Tsagkari 2022). For instance, ensuring that women have equal access to resources, training, and decision-making opportunities is vital for the success of these pathways.

Placing equity and justice at the centre of these solution pathways highlights that many energy transformation projects face opposition and contested debate around the real and perceived trade-offs. This opposition stems partly from historically and presently marginalized communities, at local to global scales, who are excluded from decision-making that affects their lives. For instance, pipelines in North America cut through land owned by Indigenous Peoples or land that was inappropriately expropriated through colonialism (Spice 2018; Hurlbert and Datta 2022; Gobby et al. 2022). Due to systemic marginalization, these communities may occupy land considered of lower value, and thus, from a government perspective, an attractive place for new energy infrastructure. Policies that promote Indigenous Peoples' active involvement in rights-based, equitable, culturally safe, and community-led participatory processes in energy projects are essential to honour Indigenous Peoples as leaders, rights holders, and knowledge keepers, and to prepare future Indigenous leaders (GEO-7 IK&LK Dialogues 2025). Policies respecting Indigenous territorial rights and legal frameworks, enabling self-management of resources, supporting community-led environmental monitoring, safeguarding labour rights, and ensuring fair revenue distribution can help reduce inequities in the mineral value chain.

Recognizing that energy transformations unfold within already affected and inequitable spaces can provide a point of departure for considering how to address and redress existing injustices, including co-ownership, revenue sharing, and adherence to free, prior and informed consent principles. Self-determination – guided by the principles of free, prior, and informed consent – supports the equitable distribution of benefits from mining and land use for Indigenous Peoples.

Energy sovereignty is also a key factor in ensuring access to clean and affordable energy, promoting self-governance by Indigenous Peoples, and supporting emission reduction efforts. Energy sovereignty initiatives for Indigenous Peoples require safeguarding and implementation in regional, national and local policies through international instruments such as ILO 169/UNDRIP.

Large-scale deployment of land-intensive energy sources and mitigation options such as BECCS can perpetuate inequities (Fyson et al. 2020). Disputes can also arise when exclusion is perceived or when benefits are not shared equally. Certain interventions may shift power dynamics within communities, leading to further exclusion of already marginalized groups, including older adults, people with visible or invisible disabilities, or those affected by income differences. This also spans generations, recognizing that establishing more just processes and structures now is a vital part of ensuring intergenerational equity. An increasing number of indicators are being developed to operationalize this idea and enhance the ability to monitor progress (Kime et al. 2023).

16.3 Combination of solutions to achieve the desired goals

The solutions outlined in the previous section contribute to achieving sustainable and equitable energy for all. However, realizing system-wide transformation in the coming decades requires these solutions to be combined and tailored to specific contexts. These solutions are interconnected and can serve a different purpose depending on the strategy adopted. For example, the scale of zero-carbon energy required will partly depend on the growth in energy demand and the reliance on CDR, while lower energy demand and higher energy efficiency will reduce dependence on CDR (Grubler et al. 2018).

Energy system transformation strategies will vary across countries and regions and are shaped by a wide variety of factors and contexts that go beyond economic and technological dimensions. As highlighted in different parts of the chapter, sociocultural, environmental, geophysical and institutional dimensions are also important. These six dimensions are framed within IPCC's Multidimensional Feasibility Assessment and help assess actions through different lens. Such lenses include resource endowments, trade and integration with other countries and regions, carbon sequestration potential, public acceptability of various technologies, the nature of domestic industries, and the degree of urbanization. As well the relationships with other societal priorities such as energy access, energy security, air pollution, and economic competitiveness were examined (IPCC 2022c, 2022d).

As such, the levers and solutions provided in the Goals-Solutions-Levers (GSL) diagrams should be understood as strongly supported by the literature and generally applicable, but they are not exhaustive (IPCC 2023a). Effective approaches must be tailored to local circumstances, utilizing a combination of regulatory tools, funding mechanisms, and training programmes. The best strategies need to be regionally customized and culturally appropriate.

16.3.1 Governance across solution pathways

National governments play a critical role in establishing the regulatory and fiscal landscape that guides decision-making of subnational entities, the private sector, and households. Importantly, they can set in place a credible, coherent set of policies and long-term strategies (Averchenkova, Fankhauser and Finnegan 2021).

In the near term, governments can take a range of integrated actions to accelerate transitions, including:

- Support both market and non-market structures, such as energy communities to reduce energy poverty
- Align trade and investment practices to promote the regional integration of transmission grids and renewable energy
- Apply stricter minimum energy performance standards and upgrade infrastructure
- Establish environmental policies and rights-based approaches to ensure that emerging technologies and activities, such as mining, do not reinforce inequities

Governments can develop policy measures to support energy transitions to low-carbon systems by using various domestic governance and regulation tools, including market-based instruments such as carbon taxes, emission trading schemes, fuel standards, and energy efficiency codes (Eskander and Fankhauser 2020). For instance, China's and the European Union's emission trading schemes have extensive coverage across sectors and regions and their histories offer valuable insights into how to enhance the effectiveness of these systems (Stoerk, Dudek and Yang 2019; Bruninx, Ovaere and Delarue 2020). Other regulatory approaches have also been implemented to support decarbonization, including renewable energy and energy efficiency standards, using tax codes to encourage the purchase of low-carbon technologies such as heat pumps and electric vehicles, subsidies for alternative energy sources, and research and development subsidies (Cabeza et al. 2022). Recent evidence shows that a combination of these tools is most effective (Stechemesser et al. 2024).

Laws, regulatory approaches, and other methods to align policies can be sequenced to achieve the high

levels of stringency. However, since some policies may face greater public opposition or other barriers, intentional and strategic planning about these barriers and ways to overcome them should be integrated into policy design (Pahle et al. 2018). This planning must also align with public and national priorities and contexts (Drews et al. 2016). As transformations require establishing structures that can push incremental changes into lasting ones, signals from governments demonstrating credible commitments to the long-term goals of decarbonization can play a critical role.

Broad-based framework laws that are working include the UK Climate Act (OECD 2021), and other variants including Korea's Framework Act on Low Carbon, Green Growth, Kenya's Climate Change Framework, and Mexico's General Law on Climate Change. Such framework laws can establish the structures, responsibilities, and accountability necessary for reaching climate goals and provide the legal foundation for systemic change (IPCC 2022b).

Legislative frameworks and policies that focus solely on decarbonization, however, may be more vulnerable to political backsliding, especially as they involve trade-offs with other objectives and can be more difficult in contexts with a high reliance on fossil fuels. Therefore, more systemic, economy-wide approaches can be truly transformative, such as Green New Deal-style strategies (Boyle et al. 2021) that address complex drivers and barriers, such as macroeconomic and fiscal constraints. Ensuring broad support requires attention to the distributional aspects and the contextual nature of these changes (McCauley and Heffron 2018; Roberts et al. 2018). Just-transition frameworks that emphasize fairness, participatory processes, and preservation of livelihoods and social protection, especially for the most vulnerable groups, can play a key role in accelerating these changes (McCauley and Heffron 2018).

While national and subnational governments implement many solutions to environmental issues caused by development, this can lead to problems related to national capacity and the social and political contexts of any given location. Such issues can result in significant political feasibility gaps. For example, even if policies are adopted, they may not be enforced or enforceable, and may create new opportunities for elite capture and corruption, potentially exposing communities to harm in the name of environmental protection. Political commitment to transparency, oversight, and anti-corruption measures can address these risks (Cloke, Mohr and Brown 2017).

16.3.2 Individual and collective action across solution pathways

Engaging diverse actors is essential in all aspects of energy transformation. Governments are responsible for creating supportive environments for change, but the private sector, scientists, communities, households, and individuals also play vital roles. Building societal support involves both providing information and enhancing empowerment and equity throughout the transition process. Processes that ensure all voices are heard, especially those rooted in equity and justice, are crucial for achieving transformative outcomes and lay the groundwork for addressing distributional challenges, including the risk of increasing inequality (Ahlborg 2017). Diverse values, worldviews, voices and perspectives, including Indigenous Knowledge and Local Knowledge, must be given space to contribute to planning and implementation of the various actions outlined above, such as through participatory governance, self-determination, and reconciliation. Creating these conditions may require addressing past inequities and injustices, emphasizing human rights-based approaches. All voices should be heard, and as a recognized by the SDGs, no one should be left behind.

16.3.3 Economics and finance across solution pathways

Finance – particularly its availability and accessibility – serves as a vital enabler for climate action and the energy transition by encouraging investment in new projects and locations. It also involves directing support to communities and other locally led initiatives. Additionally, it helps shape the financial incentives surrounding investment across all solution pathways. Enhancing access to finance, creating new sources like green bonds designated for energy investments, and implementing innovative pricing, including domestic and international carbon pricing, can help stimulate investments. This can be complemented by public-private finance and other de-risking strategies to reduce capital costs. Structural changes, such as relocating industries with high energy consumption, and aligning development and climate policies, may also promote long-term transformations (Calcaterra et al. 2024).

Climate policy is increasingly shifting focus beyond emissions reduction to addressing the root causes of fossil-fuel production. This brings greater attention to fossil-fuel subsidies (Skovgaard and van Asselt 2019) and underscores the need for careful evaluation of both direct and indirect effects. Effective climate and energy transition policies, such as carbon pricing, must account for subsidies as well as cover the entire fossil-fuel value chain.

Developing a policy framework for an orderly transition from fossil fuels requires acknowledging the unequal challenges faced by countries, especially those with high fossil-fuel dependency, and the need for financial support to facilitate these transitions (Newell, Van Asselt, and Daley 2022). Identifying and phasing out subsidies – both direct subsidies such as undercharging for supply costs and indirect fossil-fuel subsidies such as undercharging for environmental damages and external costs such as pollution – can support the energy transition by improving macroeconomic performance and creating fiscal space for stable renewable energy investment (Monasterolo 2019; Kamali Saraji and Streimikiene 2023; WEF 2023a). However, coordination with other policy tools that support clean energy is required to meet deep decarbonization goals (Schwanitz et al. 2014; Belfiori 2021)

Global fossil fuel subsidies continue to pose a major obstacle to decarbonization and are at record levels (WEF 2023a; IEA 2025a). In 2022, fossil-fuel subsidies hit a historic US$7 trillion worldwide, equal to 7.1 per cent of global GDP.

However, reforming these subsidies is politically challenging due to their integration into national economic policies and the benefits they provide to existing industries and consumers (Skovgaard and Asselt 2019). Effective reform requires tailoring measures to specific political and economic settings (Mahdavi, Martinez-Alvarez and Ross 2022). Repurposing subsidy savings may also be difficult; however, redirecting these funds to help lower-income populations manage costs can offer crucial social support during the transition (Malerba 2023). Such support has shown to be particularly vital for effectiveness in low-income contexts (Kyle 2018).

The costs of inaction are higher than the costs of mitigation for pathways that achieve 2°C (Riahi et al. 2022).. Economic instruments have proven effective in regulatory settings, including approaches to internalize damages such as the social cost of carbon.

Incorporating the social cost of carbon, which estimates economic damages caused by emitting one additional ton of carbon dioxide, into regulatory cost-benefit analysis helps support decarbonization policies (Nordhaus 2017). Although the development and use of the social cost of carbon have been debated, recent estimates and its application in several countries – including the United States, Canada, France, Germany, and the The United Kingdom of Great Britain and Northern Ireland – have reinforced its value (IPCC 2022b). Moreover, the latest estimates likely underestimate the true damages, suggesting that more stringent decarbonization may be justified (IPCC 2022b).

16.3.4 Science and technology across all solution pathways

The technological pathways above also highlight the need for substantial innovation in new fuels, processes and technologies, especially those required for CDR (Blanco et al. 2022). To achieve this, research and development policies must complement pricing policies and other legislative commitments. Targeted subsidies for research and development have been shown to enhance innovation at the firm level (Stucki et al. 2018; Bai et al. 2019). Strengthening research and development capabilities across universities and industries can serve as vital levers in promoting new technologies. in promoting new technologies.

The deployment of digital technologies in energy sectors seems to be a promising way to support these innovations. Including smart grids and digital governance systems can improve operational efficiency, while enhancing resource management and energy trading (Mahmood et al. 2024). This aligns with ongoing sector changes that aim not only to meet carbon reduction goals but also to boost economic resilience and sustainability in energy supplies.

Research is also necessary beyond technological innovations. Social contexts are not yet fully understood in all geographical regions. While understanding that solutions depend on the context is commonly accepted, knowledge gaps remain. Ongoing research on behaviour and emotions influencing climate responses can enhance

Credit: YanMednis/Envato

understanding of perceptions and expectations. More research is still needed on governance, shifting power dynamics within decision-making, and the contributions of Indigenous Peoples and Indigenous Knowledge in guiding behavioural change.

16.3.5 Capacity-building across all solution pathways

A clear need exists across all pathways for capacity-building at all levels, with workforce development being essential for deployment. More energy technicians are needed in various fields, such as installing and maintaining heat pumps and solar energy systems, both stand-alone and as part of distributed generation systems. Local planners also require training to design compact urban spaces that consider sociocultural contexts while prioritizing inclusion and accessibility.

This can be achieved by working more closely with professional societies and unions, as well as in rural areas, by integrating these topics into school curricula and offering training programmes in other languages, including Indigenous languages. Initiating these programmes early and ensuring they are customized to the needs of target audiences can facilitate the just transition. Collaboration across sectors and governance levels also requires capacity-building to improve cooperation and coordination of actions within energy systems and across different systems.

Box 16.1 Climate adaptation for energy systems

Climate change is resulting in increasing challenges to the energy system, underscoring the need for accelerating considerations for climate change adaptation. Parties to the United Nations Framework Convention on Climate Change acknowledge that different energy-generation systems have distinct vulnerabilities and varying needs to build resilience (United Nations Framework Convention on Climate Change (IPCC 2022a).

For example, hydropower capacity may decline due to increased drought (IPCC 2022b, Esquivel et al. 2016), with predictions of a significant per cent reduction in hydroelectricity generation in Costa Rica and Panamá in 2024 because of El Niño. Less specifically, flash floods and high winds can damage energy infrastructure, power lines through forested areas may face increased wildfire risks, and extreme heat can put greater demand on water supplies used for cooling and decrease the efficiency of solar panels. As well, storms and cyclones can trigger slope collapses that damage hydroelectric installations and severely impact local communities (IEA 2020, IPCC 2022c).

Providing reliable electricity is a crucial component of climate adaptation (Davide, De Cian and Bernigaud 2019). Increased resilience can be achieved through backup systems, multiple storage systems, and smart grid technology, as well as by updating and improving construction standards, strengthening infrastructure assets, and diversifying energy sources (IPCC 2022a). Importantly, early warning systems can be powered by more reliable energy sources.

Energy systems were included in the IPCC's WGII assessment for the first time in the Sixth Assessment Report, highlighting their vulnerability but also underscoring the vital role of energy in adaptation – both directly and as an enabler of other options. Considerations for adaptation are also crucial, as some mitigation strategies may increase the vulnerability of ecosystems and communities, such as through BECCS and the mining of CETMs. Similarly, stringent mitigation strategies are critical for ensuring that energy use for adaptation does not lead to increases in emissions (Colelli 2022).

Therefore, using analytical tools such as multidimensional feasibility assessments can be helpful, as they enable the evaluation of synergies and trade-offs among mitigation and adaptation options.

16.4 Case studies

Two comparative case studies highlight the importance of engaging multiple and diverse groups, providing appropriate incentives, and applying an equity lens to create lasting change, while also emphasizing the significance of context. These case studies further demonstrate that the ability to respond to unexpected shocks with prompt, feasible, and suitable actions can open a window of opportunity for rapid shifts that might otherwise have faced significant barriers.

16.4.1 Case study 1: Heat Pump Installation

Heat pumps are widely recognized as a cornerstone technology for decarbonizing the building sector (Rosenow et al. 2022). This case study assesses its deployment and diffusion, highlighting contextual factors that enabled or created barriers.

Heat pumps hold tremendous promise as they are three to five times more efficient at heating buildings than conventional gas furnaces or boilers (IEA 2022a).

One misconception about heat pumps is that they only work in temperate climates, but newer models have been shown to work in extremely cold conditions such as Alaska (Gibb et al. 2023, Crownhart 2023). Moreover, they can be retrofitted onto existing heating systems to use conventional radiators and underfloor heating systems. Another benefit is that they can be used for cooling as well as heating, and cooling needs are rapidly increasing worldwide with climate change. existing heating systems to use conventional radiators and underfloor heating systems. Another benefit is that they can be used for cooling as well as heating, and cooling needs are rapidly increasing worldwide with climate change.

Rolling out heat pumps on a massive scale can be challenging. Specifically, not enough engineers are trained to install and maintain heat pumps. Providing the public with reliable and easy-to-access information about the financial and energy advantages of heat pumps will promote adoption by households.

Ground-source heat pumps cost more to install because they require digging, but they are more efficient and better suited for larger buildings. Air-source heat pumps are similar in shape and size to outdoor air conditioners and are used for both heating and cooling.

Government-supported transitions to heat pumps can evolve for varied reasons. The European Union responded to the war in Ukraine by sanctions on the export of natural gas and oil from the Russian Federation. This change has affected access to natural gas in Europe and may be encouraging a long-term shift away from natural gas. Of all the natural gas used in Europe, one-third is used to heat buildings (IEA 2022a). Generally, space heating and cooling account for 50 per cent of building energy use (European Commission 2023b). The European Union has enacted several laws to promote heat pumps, including the Fit-for-55 climate strategy (European Commission 2021) and REPowerEU (European Commission 2022), which can help reduce energy demand and facilitate a fair and just transition by prioritizing investments in renewables and energy efficiency. Member states are also encouraged to phase out subsidies for fossil-fuel boilers (Adamo et al. 2024).

In 2022, the global sales of heat pumps grew by 11 per cent (IEA 2023a). In Europe, the sales grew by 40 per cent to more than 3 million units. Air-to-water models have been particularly popular as they are compatible with older heating systems. The European Union plans to have an additional 10 million heat pumps installed by 2027 (European Commission 2023b).

Linked with government energy security concerns and climate commitments, heat pumps have been at the forefront of the energy transition. In addition to heating and cooling, heat pumps can also be used for water heating, which is often another large energy end-use in buildings.

As electric appliances, heat pumps can strain local power grids during peak demand on cold days. To address this, promoting weatherization programmes to retrofit buildings and therefore lower energy demand is important, alongside efforts to decarbonize regional power grids. While the energy transition unfolds amid ongoing disruptions and geopolitical tensions, recognizing that this is an evolving context is highly relevant. Seizing emerging opportunities and implementing options that foster resilience to future disruptions will be key to successful transformations.

16.4.2 Case Study 2: Renewable Energy Communities

Community-scale renewable energy generation, unlike a top-down approach typical for utility-scale plants, can better reflect user priorities and equitable gender representation (Bauwens and Devine-Wright 2018; Berka and Creamer 2018). Renewable energy communities are increasingly viewed as an alternative to grid connection, providing a transformational process centred on the community's priorities (Gui and MacGill 2018). As such, this approach can play a crucial role in facilitating just transitions (Hoicka et al. 2021). Local governance of these systems offers opportunities for broader social transformations. This can be especially important in low and middle-income contexts (Cloke, Mohr and Brown 2017) and Indigenous communities (Velasco-Herrejón, Bauwens and Calisto Friant 2022).

Depending on the context, energy communities can engage and protect community needs, thereby promoting inclusion and reducing barriers to adoption (Noll, Dawes and Rai 2014; Koirala et al. 2016). While there are various models for energy communities, fundamentally, they are

projects owned by or heavily involving the community, with communities participating in the production and use of sustainable energy (IRENA Coalition for Action 2018). Examples of energy communities now exist in both developed and developing countries, with many communities pursuing ambitious visions of sustainable and renewable energy (Seyfang, Park and Smith 2013; Van Der Schoor and Scholtens 2015).

However, it is essential to acknowledge the differences in conceptualization and execution between developed and developing countries (Okem and Ley 2023). Examples include use of solar panels in favelas in Brazil (Abraham 2023), solar-projects in India (Joshi and Yanneti 2020), numerous projects and networks in Europe (Santos 2023), shared solar energy in the United States of America, (Grimley et al. 2022), and Indigenous-led projects in Canada (Indigenous Clean Energy 2023). But in some examples, such as in Spain, this scheme is only for higher-income families, and excludes lower-income people who can't afford to buy into the scheme (Okem and Ley 2023). These decentralized models have several advantages over the top-down approach, including building strong communities, reducing payback periods and energy costs, and supporting sustainable policies from local to national scales (Klein and Coffey 2016). These efforts also have benefits for climate adaptation by building resilience of the energy systems and communities (Sapkota et al. 2014).

Scaling up renewable energy communities requires collaboration among multiple actors including communities, governments, the private sector, and researchers. Governments play a key enabling role by creating opportunities that support community-led efforts (Oteman, Wiering and Helderman 2014). As observed in the European Union, legislative frameworks were introduced to formalize and support community efforts, ensuring that large-scale developments do not dominate by default (Hoicka et al. 2021).

16.5 Implication of the solution pathways on the other systems

All systems have complex interdependencies, where achieving one goal can create synergies and trade-offs affecting other systems (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES] 2024a). **Table 16.2** highlights the key interactions from energy solutions to these different systems, including food, environment, economy and circularity. It can serve as a foundation for a comprehensive evaluation of how to minimize trade-offs and enhance synergies (IPBES 2024a).

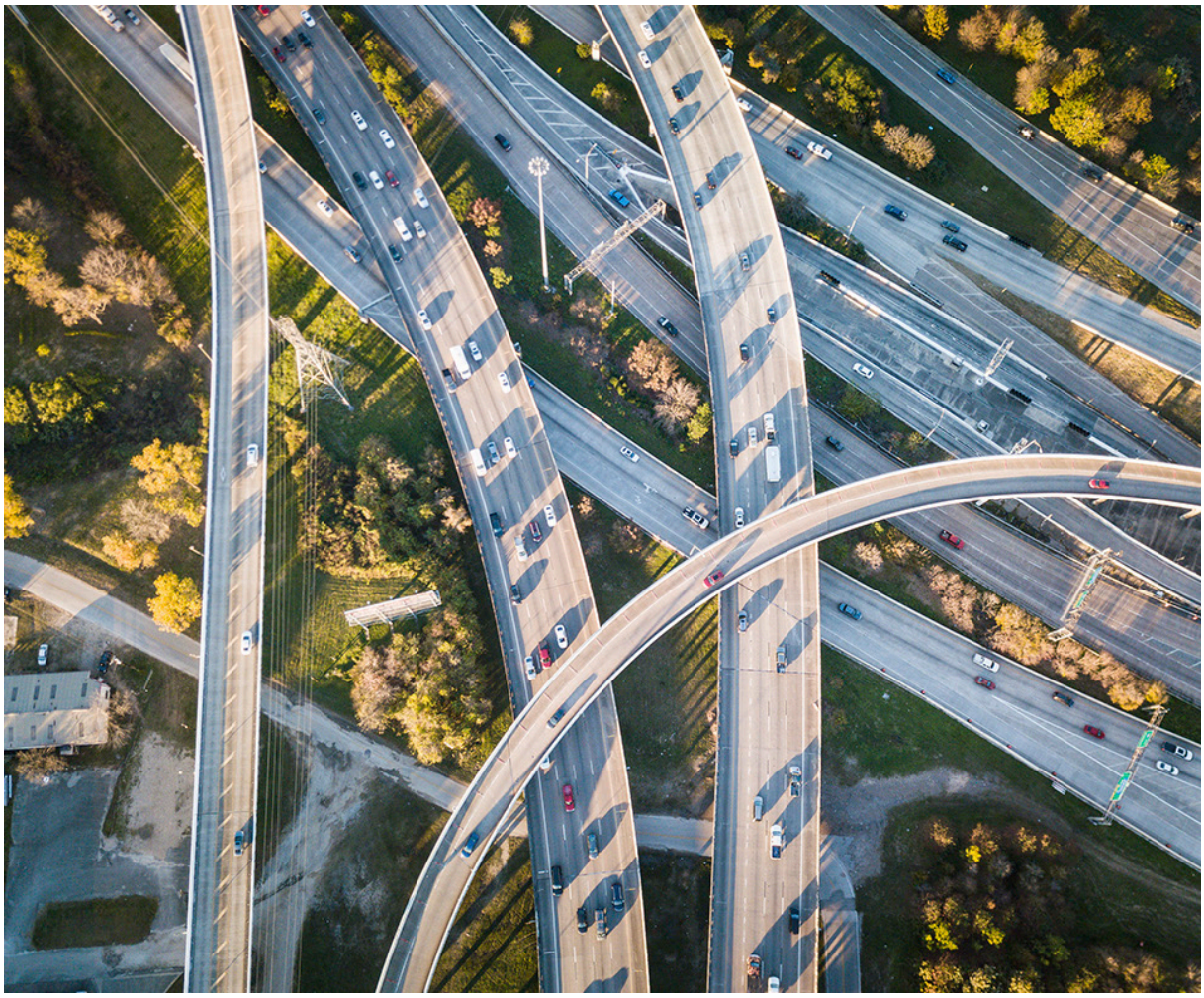
16.5.1 Food systems

Energy system transitions intersect with food systems in various ways. Access to energy directly supports food system transformation, especially through modern fuels that enhance food preparation and reduce demand for land and fuel production. Infrastructure development, like transmission grids and renewable energy generation, can contribute to land degradation or compete with agricultural land use (Nwaigwe, Mutabilwa, and Dintwa 2019; Candelise, Saccone and Vallino 2021; He et al. 2024). Nonetheless, innovations such as agrivoltaics provide co-benefits for both energy and agriculture, enabling the dual use of land.

Electrification can further enhance food production by increasing access to irrigation, which can boost agricultural productivity and farmers' incomes (Peters and Sievert 2016). Bioenergy applications also have mixed effects: while large-scale cultivation may compete with cropland and influence food supply and prices (Fujimori et al. 2022), targeted use of biochar can improve soil health and crop yields (Prütz et al. 2024). Reducing demand and increasing circularity in mining and other resource extraction can indirectly benefit the food system through pollution reduction and sustainable resource use, particularly for water.

16.5.2 Environmental systems

Electrification – particularly when combined with renewable energy sources – can significantly improve air quality and reduce health risks (Peng et al. 2018). There are strong co-benefits where climate mitigation policies that control air pollution emissions could reduce global warming by 0.5°C and save 2.4 million lives annually (Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants 2014). Renewable-based microgrids and distributed generation can replace traditional biomass and diesel generators. The transition to modern, low-carbon fuels combined with the use of organic waste can lead to further improvements in air quality and health, as well as reduce GHG emissions from household energy use. Many renewable technologies also decrease water use compared to conventional power systems (Lohrmann



Credit: Daemaine/Envato

et al. 2019). Large-scale renewable deployment, such as hydropower, and mineral mining for clean energy technology, can damage biodiversity and ecosystems if not planned properly (IRENA 2023; Sonter et al. 2020). Responsible infrastructure development and mining practices are crucial for protecting biodiversity, particularly within CETM value chains.

Water savings is an important measure to reduce emissions and increase resilience in the energy system transition. A more efficient water use, for example, for cooling of generation plants, independently of fuel source, can make energy generation more efficient while also being beneficial for the surrounding ecosystem. Water savings is also a measure for climate adaptation, however, water based adaptation options will significantly reduce their efficiency as we approach and surpass 2C (Schipper et al. 2022) and this will also affect the energy transition. Water use in the energy solution pathway will have an impact in other solution pathways as water is an element that cuts across different transitions (Schipper et al. 2022; Caretta et al. 2022, United Nations Environment Programme, United Nations Technology Centre and Network, United Nations Climate Change Technology Executive Committee, UNEP Copenhagen Climate Centre 2024). For example, water use for hydroelectric plants, independent of the scale, can affect agriculture, forests, and communities or other settlements that are downstream (Jiang, Zhang and Hou 2020; Lobo et al. 2025).

16.5.3 Circularity

The energy transition can reduce material demand, manage waste, and enhance system efficiency. Throughout the system, principles of the circular economy must be integrated to prevent trade-offs. For distributed energy systems, reusing and recycling components like batteries helps prevent environmental impacts. In sectors that are harder to decarbonize, circularity can decrease dependence on critical raw materials and boost overall resource efficiency (e.g., Kalundborg). Circular practices in the CETM value

chain, such as water recycling, waste reduction, and closed-loop systems, offer important opportunities to cut pollution, lower the need for new mining, and promote innovation. Transparency and traceability in supply chains can further strengthen circularity by supporting informed resource governance and encouraging long-term sustainability.

16.5.4 Economic systems

Microgrids and decentralized systems are cost-effective solutions when extending the national grid is financially or logistically unfeasible, as they can transform livelihoods and support education in rural areas. Modern fuels reduce household labour burdens and health costs and improve household resilience. Electrification further supports economic goals by enhancing education, health services, and local job creation. The shift to renewables and low-carbon energy sources can increase employment opportunities. These effects can be transformative when paired with suitable training and industrial policies, though extra support will be necessary to prevent economic disruptions, particularly in fossil fuel-dependent regions. Governance strategies, including the establishment of a mining fund to encourage sustainable mining practices, can promote more equitable, long-term economic benefits (Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development 2024). Channelling international finance sources, particularly from highly industrialized developed countries to low and middle-income economies can be transformative, enabling renewable energy infrastructure roll-out. As well, such channelling can produce broader development advantages, provided there is appropriate access, availability, implementation oversight and capacity development, along with mechanisms to facilitate this finance and stimulate investment.

Biodiversity loss can be worsened by actions taken during energy system transitions. Some measures that greatly cut emissions may cause, sometimes irreversible, ecosystem harm and biodiversity decline. However, considering environmental and biodiversity consequences in energy projects can create mutual

Table 16.1: Synergies and trade-offs with other systems

Energy Systems Solutions	Food Systems	Environmental Systems	Circularity	Economic Systems
Provide modern fuels to households for cooking (Goal 1)	Ý	Ý	Ý	Ý
Expansion of existing grid network and mini-grids (Goal 1)	Û	Ý	Û	indirect
Implement more compact land planning practices (Goal 2)	Ý	Û	indirect	indirect
Achieve diversified, reliable and resilient electrification of all sectors where feasible (Goal 3)	Ý	Ý	indirect	Ý
Decarbonize power generation transitioning away from fossil fuels (Goal 3)	Û	ß	ß	Û
Strengthen circularity in CETM value chain (Goal 4)	Ý	Ý	Ý	Ý

*Ý = generally positive direct effects; Û = mixed direct effects; ß = generally direct *negative, indirect effects are not included*

benefits. Evidence shows that certain actions, like nature-based solutions and some small-scale bioenergy, can be good for both climate change and biodiversity (IPBES 2024a). Given the interconnected nature of the drivers of the planetary crises society faces, responses must also be approached in an integrated manner. The IPBES Transformative Change Assessment (IPBES 2024a) highlights the structural changes that enable transformation, including shifting power dynamics and incorporating diverse values and worldviews that offer a different perspective on the relationship between humans and nature.

Addressing biodiversity loss goes beyond incorporating environmental and biodiversity concerns into project planning, it also involves valuing Indigenous Knowledge. For example, the IPBES Nexus Assessment highlights the cost savings, as as well as the reduction in trade-offs of a nexus approach, compared to siloed strategies, that recognizes the value of Indigenous Knowledge (IPBES 2024a). Addressing biodiversity considerations can also help achieve climate change adaptation goals, especially when Indigenous Knowledge and visions are included.

While renewable energy offers many benefits, it can still harm ecosystems and biodiversity if not developed with robust spatial planning or stakeholder consultations. Therefore, an integrated approach is essential. For example, hydroelectric plants, regardless of scale, can significantly disrupt watersheds while also benefiting reforestation efforts, supporting irrigation for crops, offering flood protection, and enhancing the water supply.

16.6 Conclusions

This chapter underscores the urgency for coordinated and equity-focused approaches to transforming the energy system. There is ample evidence to guide and start this transition, specifically that relying solely on technological fixes is not sufficient. Broader systematic changes in finance, economics, innovation, and capacity-building are necessary.

The energy transition will involve a combination of short-term actions and long-term structural changes. While some measures—such as deploying decentralized renewable energy—can begin straight away, others require sustained investments in research, institutional coordination, and innovation. A core aim of the energy solution pathway is to advance equity by addressing existing inequalities and injustices embedded in the current energy system and development paradigms (Keady et al. 2021). For example, creating policy space and international support for universal access to modern energy services in developing countries is both urgent and fundamental for energy transitions.

While national actions are the primary means through which carbon policy and systemic changes are implemented, the international arena, particularly through processes of the Framework Convention on Climate Change, offers a platform for government coordination. The decision at COP28, in the context of negotiations for the 2nd Global Stocktake, clearly emphasized global efforts to transition "…away from fossil fuels in energy systems in a just, orderly and equitable manner, accelerating action in this critical decade, so as to achieve net zero by 2050 in keeping with the science."

Achieving this transition will require mechanisms that support equitable decarbonization with transformative potential, including targeted financial support, technology transfer and capacity-building (IPCC 2022b). Transnational climate-social movements – advocating for climate justice and led by youth, Indigenous Peoples, women, labour, non-governmental organizations, and civil society – also play a crucial role by influencing these processes and challenging status quo approaches, and they are vital for meaningful transformation (Almeida 2019).

A systems-oriented approach is crucial (IPBES 2024b). For example, bioenergy is a particularly complex but strategically significant component of the energy transition. At small scales, bioenergy solutions – such as biogas or bioethanol – can enhance household energy access and reduce reliance on polluting cooking fuels. At larger scales, BECCS can contribute to CDR, helping to mitigate hard-to-abate emissions and address potential overshoot (IPCC 2022b; Smith et al. 2024). Nevertheless, large-scale bioenergy deployment must be carefully managed to prevent intensifying competition for land and negative effects on food security and biodiversity. Effective regulatory frameworks, participatory planning, and integrated land-use strategies are critical to balancing these risks.

Climate-resilient development can guide transformation by promoting equity, learning from diverse knowledges, including Indigenous Peoples, and local communities, generating shifts in behaviours and values, and reforming financial systems (IPCC 2022c; Eriksen et al. 2024). This approach places equitable development at the heart of climate action and can be especially critical when trade-offs arise.

While the increased energy demand from expanding access may seem to challenge decarbonization efforts, the IPCC Special Report on 1.5°C identified pathways that meet energy service demands when coupled with enhanced energy efficiency and accelerated electrification (IPCC 2018). Thus, critical support for Goal 3 comes from Goal 2 where consumption of energy is decreased.

However, hard-to-abate sectors, such as aviation, agriculture, shipping and industry, require shifts to low-carbon alternatives, alongside efforts to scale CDR technologies to compensate for residual emissions. Additionally, mitigation pathways that align not just with the temperature limits but with the commitment to sustainable development under the Paris Agreement face fewer challenges, rely less on CDR, and place less pressure on land and biodiversity (Smith et al. 2024, Soergel et al. 2024). Similarly, approaches that consider synergies and trade-offs, such as climate-resilient development pathways that address climate mitigation, climate adaptation and sustainable development simultaneously, can help reduce conflicts, increase cost efficiency, and improve the public acceptance.

From the analysis of solution pathways, four overarching goals emerge, each of which can be supported by a portfolio of policy levers, preconditions and actor-specific actions. These levers can be employed by various actors, including national governments, subnational entities, private sector, community organizations, scientists, and individuals. Using the feasibility assessment framework outlined by IPCC Working Group II and III enables a comprehensive evaluation of potential transition pathways (IPCC 2022c; IPCC 2023a).

While technological feasibility for decarbonization is generally high, particularly for scalable, mature technologies, feasibility must be considered across six interrelated dimensions: economic, environmental-ecological, geophysical, institutional, technological, and sociocultural (Singh et al. 2020). Certain levers especially those related to governance can influence multiple goals. Integrated policy design that aligns sectoral actions and anticipates synergies and trade-offs, is essential to maximize co-benefits and minimize unintended consequences.

It is vital to take action while systematically evaluating what works and how to accelerate successful initiatives. This chapter emphasizes that suitable top-down support can improve technical and financial effectiveness and help maintain infrastructure for more decentralized and community-led systems (Joshi and Yanneti 2020). There is also the need for more systematic assessment behind the diverse motivations of energy transitions and the distinction between place-based and non-place-based communities (Moroni et al. 2019). This includes further research in developing country contexts (Holstenkamp 2019; Van Der Schoor and Scholtens 2019) and on the outcomes of different ownership models to ensure the project benefits are distributed equitably (Berka and Creamer 2018)

References

Abraham, S. (2023). How organizers in Rio's favelas are harnessing solar energy. 8 November 2023. Shelterforce. Accessed 10 October 2025

Adamo, A., Martín, H., de la Hoz, J., Rubio, J. and Valero, J. (2024). Regulatory framework for the promotion of heat pumps in the European Union. Energy Reports 12, 5909-5930. https://doi.org/10.1016/j.egyr.2024.11.043

Agarwal, N.D., Kumar, V.V.R., Gunasekaran, A. (2024). Leveraging social media to examine sustainability communication of home appliance brands. Technology in Society 77, 102550. https://doi.org/10.1016/j.techsoc.2024.102550

Ahlborg, H. (2017). Towards a conceptualization of power in energy transitions. Environmental Innovation and Societal Transitions 25, 122-141. https://doi.org/10.1016/j.eist.2017.01.004

Almeida, P. (2019). Climate justice and sustained transnational mobilization. Globalizations 16(7), 973-979. https://doi.org/10.1080/14747731.2019.1651518

Aneke, M. and Wang, M. (2016). Energy storage technologies and real-life applications – A state of the art review. Applied Energy 179, 350-377. https://doi.org/10.1016/j.apenergy.2016.06.097

Ang, Y.Q., Berzolla, Z.M., Letellier-Duchesne, S. et al. (2023) Carbon reduction technology pathways for existing buildings in eight cities. Nature Communications 14, 1689. https://doi.org/10.1038/s41467-023-37131-6

Aramendia, E., Brockway, P.E., Taylor, P.G. and Norman, J. (2023). Global energy consumption of the mineral mining industry: Exploring the historical perspective and future pathways to 2060. Global Environmental Change 83, 102745. https://doi.org/10.1016/j.gloenvcha.2023.102745

Austria Federal Ministry of Finance and International Organizing Committee for the World Mining Congresses (2023). World Mining Data 2023. https://www.world-mining-data.info/wmd/downloads/PDF/WMD2023.pdf.

Averchenkova, A., Fankhauser, S., & Finnegan, J. J. (2021). The influence of climate change advisory bodies on political debates: evidence from the UK Committee on Climate Change. Climate Policy, 21(9), 1218–1233. https://doi.org/10.1080/14693062.2021.1878008

Babbitt, C.W., Althaf, S., Cruz Rios, F., Bilec, M.M. and Graedel, T.E. (2021). The role of design in circular economy solutions for critical materials. One Earth 4(3), 353-362. https://doi.org/10.1016/j.oneear.2021.02.014

Bai, Y., Song, S., Jiao, J. and Yang, R. (2019). The impacts of government R&D subsidies on green innovation: Evidence from Chinese energy-intensive firms. Journal of Cleaner Production 233, 819-829. https://doi.org/10.1016/j.jclepro.2019.06.107

Basiru, I., Xu, Y., Arkorful, V.E., Lugu, B.K., Ibrahim, A.H. (2024). Energy efficiency labels and urban residents' intention to purchase energy-efficient household appliances: an empirical study based on the theory of planned behavior. Clean Technologies and Environmental Policy. https://doi.org/10.1007/s10098-024-03070-z

Bauwens, T. and Devine-Wright, P. (2018). Positive energies? An empirical study of community energy participation and attitudes to renewable energy. Energy Policy 118, 612-625. https://doi.org/10.1016/j.enpol.2018.03.062

Bebbington, A. and Humphreys Bebbington, D. (2018). Mining, movements and sustainable development: Concepts for a framework. Sustainable Development 26(5), 441-449. https://doi.org/10.1002/sd.1888

Beck, M. and Özçaglar Toulouse, N. (2023). Assessing the impact of energy labels on attitude and behavioral intention: An empirical investigation. Journal of Cleaner Production 415, 137751. https://doi.org/10.1016/j.jclepro.2023.137751

Bell, S.E. and York, R. (2010). Community Economic Identity: The Coal Industry and Ideology Construction in West Virginia. Rural Sociology 75(1), 111-143. https://doi.org/10.1111/j.1549-0831.2009.00004.x

Belleri, A., Lollini, R., Pozza, C., Segura, I.L., Pistore, L., Türk, A. et al. (2023). Understanding Positive Energy Buildings and Neighbourhoods – towards a common definition. Zenodo 1. https://doi.org/10.5281/zenodo.7640333

Belfiori, M. E. (2021). Fossil fuel subsidies, the green paradox and the fiscal paradox. Economics of Energy & Environmental Policy, 10(1), 183-192. https://www.jstor.org/stable/27030685

Berka, A.L. and Creamer, E. (2018). Taking stock of the local impacts of community owned renewable energy: A review and research agenda. Renewable and Sustainable Energy Reviews 82, 3400-3419. https://doi.org/10.1016/j.rser.2017.10.050

Bharadwaj, B., Pullar, D., Seng To, L. and Leary, J. (2021). Why firewood? Exploring the co-benefits, socio-ecological interactions and Indigenous Knowledge surrounding cooking practice in rural Nepal. Energy Research & Social Science 75, 101932. https://doi.org/10.1016/j.erss.2021.101932

Bhukya, R. and Paul, J. (2023). Social influence research in consumer behavior: What we learned and what we need to learn? – A hybrid systematic literature review. Journal of Business Research 162, 113870. https://doi.org/10.1016/j.jbusres.2023.113870

Black, S., Liu, A. and Parry, I. (2023). IMF fossil fuel subsidies data: 2023 update. IMF Working papers 2023, 169 (2023). https://doi.org/10.5089/9798400249006.001

Blanco, H., Leaver, J., Dodds, P.E., Dickinson, R., García-Gusano, D., Iribarren, D. et al. (2022). A taxonomy of models for investigating hydrogen energy systems. Renewable and Sustainable Energy Reviews 167, 112698. https://doi.org/10.1016/j.rser.2022.112698

Bonan, J., Pareglio, S. And Tavoni, M. (2017). Access to modern energy: a review of barriers, drivers and impacts. Environment and Development Economics 22(5), 491-516. https://doi.org/10.1017/S1355770X17000201

Bowley, W. and Evins, R. (2020). Assessing energy and emissions savings for space conditioning, materials and transportation for a high-density mixed-use building. Journal of Building Engineering 31, 101386. https://doi.org/10.1016/j.jobe.2020.101386

Boyle, A.D., Leggat, G., Morikawa, L., Pappas, Y. and Stephens, J.C. (2021). Green New Deal proposals: Comparing emerging transformational climate policies at multiple scales. Energy Research & Social Science 81, 102259. https://doi.org/10.1016/j.erss.2021.102259

Braun, J., Werner, C., Gerten, D., Stenzel, F., Schaphoff, S., and Lucht, W. (2025). Multiple planetary boundaries preclude biomass crops for carbon capture and storage outside of agricultural areas. Commun Earth Environ 6, 102. https://doi.org/10.1038/s43247-025-02033-6

Bruninx, K., Ovaere, M. and Delarue, E. (2020). The long-term impact of the market stability reserve on the EU emission trading system. Energy Economics 89, 104746. https://doi.org/10.1016/j.eneco.2020.104746

Buck, H.J., Carton, W., Lund, J.F., and Markusson, N. (2023). Why residual emissions matter right now. Nat. Clim. Chang. 13, 351–358. https://doi.org/10.1038/s41558-022-01592-2

Buliung, R. (2024). 15-minute cities, 'walkability' and last millimeter problems. Disability & Society 40(5), 1425–1429. https://doi.org/10.1080/09687599.2024.2385919

Burton, J., Kemp, D., Barnes, R. and Parmenter, J. (2024). Mapping critical minerals projects and their intersection with Indigenous peoples' land rights in Australia. Energy Research & Social Science 113, 103556. https://doi.org/10.1016/j.erss.2024.103556

Byers, E., Krey, V., Kriegler, E., Riahi, K., Schaeffer, R., Kikstra, J. et al. (2022). AR6 Scenarios Database (1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.5886912

Cabeza, L. F., Bai, Q., Bertoldi, P., Kihila, J. M., Lucena, A.F.P, Mata, É. et al. (2022). Buildings. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter09.pdf.

Calcaterra, M., Aleluia Reis, L., Fragkos, P. et al. Reducing the cost of capital to finance the energy transition in developing countries. Nat Energy 9, 1241–1251 (2024). https://doi.org/10.1038/s41560-024-01606-7.

Calvão, F. and Archer, M. (2021). Digital extraction: Blockchain traceability in mineral supply chains. Political Geography 87, 102381. https://doi.org/10.1016/j.polgeo.2021.102381

Candelise, C., Saccone, D. and Vallino, E. (2021). An empirical assessment of the effects of electricity access on food security. World Development 141, 105390. https://doi.org/10.1016/j.worlddev.2021.105390.

Carbon Disclosure Project (2018). Treading Water: Global Water Report 2018. https://www.cdp.net/en/research/global-reports/global-water-report-2018

Caretta, M.A., Mukherji, A., Arfanuzzaman, M., Betts, R.A., Gelfan, A., Hirabayashi, Y. et al. (2022). Water. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 551-712. 10.1017/9781009325844.006

Carlander, J. and Thollander, P. (2023). Barriers to implementation of energy-efficient technologies in building construction projects – Results from a Swedish case study. Resources, Environment and Sustainability 11, 100097. https://doi.org/10.1016/j.resenv.2022.100097

Chance, E., Ashton, W., Pereira, J., Mulrow, J., Norberto, J. Derrible, S. et al. (2017). The Plant – An experiment in urban food sustainability. Environmental Progress & Sustainable Energy 37(1), 82-90. https://doi.org/10.1002/ep.12712

Clarke, L., Wei, Y.-M., De La Vega Navarro, A., Garg, A., Hahmann, A.N, Khennas, S. et al. (2022) Energy Systems. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://www.ipcc.ch/report/ar6/wg3/chapter/chapter-6/

Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (2014) Time to act to reduce short-lived climate pollutants. https://www.ccacoalition.org/sites/default/files/resources/Time%20To%20Act%20to%20reduce%20Short-Lived%20Climate%20Pollutants.pdf

Cloke, J., Mohr, A. and Brown, E. (2017). Imagining renewable energy: Towards a Social Energy Systems approach to community renewable energy projects in the Global South. Energy Research & Social Science 31, 263-272. https://doi.org/10.1016/j.erss.2017.06.023

Coldrey, O., Lant, P., and Ashworth, P. (2023). Elucidating Finance Gaps through the Clean Cooking Value Chain. Sustainability 2023, 15, 3577. https://doi.org/10.3390/su15043577.

Colelli, F.P., Emmerling, J., Marangoni, G., Mistry, M.N. and De Cian, E. (2022). Increased energy use for adaptation significantly impacts mitigation pathways. Nature Communications 13(1), 4964. https://doi.org/10.1038/s41467-022-32471-1

Cortinovis, C., Geneletti, D. and Haase, D. (2022). Higher immigration and lower land take rates are driving a new densification wave in European cities. npj Urban Sustainability 2, 19. https://doi.org/10.1038/s42949-022-00062-0

Creutzig, F., J. Roy, P. Devine-Wright, J. Díaz-José, F.W. Geels, A. Grubler, N. et al. (2022). Demand, services and social aspects of mitigation. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter05.pdf.

Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf, E., et al. (2024). GHG emissions of all world countries. Luxembourg: Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC138862

Crownhart, C. (2023) Everything you need to know about the wild world of heat pumps. MIT Technology Review. https://www.technologyreview.com/2023/02/14/1068582/everything-you-need-to-know-about-heat-pumps/ Accessed 12 August 2025

C40 Cities Climate Leadership Group (2022). Benchmark: 15-minute cities. https://www.c40knowledgehub.org/s/article/Benchmark-15-minute-cities?language=en_US

Davide, M., De Cian, E. and Bernigaud, A. (2019). Building a Framework to Understand the Energy Needs of Adaptation. Sustainability, 15. https://doi.org/10.3390/su11154085

Dechezleprêtre, A., Fabre, A., Tobias, K., Planterose, B., Sanchez Chico, A. and Stantcheva, S. (2025). Fighting climate change: International attitudes toward climate policies. American Economic Review 115.4 (2025): 1258-1300. https://doi.org/10.1257/aer.20230501.

Dhakal, K.P. and Chevalier, L.R. (2017). Managing urban stormwater for urban sustainability: Barriers and policy solutions for green infrastructure application. Journal of Environmental Management 203, 171-181. https://doi.org/10.1016/j.jenvman.2017.07.065

de Castro Pena, J.C., Goulart, F., Wilson Fernandes, G., Hoffmann, D., Leite, F.S.F., Britto dos Santos, N. et al. (2017). Impacts of mining activities on the potential geographic distribution of eastern Brazil mountaintop endemic species. Perspectives in Ecology and Conservation 15(3), 172-178. https://doi.org/10.1016/j.pecon.2017.07.005

Deprez, A., Leadley, P., Dooley, K., Williamson, P., Cramer, W., Gattuso, J.P. et al. (2024). Sustainability limits needed for CO_2 removal. Science 383, 484-486. https://doi.org/10.1126/science.adj6171

Derrible, S. (2025). The Infrastructure Book: How Cities Work and Power Our Lives. Prometheus Books https://www.prometheusbooks.com/9781493086641/the-infrastructure-book/

Derrible, S., Cheah, L., Arora, M. and Yeow, L.W. (2021). Urban Metabolism. In: Urban Informatics. Shi, W., Goodchild, M.F., Batty, M., Kwan, MP., Zhang, A. (eds). Singapore: Springer. https://doi.org/10.1007/978-981-15-8983-6_7

Drews, S. and van den Bergh, J.C.J.M. (2016). What explains public support for climate policies? A review of empirical and experimental studies.Climate Policy 16(7), 855-876 https://doi.org/10.1080/14693062.2015.1058240

Dudka, A. (2024). Women in Energy Communities: An Intersectional Analysis of Their Participation. In Women and the Energy Sector: Gender Inequality and Sustainability in Production and Consumption. Rocha Lawton, N. and Forson, C. (eds.). Cham: Springer International Publishing. 243-262. https://doi.org/10.1007/978-3-031-43091-6_10

Echevarría, C., Jesurun-Clements, N., Mercado Díaz, J. E., & Trujillo, C. (2017). Integración eléctrica centroamericana: Génesis, beneficios y prospectiva del Proyecto SIEPAC: Sistema de Interconexión Eléctrica de los Países de América Central. https://doi.org/10.18235/0012708

Elabbas, M., Vries, L.J. and Correljé, A. (2023). African power pools and regional electricity market design: Taking stock of regional integration in energy sectors. Energy Research & Social Science 105, 103291. http://dx.doi.org/10.1016/j.erss.2023.103291

Energy Institute (2023). Home. Statistical Review of World Energy. https://www.energyinst.org/statistical-review

Energy Institute (2024). Statistical Review of World Energy. https://www.energyinst.org/__data/assets/pdf_file/0006/1542714/684_EI_Stat_Review_V16_DIGITAL.pdf

Energy Sector Management Assistance Program, GOGLA, Dalberg (2024). Off-Grid Solar Market Trend Report 2024. Washington, DC: The World Bank. https://www.esmap.org/sites/default/files/esmap-files/2024-Off-Grid-Solar-Market-Trends-Report.pdf

Eriksen, S.H., Simpson, N.P., Glavovic, B., Ley, D., Carr, E.R., Fernández-Carril, L. et al. (2024). Pathways for urgent action towards climate resilient development. Nature Climate Change 14(12), 1212-1215. https://doi.org/10.1038/s41558-024-02190-0

Eskander, S.M.S.U. and Fankhauser, S. (2020). Reduction in greenhouse gas emissions from national climate legislation. Nat. Clim. Chang. 10, 750–756 https://doi.org/10.1038/s41558-020-0831-z

Esquivel, M., Grunwaldt, A., Paredes, J. R., & Rodríguez-Flores, E. (2016). Vulnerability to Climate Change of Hydroelectric Production Systems in Central America and their Adaptation Options: Executive Summary. https://doi.org/10.18235/0006338

Estiri, H. (2015). Differences in Residential Energy Use between US City and Suburban Households. Regional Studies 50(11), 1919–1930. https://doi.org/10.1080/00343404.2015.1079310

European Commission (2021) Fit for 55: Delivering the EU's 2030 Climate Target on the way to climate neutrality. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0550

European Commission (2022). Resolution of the European Committee of the Regions — REPowerEU: cities and regions accelerating the energy transition. (2022/C 301/02). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022XR1800&qid=1752787358397

European Commission (2023a). Batteries. https://environment.ec.europa.eu/topics/waste-and-recycling/batteries_en

European Commission (2023b). Heat Pumps. [https://energy.ec.europa.eu/topics/energy-efficiency/heat-pumps_en

Facchini, A., Kennedy, C., Stewart, I. and Mele, R. (2017). The energy metabolism of megacities. Applied Energy 186(2), 86-95. https://doi.org/10.1016/j.apenergy.2016.09.025

Fares, O.H. and Lee, S. H. (2024). Understanding 'underconsumption core': How a new trend is challenging consumer culture. The Conversation. https://theconversation.com/understanding-underconsumption-core-how-a-new-trend-is-challenging-consumer-culture-235417

Fontecha, J.E., Nikolaev, A., Walteros, J.L. and Zhu, Z. (2022). Scientists wanted? A literature review on incentive programs that promote pro-environmental consumer behavior: Energy, waste, and water. Socio-Economic Planning Sciences 82, 101251. https://doi.org/10.1016/j.seps.2022.101251

Fujimori, S., Wu, W., Doelman, J. et al. (2022). Land-based climate change mitigation measures can affect agricultural markets and food security. Nat Food 3, 110–121. https://doi.org/10.1038/s43016-022-00464-4

Fuss, S. et al. (2020). Commentary on Moving toward net-zero emissions requires new alliances for carbon dioxide removal. One Earth 3, 145–149. https://doi.org/10.1016/j.oneear.2020.08.002

Future Earth, The Earth League, World Climate Research Programme (2024). 10 New Insights in Climate Science 2024/2025. Stockholm. https://doi.org/10.5281/zenodo.13950098

Fyson, C.L., Baur, S., Gidden, M., and Schleussner, C.F. (2020). Fair-share carbon dioxide removal increases major emitter responsibility. Nat. Clim. Chang. 10, 836–841. https://doi.org/10.1038/s41558-020-0857-2

Gerassimenko, A., Defau, L. and De Moor, L. (2024). The impact of energy certificates on sales and rental prices: a comparative analysis. International Journal of Housing Markets and Analysis 17(5), 1267-1281. https://doi.org/10.1108/IJHMA-03-2023-0041

Ghosh, D., Bryant, G. and Pillai, P. (2023). Who wins and who loses from renewable energy transition? Large-scale solar, land, and livelihood in Karnataka, India. Globalizations 20, 1328-1343. https://doi.org/10.1080/14747731.2022.2038404

Gibb, D., Rosenow, J., Lowes, R. and Hewitt, N.J., (2023). Coming in from the cold: Heat pump efficiency at low temperatures. Joule, 7(9), pp.1939-1942

Gilbert, N. (2024). First approval fro controversial sea-bed mining worries scientists. https://www.nature.com/articles/d41586-024-00088-7. Accessed 15 November 2025.

Gobby, J., Temper, L., Burke, M. and von Ellenrieder, N. (2022). Resistance as governance: Transformative strategies forged on the frontlines of extractivism in Canada. The Extractive Industries and Society 9, 100919. https://doi.org/10.1016/j.exis.2021.100919

Goodhew, S., Boutouil, M., Streiff, F., Le Guern, M., Carfrae, J. and Fox, M. (2021). Improving the thermal performance of earthen walls to satisfy current building regulations. Energy and Buildings 240, 110873. https://doi.org/10.1016/j.enbuild.2021.110873

Government of Canada (2022). The Canadian Critical Minerals Strategy. https://www.canada.ca/en/campaign/critical-minerals-in-canada/canadian-critical-minerals-strategy.html.

Gould, C. F., Bailis, R., Balakrishnan, K., Burke, M., Espinoza, S., Mehta, S., et al. (2024). In praise of cooking gas subsidies: transitional fuels to advance health and equity. Environ Res Lett. https://doi.org/10.1088/1748-9326/ad5d06

Greening, L.A. (2010). Demand response resources: Who is responsible for implementation in a deregulated market? Energy 35(4), 1518–1525. https://doi.org/10.1016/j.energy.2009.12.013

Grimley, M., Shastry, V., Kânoğlu-Özkan, D.G., Blevins, E., Beck, A.L., Chan, G. et al. (2022). The grassroots are always greener: Community-based organizations as innovators of shared solar energy in the United States. Energy Research & Social Science 90, 102628. https://doi.org/10.1016/j.erss.2022.102628

Grubler, A., Wilson, C., Bento, N. et al. (2018). A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nat Energy 3, 515–527. https://doi.org/10.1038/s41560-018-0172-6

Gui, E.M. and MacGill, I. (2018). Typology of future clean energy communities: An exploratory structure, opportunities, and challenges. Energy Research & Social Science 35, 94-107. https://doi.org/10.1016/j.erss.2017.10.019

Gupta, V., Kumar, P. and Singh, R. (2024). Unveiling the potential of bifacial photovoltaics in harvesting indoor light energy: A comprehensive review. Solar Energy 276, 112660. https://doi.org/10.1016/j.solener.2024.112660

He, J., Osabohien, R., Yin, W., Adeleke, O.K., Uduma, K., Agene, D. et al. (2024). Green economic growth, renewable energy and food security in Sub-Saharan Africa. Energy Strategy Reviews 55, 101503. https://doi.org/10.1016/j.esr.2024.101503.

Hoicka, C.E., Lowitzsch, J., Brisbois, M.C., Kumar, A. and Ramirez Camargo, L. (2021). Implementing a just renewable energy transition: Policy advice for transposing the new European rules for renewable energy communities. Energy Policy 156, 112435. https://doi.org/10.1016/j.enpol.2021.112435

Holstenkamp, L. (2019). What do we know about cooperative sustainable electrification in the global South? A synthesis of the literature and refined social-ecological systems framework. Renewable and Sustainable Energy Reviews 109, 307-320. https://doi.org/10.1016/j.rser.2019.04.047

Horowitz, L.S., Keeling, A., Lévesque, F., Rodon, T., Schott, S. and Thériault, S. (2018). Indigenous peoples' relationships to large-scale mining in post/colonial contexts: Toward multidisciplinary comparative perspectives. The Extractive Industries and Society 5(3), 404-414. https://doi.org/10.1016/j.exis.2018.05.004

Hund, K., Porta, D., Fabregas, T., Laing, T. and Drexhage, J. (2020). CLIMATE-SMART MINING FACILITY Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf

Hurlbert, M.A. and Datta, R. (2022). When the environment is destroyed, you're destroyed: Achieving Indigenous led pipeline justice. Energy Research & Social Science, 91, 102711. https://doi.org/10.1016/j.erss.2022.102711

Ibrahim, S. (2023). Energy Efficiency: Challenges and Solutions. Energy & Grid Management. In: Energy Central. https://www.energycentral.com/energy-management/post/energy-efficiency-challenges-and-solutions-YmUmNX7p76pzUqE

IK & LK Dialogues. Indigenous Knowledge and Local Knowledge Dialogues. Global Environment Outlook 7. (2025) Mexico City: CopIt-arXives, 2025. https://copitarxives.fisica.unam.mx/SC0011EN/SC0011EN.php Indigenous Knowledge and Local Knowledge Dialogues - Copit Arxives

India (2023). Ministry of Mines. Critical Minerals for India. https://mines.gov.in/admin/storage/app/uploads/649d4212cceb01688027666.pdf

Indigenous Clean Energy (2023). Indigenous-led Clean Energy Project Map. https://indigenouscleanenergy.com/connect-learn/indigenous-led-clean-energy-project-map/

Institute for Transportation & Development Policy (n.d.). Eight Principles of TOD. https://tod.itdp.org/what-is-tod/eight-principles-of-tod.html

Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (2024). Financial Benefit-Sharing Issues for Critical Minerals: Challenges and opportunities for producing countries. https://www.iisd.org/system/files/2024-03/financial-benefit-sharing-issues-critical-minerals.pdf

Intergovernmental Panel on Climate Change (2018). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Geneva: IPCC.https://www.ipcc.ch/sr15/

Intergovernmental Panel on Climate Change (2021). Climate Change 2021: The Physical Science Basis Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger et al. (eds.). Cambridge. https://www.ipcc.ch/report/ar6/wg1/

Intergovernmental Panel on Climate Change (2022a). Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009325844.001

Intergovernmental Panel on Climate Change (2022b). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change P.R. Shukla, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak et al. (eds.). Cambridge. https://doi.org/10.1017/9781009157926

Intergovernmental Panel on Climate Change (IPCC). (2022c). Chapter 4: Water. In H.-O. Pörtner et al. (Eds.), Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 551–712). Cambridge University Press. https://doi. org/10.1017/9781009325844.006

Intergovernmental Panel on Climate Change (2023a). AR6 Synthesis Report: Climate Change 2023. https://www.ipcc.ch/report/sixth-assessment-report-cycle/

Intergovernmental Panel on Climate Change (2023b). Summary for Policymakers. In: Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. 3–34. https://doi.org/10.1017/9781009325844.001

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2024a). Thematic Assessment Report on the Interlinkages among Biodiversity, Water, Food and Health of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Harrison, P. A., McElwee, P. D., and van Huysen, T. L. (eds.). IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.13850054

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2024b). Thematic Assessment Report on the Underlying Causes of Biodiversity Loss and the Determinants of Transformative Change and Options for Achieving the 2050 Vision for Biodiversity of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Transformative Change Assessment). O'Brien, K., Garibaldi, L., and Agrawal, A. (eds.). IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.11382215

International Energy Agency (2020), Power Systems in Transition, IEA, Paris https://www.iea.org/reports/power-systems-in-transition

International Energy Agency (2021a). Net Zero by 2050: A Roadmap for the Global Energy Sector https://www.iea.org/events/net-zero-by-2050-a-roadmap-for-the-global-energy-system

International Energy Agency (2021b). The Role of Low-Carbon Fuels in the Clean Energy Transitions of the Power Sector, IEA, Paris https://www.iea.org/reports/the-role-of-low-carbon-fuels-in-the-clean-energy-transitions-of-the-power-sector

International Energy Agency (2022a). The Future of Heat Pumps. https://www.iea.org/reports/the-future-of-heat-pumps/executive-summary

International Energy Agency (2022b). Playing my Part. https://www.iea.org/reports/playing-my-part

International Energy Agency (2022c). Skills Development and Inclusivity for Clean Energy Transitions. https://www.iea.org/reports/skills-development-and-inclusivity-for-clean-energy-transitions

International Energy Agency (2022d). The Role of Critical Minerals in Clean Energy Transitions. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/executive-summary

International Energy Agency (2023a). World Energy Outlook 2023. https://www.iea.org/reports/world-energy-outlook-2023

International Energy Agency (2023b). A Vision for Clean Cooking Access for All. https://www.iea.org/reports/a-vision-for-clean-cooking-access-for-all

International Energy Agency (2023c). Buildings. https://www.iea.org/energy-system/buildings

International Energy Agency (2024). Demand Response. https://www.iea.org/energy-system/energy-efficiency-and-demand/demand-response

International Energy Agency (2025a). Modern Renewables. https://www.iea.org/reports/sdg7-data-and-projections/modern-renewables

International Energy Agency (2025b). Energy End-uses and Efficiency Indicators Highlights. https://www.iea.org/data-and-statistics/data-product/energy-efficiency-indicators-highlights

International Institute for Sustainable Development (2022). Navigating Energy Transitions Mapping the road to 1.5°C IISD REPORT. (n.d.). https://www.iisd.org/system/files/2022-10/navigating-energy-transitions-mapping-road-to-1.5.pdf

International Labour Organization (2002). The Alaska Permanent Fund Dividend: An Experiment in Wealth Distribution. https://webapps.ilo.org/public/english/protection/ses/download/docs/gold.pdf

International Renewable Energy Agency (2023). International trade and green hydrogen supporting the global transition to a low-carbon economy. https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Dec/IRENA_WTO_International_trade_green_hydrogen_2023.pdf?rev=5478e0e6ebb141cdbd1b1c5a8f9395b1

International Union for Conservation of Nature (IUCN) (2013). Guidelines for Applying Protected Area Management Categories. Dudley, N. (ed.). https://portals.iucn.org/library/sites/library/files/documents/pag-021.pdf

IRENA Coalition for Action (2018). Community Energy: Broadening the ownershop of renewables. https://coalition.irena.org/-/media/Files/IRENA/Coalition-for-Action/Publication/Coalition-for-Action_Community-Energy_2018.pdf

Jeuland, M., Desai, M.A., Bair, E.F., Mohideen Abdul Cader, N., Natesan, D., Isaac, W.J. et al. (2023). A randomized trial of price subsidies for liquefied petroleum cooking gas among low-income households in rural India. World Development Perspectives 30, 100490. https://doi.org/10.1016/j.wdp.2023.100490

Jiang, Z., Zhang, M., & Hou, Y. (2020). Both Forest Harvesting and Hydropower Dams Yielded Negative Impact on Low Flow Regimes in the Zagunao River Watershed, Southwest China. Forests, 11(8), 787. https://doi.org/10.3390/f11080787

Joshi, G. and Yenneti, K. (2020). Community solar energy initiatives in India: A pathway for addressing energy poverty and sustainability? Energy and Buildings 210, 109736. https://doi.org/10.1016/j.enbuild.2019.109736

Kalli, R., Jena, P. R., and Managi, S. (2022). Subsidized LPG Scheme and the Shift to Cleaner Household Energy Use: Evidence from a Tribal Community of Eastern India. Sustainability, 14(4), 2450. https://doi.org/10.3390/su14042450

Kamali Saraji, M. and Streimikiene, D. (2023). Challenges to the low carbon energy transition: A systematic literature review and research agenda. Energy Strategy Reviews 49, 101163. https://doi.org/10.1016/j.esr.2023.101163

Kastner, I. And Stern, P.C. (2015) Examining the decision-making process behind household energy investments: A review. Energy Research & Social Science 10, 72-89. https://doi.org/10.1016/j.erss.2015.07.008

Keady, W., Panikkar, B., Nelson, I.L. and Zia, A. (2021). Energy justice gaps in renewable energy transition policy initiatives in Vermont. Energy Policy. 159, 112608

Khazal, A. and Sønstebø, O.J. (2023). Energy Efficiency Premium Issues and Revealing the Pure Label Effect. The Energy Journal 44(1), 33-54. https://doi.org/10.5547/01956574.44.1.akha

Khosla, R. and Bhardwaj, A. (2018). Urbanization in the time of climate change: Examining the response of Indian cities. Wiley Interdisciplinary Reviews: Climate Change https://doi.org/10.10.1002/wcc.560

Kim, J., Sovacool, B.K., Bazilian, M., Griffiths, S., Lee, J., Yang, M. et al. (2022). Decarbonizing the iron and steek industry: A systematic review of sociotechnical systems, technological innovations, and policy options. Energy Research & Social Science 89, 102565. https://doi.org/10.1016/j.erss.2022.102565

Kime, S., Jacome, V., Pellow, D. and Deshmukh, R. (2023). Evaluating equity and justice in low-carbon energy transitions. Environmental Research Letters 18(12), 123003. https://doi.org/10.1088/1748-9326/ad08f8

Klein, S.J.W. and Coffey, S. (2016). Building a sustainable energy future, one community at a time. Renewable and Sustainable Energy Reviews 60, 867-880. https://doi.org/10.1016/j.rser.2016.01.129

Koirala, B.P., Koliou, E., Friege, J., Hakvoort, R.A. and Herder, P.M. (2016). Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems. Renewable and Sustainable Energy Reviews 56, 722-744. https://doi.org/10.1016/j.rser.2015.11.080

Kotchen, M.J. (2021). The producer benefits of implicit fossil fuel subsidies in the United States. Proc Natl Acad Sci U S A 118(14). https://doi.org/10.1073/pnas.2011969118

Kyle, J. (2018). Local Corruption and Popular Support for Fuel Subsidy Reform in Indonesia. Comparative Political Studies, 51(11), 1472-1503. https://doi.org/10.1177/0010414018758755

Kunz, N.C. (2020). Towards a broadened view of water security in mining regions. Water Security 11, 100079. https://doi.org/10.1016/j.wasec.2020.100079

Lèbre, É., Stringer, M., Svobodova, K., Owen, J.R., Kemp, D., Côte, C. et al. (2020). The social and environmental complexities of extracting energy transition metals. Nature Communications 11(1), 4823. https://doi.org/10.1038/s41467-020-18661-9

Levin, L.A., Amon, D.J. and Lily, H. (2020). Challenges to the sustainability of deep-seabed mining. Nature Sustainability 3, 784-794. https://doi.org/10.1038/s41893-020-0558-x

Lobo, G.S., Gil, J.O., da Silva, R.F.B. and Moran, E.F. (2025). Downstream impacts of the Madeira Hydroelectric Complex on várzea traditional agriculture and extractivism. Ecology and Society 30(3). https://doi.org/10.5751/ES-16518-300333

Lohrmann, A., Farfan, J., Caldera, U., Lohrmann, C. and Breyer, C. (2019). Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery. Nature Energy 4(12), 1040-1048. https://doi.org/10.1038/s41560-019-0501-4

Luckeneder, S., Giljum, S., Schaffartzik, A., Maus, V. amd Tost, M. (2021). Surge in global metal mining threatens vulnerable ecosystems. Global Environmental Change 69, 102303. https://doi.org/10.1016/j.gloenvcha.2021.102303

Luderer, G., Vrontisi, Z., Bertram, C., Edelenbosch, O.Y., Pietzcker, R.C., Rogelj, J. et al. (2018). Residual fossil CO_2 emissions in 1.5–2 °C pathways. Nature Climate Change 8(7), 626-633. https://doi.org/10.1038/s41558-018-0198-6

MacFarland, A. R., Larsen, L., Yeshitela, k., Engida, A. N. and Love, N. (2019). Guide for using green infrastructure in urban environments for stormwater management. Environmental science: Water Research and Technology (4). https://pubs.rsc.org/en/content/articlelanding/2019/ew/c8ew00498f

Macklin, M.G., Thomas, C.J., Mudbhatkal, A., Brewer, P.A., Hudson-Edwards, K.A., Lewin, J. et al. (2023). Impacts of metal mining on river systems: a global assessment. Science 381(6664), 1345-1350. https://doi.org/10.1126/science.adg6704

Mahdavi, P., Martinez-Alvarez, C. B. & Ross, M. L. Why do governments tax or subsidize fossil fuels? J. Politics 84, 2123–2139 (2022). https://escholarship.org/content/qt4zm8829n/qt4zm8829n.pdf

Mahmood, M., Chowdhury, P., Yeassin, R., Hasan, M., Ahmad, T. and Chowdhury, N.-U.-R. (2024). Impacts of digitalization on smart grids, renewable energy, and demand response: An updated review of current applications. Energy Conversion and Management: X 24, 100790. https://doi.org/10.1016/j.ecmx.2024.100790

Malakar, Y. and Day, R. (2020). Differences in firewood users' and LPG users' perceived relationships between cooking fuels and women's multidimensional well-being in rural India. Nature Energy 5, 1022-1031. https://doi.org/10.1038/s41560-020-00722-4

Malerba, Daniele (2023) : The role of social protection in environmental fiscal reforms, IDOS Discussion Paper, No. 10/2023, ISBN 978-3-96021-211-9, German Institute of Development and Sustainability (IDOS), Bonn, https://doi.org/10.23661/idp10.2023

McCauley, D. and Heffron, R. (2018). Just transition: Integrating climate, energy and environmental justice. Energy Policy 119, 1-7. https://doi.org/10.1016/j.enpol.2018.04.014.

Meier, O., Gruchmann, T. and Ivanov, D. (2023). Circular supply chain management with blockchain technology: Dynamic capabilities view. Transportation Research Part E: Logistics and Transportation Review 176, 103177. https://doi.org/10.1016/j.tre.2023.103177.

Mining Technology (2022). 'Cleantech boom 2.0: Does mining have a place?'. GlobalData Thematic Intelligence, https://www.mining-technology.com/comment/cleantech-mining-place/?cf-view

Mizdrak, A., Tatah, L., Mueller, N., Shaw, C. and Woodcock, J. (2023). Assessing the health impacts of changes in active transport: An updated systematic review. Journal of Transport & Health 33, 101702. https://doi.org/10.1016/j.jth.2023.101702

Monasterolo, I. and Raberto, M. (2019). The impact of phasing out fossil fuel subsidies on the low-carbon transition. Energy Policy Volume 124, Pages 355-370. https://doi.org/10.1016/j.enpol.2018.08.051

Monyei, C.G,, Adewumi, A.O. and Jenkins, K.E.H. (2018). Energy (in)justice in off-grid rural electrification policy: South Africa in focus. Energy Research & Social Science 44, 152-171. https://doi.org/10.1016/j.erss.2018.05.002

Moroni, S., Alberti, V., Antoniucci, V. and Bisello, A. (2019). Energy communities in the transition to a low-carbon future: A taxonomical approach and some policy dilemmas. Journal of Environmental Management 236, 45-53. https://doi.org/10.1016/j.jenvman.2019.01.095

Movahedi, A. and Derrible, S. (2021). Interrelationships between electricity, gas, and water consumption in large-scale buildings. Journal of Industrial Ecology 25(4), 932-947. https://doi.org/10.1111/jiec.13097

Movahedi, A., Parsa, A.B., Rozhkov, A., Lee, D., Mohammadian, A.K. and Derrible, S. (2023). Interrelationships between urban travel demand and electricity consumption: a deep learning approach. Scientific Reports 13(1), 6223. https://doi.org/10.1038/s41598-023-33133-y

Janardhanan, N., M.M., Olsen, S.H., Murun, T., Kojima, S., Takemoto, A. et al. (2023). Critical Minerals for Net-Zero Transition: How the G7 can Address Supply Chain Challenges and Socioenvironmental Spillover. Policy Brief. https://think7.org/wp-content/uploads/2023/12/T7JP_TF2_Critical-Minerals-for-Net-Zero-Transition-How-the-G7-can-Address-Supply-Chain-Challenges-and-Socioenvironmental-Spillovers.pdf

National Association of City Transportation Officials (n.d.). Urban Bikeway Design Guide. https://nacto.org/publication/urban-bikeway-design-guide/

Nature (2024). Norway's approval of sea-bed mining undermines efforts to protect the ocean. https://www.nature.com/articles/d41586-024-00104-w

Newell, P., van Asselt, H. and Daley, F. (2022). Building a fossil fuel non-proliferation treaty: Key elements. Earth System Governance 14, 100159. https://doi.org/10.1016/j.esg.2022.100159

Noll, D., Dawes, C. and Rai, V. (2014). Solar Community Organizations and active peer effects in the adoption of residential PV. Energy Policy 67, 330-343. https://doi.org/10.1016/j.enpol.2013.12.050

NORDCAP (2020). Annual Report. https://www.nrc.no/shorthand/norcap/norcap-annual-report-2020/index.html

Nordhaus (2017). Revisiting the social cost of carbon PNAS 114 (7), 1518-1523. https://doi.org/10.1073/pnas.1609244114

Nouni, M.R., Jha, P., Srakhel, R., Banerjee, C., Tripathi, A.K. and Manna, J. (2021). Alternative fuels for decarbonisation of road transport sector in India: Options, present status, opportunities, and challenges. Fuel 305, 121583. https://doi.org/10.1016/j.fuel.2021.121583

Nwaigwe, K.N. (2022). Assessment of wind energy technology adoption, application and utilization: a critical review. International Journal of Environmental Science and Technology 19(5), 4525-4536. https://doi.org/10.1007/s13762-021-03402-2

Nwaigwe, K.N., Agarwal, A. and Anyanwu, E.E. (2018). Biogas Potentials Evaluation of Household Wastes in Johannesburg Metropolitan Area Using the Automatic Methane Potential Test System (AMPTS) II. ASME 2018 12th International Conference on Energy Sustainability collocated with the ASME 2018 Power Conference and the ASME 2018 Nuclear Forum. ES2018-7553, V001T04A006. https://doi.org/10.1115/ES2018-7553

Nwaigwe, K.N., Mutabilwa, P. and Dintwa, E. (2019). An overview of solar power (PV systems) integration into electricity grids. Materials Science for Energy Technologies 2(3), 629-633. https://doi.org/10.1016/j.mset.2019.07.002

O'Fallon Illinois (2022). 2040 Master Plan, O'Fallon, Illinois. https://www.ofallon.org/DocumentCenter/View/299/2040-Master-Plan-PDF

Olówósejéjé, S., Leahy, P. and Morrison, A. (2020). A practical approach for increased electrification, lower emissions and lower energy costs in Africa. Sustainable Futures 2, 100022. https://doi.org/10.1016/j.sftr.2020.100022

Okem, A. E. and Ley, D. (2023). Enablers and constraints to energy communities: lessons for energy communities in Sub-Saharan Africa. In Sokolowski, M. M.; Visvizi, A. (Eds.). Routledge handbook of energy communities and smart cities. Abingdon, Oxon, UK: Routledge. pp.220-232. (Routledge Environment and Sustainability Handbooks) [doi: https://doi.org/10.4324/9781003280118-18]

Oksman, V., Reda, F., Karjalainen, S., Rehman, H. and Fatima, Z. (2021). Towards sustainable energy culture in the industrial sector: introducing an interdisciplinary method for understanding energy culture in business industries. Energy, Sustainability and Society 11, 28. https://doi.org/10.1186/s13705-021-00303-7

Organisation for Economic Co-operation and Development (2016). Due Diligence Guidance: towards conflict-free mineral supply chains. https://www.oecd.org/daf/inv/mne/EasytoUseGuide_English.pdf

Organisation for Economic Co-operation and Development (2018), OECD Due Diligence Guidance for Responsible Business Conduct, OECD Publishing, Paris, https://doi.org/10.1787/15f5f4b3-en

Organisation for Economic Co-operation and Development (2020). Productivity Gains from Teleworking in the Post COVID-19 era: How Can Public Policies Make It happen? OECD. https://www.oecd.org/coronavirus/policy-responses/productivity-gains-from-teleworking-in-the-post-covid-19-era-a5d52e99/

Organisation for Economic Co-operation and Development (2021). The United Kingdom's pioneering Climate Change Act. https://www.oecd.org/climate-action/ipac/practices/the-united-kingdom-s-pioneering-climate-change-act-c08c3d7a/

Oteman, M., Wiering, M. and Helderman, J.-K. (2014). The institutional space of community initiatives for renewable energy: a comparative case study of the Netherlands, Germany and Denmark. Energy, Sustainability and Society 4(1), 11. https://doi.org/10.1186/2192-0567-4-11

The Oxford Institute for Energy Studies (2021). Beyond Energy: Incentivizing Decarbonization through the Circular Economy. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2021/04/Beyond-Energy-Incentivizing-Decarbonization-through-the-Circular-Economy-EL-44.pdf

Owen, J.R., Kemp, D., Lechner, A.M., Harris, J., Zhang, R. and Lèbre, É. (2022). Energy transition minerals and their intersection with land-connected peoples. Nature Sustainability 6, 203-211. https://doi.org/10.1038/s41893-022-00994-6

Owen, J.R., Kemp, D., Lechner, A.M. et al. (2023). Energy transition minerals and their intersection with land-connected peoples. Nature Sustainability 6, 203–211. https://doi.org/10.1038/s41893-022-00994-6

Pahle, M., Burtraw, D., Flachsland et al. (2018). Sequencing to ratchet up climate policy stringency. Nature Clim Change 8, 861–867 https://doi.org/10.1038/s41558-018-0287-6

Peng, W., Yang, J., Lu, X. and Mauzerall, D.L. (2018). Potential co-benefits of electrification for air quality, health, and CO_2 mitigation in 2030 China. Applied Energy 218, 511-519. https://doi.org/10.1016/j.apenergy.2018.02.048

Toledano, P., Brauch, M.D. and Arnold J. (2023). Circularity in mineral and renewable energy value chains: Overview of Technology, Policy, and Finance Aspects. https://ccsi.columbia.edu/sites/default/files/content/docs/ccsi-circular-economy-mineral-renewable-energy.pdf

Peters, J. and Sievert, M. (2016). Impacts of rural electrification revisited – the African context. Journal of Development Effectiveness 8(3), 327-345. https://doi.org/10.1080/19439342.2016.1178320

Prütz, R., Fuss, S., Lück, S., Stephan, L., and Rogelj, J. (2024). A taxonomy to map evidence on the co-benefits, challenges, and limits of carbon dioxide removal. Commun Earth Environ 5, 197. https://doi.org/10.1038/s43247-024-01365-z

Puig, D., Moner-Gironda, M., Kammen, D. M., Mulugetta, Y., Marzouk, A., Jarrett, M. et al. (2021). An action agenda for Africa's electricity sector. Modernization and expansion require heightened efforts. Science 373 (6555), 616-619. https://doi.org/10.1126/science.abh1975

Reinhart, C. (2025). Climate Driven Design I. Building Technology Press. https://buildingtechnologypress.com/our-books-new/

Ritchie, P.D.L., Clarke, J.J., Cox, P.M. et al. (2021). Overshooting tipping point thresholds in a changing climate. Nature 592, 517–523. https://doi.org/10.1038/s41586-021-03263-2

Ritchie, P., Alkhayuon, H., Cox, P. and Wieczorek, S. (2022). Rate-induced tipping in natural and human systems. EGUsphere 2022, 1-19. https://doi.org/10.5194/egusphere-2022-1176

Roberts, C., Geels, F.W., Lockwood, M., Newell, P., Schmitz, H., Turnheim, B. et al. (2018). The politics of accelerating low-carbon transitions: Towards a new research agenda. Energy Research & Social Science 44, 304-311. https://doi.org/10.1016/j.erss.2018.06.001

Rochman, N. N., Kasim, A. And Atmoko, A. W. (2023). Analysis of governance complexity on subsidized LPG in Indonesia: A three-level institutional approach. IAPA 2022 International Conference and International Indonesia Conference on Interdisciplinary Studies. KnE Social Sciences. https://knepublishing.com/index.php/KnE-Social/article/download/12987/20928

Rogelj, J., Popp, A., Calvin, K.V., Luderer, G., Emmerling, J., Gernaat, D. et al. (2018a). Scenarios towards limiting global mean temperature increase below 1.5 °C. Nature Climate Change 8(4), 325-332. https://doi.org/10.1038/s41558-018-0091-3

Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. et al. (2018b). Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla et al. (eds.). In Press. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter2_High_Res.pdf

Rosenow, J., Gibb, D., Nowak, T. and Lowes, R. (2022). Heating up the global heat pump market. Nature Energy 7(10), 901-904. https://doi.org/10.1038/s41560-022-01104-8

Rosenthal, J., Quinn, A., Grieshop, A.P., Pillarisetti, A. and Glass, R.I. (2018). Clean cooking and the SDGs: Integrated analytical approaches to guide energy interventions for health and environment goals. Energy for Sustainable Development 42, 152-159. https://doi.org/10.1016/j.esd.2017.11.003

Ruiz-Agudelo, C.A. and Gutiérrez-Bonilla, F.d.P. (2025). The natural capital of the Colombian Caribbean Basins. Evidence of rapid anthropic transformation. Sustainable Futures 9, 100524. https://doi.org/10.1016/j.sftr.2025.100524

Safarzynska, K., Di Domenico, L. and Raberto, M. (2023). The leakage effect may undermine the circular economy efforts. Scientific Reports 13(1), 16677. https://doi.org/10.1038/s41598-023-44004-x

Salvador, G.N., Leal, C.G., Brejão, G.L., Pessali, T.C., Alves, C.B.M., Rosa, G.R. et al. (2020). Mining activity in Brazil and negligence in action. Perspectives in Ecology and Conservation 18(2), 139-144. https://doi.org/10.1016/j.pecon.2020.05.003

Santos, M. (2023). 'Sunny Short: A decade of empowerment: Celebrating 10 years of advancing community energy'. https://caneurope.org/advancing-community-energy/

Sapkota, A., Lu, Z., Yang, H. and Wang, J. (2014). Role of renewable energy technologies in rural communities' adaptation to climate change in Nepal. Renewable Energy 68, 793-800. https://doi.org/10.1016/j.renene.2014.03.003

Schipper, E.L.F., Revi, A., Preston, B. L, Carr, E.R,, Eriksen, S.H., Fernandez-Carril, B. et al. (2022). Climate Resilient Development Pathways. In Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2655-2807. https://doi.org/10.1017/9781009325844.027

Schwab, A., Thomas, A., Bennett, J., Robertson, E. and Cary, S. (2021). Electrification of Aircraft: Challenges, Barriers, and Potential Impacts. United States. https://www.osti.gov/biblio/1827628

Schwanen, T. (2021). Chapter 2: Urban transport and wellbeing: a critical analysis. In: Transport in Human Scale Cities. Cheltenham, UK: Edward Elgar Publishing. https://www.elgaronline.com/view/edcoll/9781800370500/9781800370500.00011.xml

Schwanitz, V.J., Piontek, F., Bertram, C. and Luderer, G. (2014). Long-term climate policy implications of phasing out fossil fuel subsidies, Energy Policy 67, Pages 882-894. https://doi.org/10.1016/j.enpol.2013.12.015

Seidu, S., Chan, D.W.M., Edwards, D.J. and Owusu-Manu, D.-G. (2025). A systematic review of green infrastructure and ecosystem-based technologies for climate resilience: development trends, research outlook and future projections. Environmental Research Letters 20(8), 083001. https://dx.doi.org/10.1088/1748-9326/ade730

Semprini, G., Ferrante, A., Cattani, E. and Fotopololou, A. (2017). New strategies towards nearly zero energy in existing buildings: the ABRACADABRA project. Energy Procedia 140, 151-158. https://doi.org/10.1016/j.egypro.2017.11.131

Sethi, M., Lamb, W., Minx, J. and Creutzig, F. (2020). Climate change mitigation in cities: a systematic scoping of case studies. Environmental Research Letters 15(9). https://doi.org/10.1088/1748-9326/ab99ff.

Seyfang, G., Park, J.J. and Smith, A. (2013). A thousand flowers blooming? An examination of community energy in the UK. Energy Policy 61, 977-989. https://doi.org/10.1016/j.enpol.2013.06.030

Shindell, D. and Rogelj, J. (2025). Preserving carbon dioxide removal to serve critical needs. Nat. Clim. Chang. https://doi.org/10.1038/s41558-025-02251-y

Shupler, M., Hystad, P., Birch, A., Miller-Lionberg, D., Jeronimo, M., Arku, R.E. et al. (2020). Household and personal air pollution exposure measurements from 120 communities in eight countries: results from the PURE-AIR study. The Lancet Planetary Health 4(10), e451-e462. https://doi.org/10.1016/S2542-5196(20)30197-2

Siqueira-Gay, J., Sonter, L.J. and Sánchez, L.E. (2020). Exploring potential impacts of mining on forest loss and fragmentation within a biodiverse region of Brazil's northeastern Amazon. Resources Policy 67, 101662. https://doi.org/10.1016/j.resourpol.2020.101662

Singh, Ford, C., Ley, J. and et al (2020). Assessing the feasibility of adaptation options: methodological advancements and directions for climate adaptation research and practice. Climatic Change 162, 255–277 https://doi.org/10.1007/s10584-020-02762-x

Skovgaard, J. and van Asselt, H. (2019). The politics of fossil fuel subsidies and their reform: Implications for climate change mitigation. WIREs Climate Change 10(4), e581. https://doi.org/10.1002/wcc.581

Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C. et al. (2024). The State of Carbon Dioxide Removal 2024 - 2nd Edition. http://dx.doi.org/10.17605/OSF.IO/F85QJ

Soergel, B., Rauner, S., Daioglou, V., Weindl, I., Mastrucci, A., Carrer, F. et al. (2024). Multiple pathways towards sustainable development goals and climate targets. Environmental Research Letters 19(12), 124009. https://dx.doi.org/10.1088/1748-9326/ad80af

Sonter, L.J., Dade, M.C., Watson, J.E.M. and Valenta, R.K. (2020). Renewable energy production will exacerbate mining threats to biodiversity. Nature Communications 11(1), 4174. https://doi.org/10.1038/s41467-020-17928-5

Source Heat Pump (2024). Return On Investment For Air Source Heat Pumps. https://sourceheatpump.com/return-on-investment-air-source-heat-pumps/

Spice, A. (2018) Chapter 3: Fighting Invasive Infrastructures: Indigenous Relations against Pipelines in Indigenous Resurgence. Dhillon, J. [eds.]. https://doi.org/10.3167/9781800732452

Stechemesser, A., Koch, N., Mark, E., Dilger, E., Klösel, P., Menicacci, L. et al. (2024). Climate policies that achieved major emission reductions: Global evidence from two decades. Science 385(6711), 884-892. https://doi.org/10.1126/science.adl6547

Stoerk, T., Dudek, D.J. and Yang, J. (2019). China's national carbon emissions trading scheme: lessons from the pilot emission trading schemes, academic literature, and known policy details. Climate Policy 19(4), 472-486. https://doi.org/10.1080/14693062.2019.1568959

Strefler, J., Amann, T., Bauer, N., Kriegler, E. and Hartmann, J. (2018). Potential and costs of carbon dioxide removal by enhanced weathering of rocks. Environmental Research Letters 13(3), 034010. https://doi.org/10.1088/1748-9326/aaa9c4

Stritzke, S., Sakyi-Nyarko, C., Bisaga, I., Bricknell, M., Leary, J., & Brown, E. (2021). Results-Based Financing (RBF) for Modern Energy Cooking Solutions: An Effective Driver for Innovation and Scale? Energies, 14(15), 4559. https://doi.org/10.3390/en14154559

Stucki, T., Woerter, M., Arvanitis, S., Peneder, M. and Rammer, C. (2018). How different policy instruments affect green product innovation: A differentiated perspective. Energy Policy 114, 245-261. https://doi.org/10.1016/j.enpol.2017.11.049

Succar, S.A, Brissaud, D., Evrard, D., flick, D. and Fontaine, D. (2023). Decarbonization Measure: A Concept towards the Acceleration of the Automotive Plant Decarbonization. Systems 11(7), 335. https://doi.org/10.3390/systems11070335

Susskind, L., Chun, J., Gant., A., Hodgkins, C., Cohen., J. and Lohmar, S. (2022). Sources of opposition to renewable energy projects in the United States. Energy Policy 165, 112922. https://doi.org/10.1016/j.enpol.2022.112922

Sustainable Energy for All (SEforALL) (2020). Sustainable Energy for All Chilling Prospects: Tracking Sustainable Cooling for All 2020

Sutradhar, U., Spearing, L. and Derrible, S. (2024). Depopulation and associated challenges for US cities by 2100. Nature Cities 1, 51-61. https://doi.org/10.1038/s44284-023-00011-7

Tao, Y., Steckel, D., Klemeš, J.J. and You, F. (2021). Trend towards virtual and hybrid conferences may be an effective climate change mitigation strategy. Nature Communications 12 (1). https://doi.org/10.1038/s41467-021-27251-2

Tornel-Vázquez, R., Iglesias, E. and Loureiro, M. (2024). Adoption of clean energy cooking technologies in rural households: the role of women. Environment and Development Economics 29(6), 499-517. https://www.cambridge.org/core/product/5754DA693A89DE39CE11BBA9D0324EA2

Touati, K., Le Guern, M., El Mendili, Y., Azil, A., Streiff, F., Carfrae, J. et al. (2023). Earthen-based building: In-situ drying kinetics and shrinkage. Construction and Building Materials 369, 130544. https://doi.org/10.1016/j.conbuildmat.2023.130544

Tsagkari, M. (2022). The need for gender-based approach in the assessment of local energy projects. Energy for Sustainable Development 68, 40-49. https://doi.org/10.1016/j.esd.2022.03.001

Turner, S.D. (2012). World Heritage Sites and the extractive industries. https://whc.unesco.org/document/140635

United Nations (1948). Universal Declaration of Human Rights. https://www.un.org/en/about-us/universal-declaration-of-human-rights

United Nations (2007). United Nations Declaration on the Rights of Indigenous Peoples. https://social.desa.un.org/issues/indigenous-peoples/united-nations-declaration-on-the-rights-of-indigenous-peoples

United Nations (2020). The Sustainable Development Goals Report. https://unstats.un.org/sdgs/report/2020/The-Sustainable-Development-Goals-Report-2020.pdf

United Nations (2023). Goal 7 | Department of Economic and Social Affairs. Sdgs.un.org; United Nations. https://sdgs.un.org/goals/goal7

United Nations (2024). PRINCIPLES TO GUIDE CRITICAL ENERGY TRANSITION MINERALS TOWARDS EQUITY AND JUSTICE. https://www.un.org/sites/un2.un.org/files/report_sg_panel_on_critical_energy_transition_minerals_11_sept_2024.pdf

United Nations Development Programme (2016). Mapping Mining to the Sustainable Empowered lives. Resilient nations. Development Goals: An Atlas. https://www.undp.org/sites/g/files/zskgke326/files/publications/Mapping_Mining_SDGs_An_Atlas_Executive_Summary_FINAL.pdf

United Nations Development Programme (2021). World's largest survey of public opinion on climate change: a majority of people call for wide-ranging action https://www.undp.org/press-releases/worlds-largest-survey-public-opinion-climate-change-majority-people-call-wide-ranging-action

United Nations Environment Programme (2023). Global Cooling Watch 2023. https://www.unep.org/resources/global-cooling-watch-2023

United Nations Environment Programme (2024a). Emissions Gap Report 2024. https://www.unep.org/resources/emissions-gap-report-2024

United Nations Environment Programme (2024b). Critical Transitions: Circularity, equity, and responsibility in the quest for energy transition minerals. https://wedocs.unep.org/bitstream/handle/20.500.11822/46623/critical_transitions.pdf?sequence=3&isAllowed=y

United Nations Environment Programme, United Nations Technology Centre and Network, United Nations Climate Change Technology Executive Committee, United Nations Environment Programme Copenhagen Climate Centre (2024). The Climate Technology Progress Report 2024: Unleashing Renewable Energy for Ambitious NDCs. https://unfccc.int/ttclear/misc_/StaticFiles/gnwoerk_static/TEC_documents/c2929538b63e407c8785640271db2b58/a05a3b5cbf3341c08e78b9443cf90c6d.pdf

United Nations Framework Convention on Climate Change (2022). Just Transition of the Workforce, and the Creation of Decent Work and Quality Jobs. https://unfccc.int/sites/default/files/resource/Just%20transition.pdf

United Nations Framework Convention on Climate Change (2023a). EcoDataCenter – Sweden. https://unfccc.int/climate-action/momentum-for-change/activity-database/ecodatacenter

United Nations Framework Convention on Climate Change. Outcome of the first global stocktake: Draft decision -/CMA.5. Conference of the Parties serving as the meeting of the Parties to the Paris Agreement, fifth session. Dubai: UNFCCC. https://unfccc.int/sites/default/files/resource/cma5_auv_4_gst.pdf

United Nations Industrial Development Organization (2022). Industrial Development Report. https://www.unido.org/sites/default/files/files/2021-11/IDR%202022%20-%20EBOOK.pdf

United Nations Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States. Connectivity in the Least Developed Countries: Status Report 2021. United Nations.

United States of America Department of Energy (2007). Mining Industry Energy Bandwidth Study https://www.energy.gov/eere/iedo/articles/us-mining-industry-energy-bandwidth-study

van der Schoor, T. and Scholtens, B. (2015). Power to the people: Local community initiatives and the transition to sustainable energy. Renewable and Sustainable Energy Reviews 43, 666-675. https://doi.org/10.1016/j.rser.2014.10.089

van der Schoor, T. and Scholtens, B. (2019). The power of friends and neighbors: a review of community energy research. Current Opinion in Environmental Sustainability 39, 71-80. https://doi.org/10.1016/j.cosust.2019.08.004

van de Ven, DJ., Capellan-Peréz, I., Arto, I. et al. (2021). The potential land requirements and related land use change emissions of solar energy. Sci Rep 11, 2907. https://doi.org/10.1038/s41598-021-82042-5

Velasco-Herrejón, P., Bauwens, T. and Calisto Friant, M. (2022). Challenging dominant sustainability worldviews on the energy transition: Lessons from Indigenous communities in Mexico and a plea for pluriversal technologies. World Development 150, 105725. https://doi.org/10.1016/j.worlddev.2021.105725

Victoria Transport Policy Institute (VTPI). Online Transportation Demand Management (TDM) Encyclopaedia. https://www.vtpi.org/tdm/

Wang, Z., Wang, G., Ren, T., Wang, H., Xu, Q. and Zhang, G. (2021). Assessment of soil fertility degradation affected by mining disturbance and land use in a coalfield via machine learning. Ecological Indicators 125, 107608. https://doi.org/10.1016/j.ecolind.2021.107608

Wiedenhofer, D., Lenzen, M. and Steinberger, J.K. (2013). Energy requirements of consumption: Urban form, climatic and socio-economic factors, rebounds and their policy implications. Energy Policy 63, 696-707. https://doi.org/10.1016/j.enpol.2013.07.035

World Bank (2021). Mongolia's Proposed Sovereign Wealth Fund in the Broader Fiscal Framework. World Bank. http://hdl.handle.net/10986/37659

World Economic Forum (2023a). Fostering Effective Energy Transition. https://www3.weforum.org/docs/WEF_Fostering_Effective_Energy_Transition_2023.pdf

World Economic Forum (2023b). Annual Report 2022-2023. https://www.weforum.org/publications/annual-report-2022-2023/

World Economic Forum (2024). Annual Report 2023-2024. https://www3.weforum.org/docs/WEF_Annual_Report_2023_2024.pdf

World Resources Institute (2021). 4 Ways to Design Safe Streets for Cyclists. https://www.wri.org/insights/ways-cities-design-safer-roads-cyclists

World Resources Institute (2023). State of Climate Action 2023. https://www.wri.org/research/state-climate-action-2023

Xia, A., Cheng, J. and Murphy, J.D. (2016). Innovation in biological production and upgrading of methane and hydrogen for use as gaseous transport biofuel. Biotechnical Advances 34(5), 451-472. https://doi.org/10.1016/j.biotechadv.2015.12.009

Yusaf, T., Faisal Mahamude, A. S., Kadirgama, K., Ramasamy, D., Farhana, K. et al. (2024). Sustainable hydrogen energy in aviation – A narrative review. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2023.02.086

Zainudin, N., Siwar, C., Ah Choy, E., Chamhuri, N., (2014). Evaluating the Role of Energy Efficiency Label on Consumers' Purchasing Behaviour. APCBEE Procedia 10, 326-330. https://doi.org/10.1016/j.apcbee.2014.10.061

Zhai, W., Jiang, Z., Meng, X., Zhang, X., Zhao, M. and Long, Y. (2022). Satellite monitoring of shrinking cities on the globe and containment solutions. iScience 25(6), 104411. https://doi.org/10.1016/j.isci.2022.104411

Zhang, Y., Bai, X., Mills, F.P. and Pezzey, J.C.V. (2018). Rethinking the role of occupant behavior in building energy performance: A review. Energy and Buildings 172, 279–294. https://doi.org/10.1016/j.enbuild.2018.05.017

Zhang, H., Yang, D. Tam, V.W.Y., Tao, Y., Zhang, G., Setunge, S. and Shi, L. (2021). A critical review of combined natural ventilation techniques in sustainable buildings. Renewable and Sustainable Energy Reviews 141, 110795. https://doi.org/10.1016/j.rser.2021.110795

Zhang, J., Wei, R. and Guo, Q. (2023). Impacts of mining activities on the spatial distribution and source apportionment of soil organic matter in a karst farmland. Science of The Total Environment 882, 163627. https://doi.org/10.1016/j.scitotenv.2023.163627

Zheng, X., Lu, Y., Ma, C., Yuan, J., Stenseth, N.C., Hessen, D.O. et al. (2023). Greenhouse gas emissions from extractive industries in a globalized era. Journal of Environmental Management 343, 118172. https://doi.org/10.1016/j.jenvman.2023.118172

Zierler, R., Wehrmeyer, W. and Murphy, R. (2017). The energy efficiency behaviour of individuals in large organizations: A case study of a major UK infrastructure operator. Energy Policy 104, 38-49. https://doi.org/10.1016/j.enpol.2017.01.033

Zivarts, A. (2021). The '15-Minute City' Isn't Made for Disabled Bodies. Bloomberg News. https://www.bloomberg.com/news/articles/2021-04-22/the-people-that-the-15-minute-city-leave-behind Accessed 21 May 2025

17 Food Systems Transformation Pathways

Coordinating Lead Authors: Peter Alexander (University of Edinburgh), Alice Odingo (University of Nairobi), Tek Sapkota (International Maize and Wheat Improvement Center (CIMMYT))

Lead Authors: Jessica Fanzo (Columbia University), Juliana Merçon (Universidad Veracruzana)

Contributing Author: Jessica Fuller (GRID-Arendal), Michele Fontefrancesco (Università Cattolica del Sacro Cuore), Lucia Reisch (University of Cambridge)

Fellows: Katie Noble (University of York)

Credit: thananit_s/Envato

Chapter summary

Credit: Ancapital/Envato

The current food system is environmentally and socially unsustainable. (*very well established*). Current food production and consumption are major drivers of climate change, biodiversity loss, land degradation, and pollution while, billions of people still lack access to sufficient nutritious food {17.1}.

An environmentally and socially sustainable food system can only be achieved through a transformation of the way foods are produced, consumed and traded (*well established*). Key goals for this transformation include close to zero loss of areas of high biodiversity importance by 2030 and a tenfold reduction in the species extinction rate by 2050, land degradation-neutrality by 2030, and elimination of unsustainable use of surface and ground water abstraction for agriculture and a reduction in nutrient leaching. They also cover halved greenhouse gas (GHG) emissions from food systems by 2050; sufficient space available for large-scale adoption of land-based renewable energy and other climate mitigation measures; and healthy, safe, affordable, accessible, and diverse food for all, with hunger ended by 2030, the rise in obesity and diet-related non-communicable diseases halted, and micronutrient deficiencies eradicated. Finally, the goals address fair treatment of workers throughout the food system, inclusion of Indigenous Peoples as well as local communities in decision-making, and resilience to shocks and stresses.

Five solution pathways have been identified to achieve the goals of the sustainable food system. Achieving each goal requires a combination of pathways with different approaches creating different trade-offs and synergies. All pathways require actions from a wide range of actors, including policymakers and regulators, non-governmental organizations, the food industry, the financial sector, farmers, researchers, communities, and individuals. The five pathways are shifting to healthy and sustainable consumption; improving crop, livestock and aquatic food production and land-use systems; reducing food loss and waste and making the food system more circular;

increasing the production and consumption of healthy and sustainable novel foods; and reforming and improving regulation of the food industry, market structure and trade {17.2}.

Achieving the internationally agreed environmental goals cannot be accomplished without changing how animal-sourced foods (ASF) are produced and consumed (*well established*). While in some setting ASF products have human nutrition and livelihood benefits, their production is a major contributor to environmental degradation. Production of ASF contributes about 60 per cent of all food-related GHG emissions, and about 14-20 per cent of all anthropogenic GHG emissions. High consumption of red and processed meat is linked to an increased risk of non-communicable diseases, such as cancer. At the same time, intensive livestock production poses risks of zoonotic diseases, infectious animal diseases, and antimicrobial resistance. Tens of billions of animals are raised and slaughtered annually, primarily in intensive farming systems {17.1; 17.2.1}.

Livestock's environmental footprint can be reduced by lowering overall demand for ASF and improving production practices (*well established*). Key strategies include improving the efficiency of livestock production practices, adopting regenerative practices including lower-intensity livestock production practices, improving animal feed to reduce GHG emissions, reducing food loss and waste, reforming subsidies and taxes, and encouraging dietary shifts towards more plant-based diets and alternative proteins. The scale and pace of change are currently too slow to meet environmental goals {17.2.1; 17.2.2}.

A shift toward healthy and sustainable diets is essential for addressing both environmental and public health challenges (*very well established*). This transition will require substantial reductions in overall ASF consumption, particularly in industrialized affluent countries, with potential for limited expansion in low-income communities affected by undernutrition. Diets should include fewer processed and ultra-processed foods and a diverse range of fresh and minimally processed foods, such as fruits, vegetables, legumes, nuts, and pulses, as well as reducing rates of over-consumption and consumer food waste. Without these changes, the environmental benefits of efficient food production technologies will be limited and negative health outcomes, such as obesity, could be exacerbated. The externalities from the global food system are estimated to be around US$20 trillion, comprising US$7 trillion in environmental costs and US$11 trillion in human health costs, which is approximately double the US$9 trillion spent on the food consumed {17.2.1; 17.4}.

Novel alternative proteins, including novel plant-based foods, cultivated meat, and fermentation-derived products, could replace conventional ASF, reducing GHG emissions, lowering land and water use and loss of biodiversity, but more research and investment is needed (*established but incomplete*). These alternative options could also reduce the risk of zoonotic disease emergence and spread, antimicrobial resistance, and animal welfare concerns. Uncertainty remains around the contribution, and possible negative effect, that these novel foods could provide and when, with acceptance and adoption at scale unlikely before 2030. Realizing the potential of alternative proteins to meet both health and sustainability goals requires greater public and private investment, along with a coordinated international research effort and regulatory adjustments. Research focus is needed to enhance the taste and texture, reduce costs, and assess the nutritional and social effects to increase consumer acceptance {17.2.4}.

Crop, livestock, and aquatic food production practices need to become more efficient, resilient, and sustainable (*very well established*). Promising approaches include developing high-yielding crop varieties and animal breeds with greater adaptability to local production conditions and tolerance to pests, diseases, and climate stressors – such as heat, drought, flooding and salinity – as well as improved resource use efficiency. These advancements need to be combined with environmentally sustainable intensification practices. Crucially, aligning both genetic innovations and management systems with local agroecological and production conditions is essential to ensure long-term resilience and productivity.

Adoption of nature-based solutions – such as regenerative practices, conservation agriculture, agroecological approaches including agroforestry, and organic agriculture – can provide benefits. Achieving biodiversity goals will require a combination of multifunctional land use, land conservation and sustainable intensification in agricultural areas, with Indigenous Knowledge and Local Knowledge playing a vital role {17.2.2}.

Credit: bilanol/Envato

Capture fisheries and aquaculture production provide a valuable source of nutrition but cause environmental damage without sustainable management measures (*well established*). Overfishing, species decline, and ecosystem disruption result from unsustainable fishing practices. At the same time, aquaculture generates additional pressure by using wild-caught fish for feed, as well as chemical and waste pollution. Effective regulation, enforcement, and improved practices should be supported by shifts in societal perceptions and market incentives for environmentally sustainable fisheries and aquaculture {17.1; 17.2.2}.

Dietary shifts must be supported by policy, as voluntary actions by the food industry and consumers are insufficient (*established but incomplete*). Voluntary changes, including shifts in consumer preferences, social norms and food environments, and food industry changes on how foods are formulated, marketed and the information provided to consumers, would support a shift to sustainable healthy diets. However, to achieve a sufficient dietary change to meet environmental goals supporting policies are required, including policies that ensure food prices more fully reflect the environmental and health outcome costs and greater regulation of food industry practices. Changes to production subsidies – US$1 trillion is currently provided globally in agricultural and US$35 billion in fisheries subsides – and imposition of consumer taxes and subsidies, can ensure food prices better reflect their true costs to society and encourage more healthy and sustainable consumption {17.2.1}.

Achieving a sustainable global food system requires moving away from pursuing the lowest-cost foods, which are often nutritionally poor and unsustainably produced (*established but incomplete*). There is an implicit assumption that lower food prices and increased supply benefit society by improving access to food for the poorest. Over the past 60 years, food production grew faster than the global population, resulting in 34 per cent more cereals produced per person in 2022 than in 1961, and food prices have declined in real terms. Yet, 700-800 million people remain undernourished and there are increasingly high rates of obesity in most countries, highlighting that delivering cheap food does not ensure equitable or healthy nutrition {17.2.1; 17.3}.

Making healthy and environmentally sustainable food affordable requires dealing with poverty (*established but incomplete*). Strengthening welfare and social safety nets is needed, particularly supporting groups that may be adversely affected by reforms, such as the true cost of food pricing. In combination such measures could reduce poverty and inequality {17.3}.

Reducing food losses, including food waste, across the food system would enhance food security and reduce environmental damage (*very well established*). Food waste occurring during retail and food service and at a household level accounts for a 19 per cent loss of available food, with additional loss during production or harvest, transport, storage, and processing. The current 30-40 per cent food system losses, worth US$1 trillion, can be reduced through combinations of behavioural and technical approaches at the farm, supply chain, retail and household levels. Where losses cannot be avoided, adopting circular approaches, including nutrient recycling of waste and by-product streams, can help minimize environmental impacts {17.2.3}.

Reforming the global food industry market and trade is needed, including diversifying agribusiness and food supply chains, and aligning private sector incentives with the societal outcomes (*established but incomplete*). Coordinated multinational policymaking is needed to regulate transnational corporations operating in the global food system. An enhanced role for local and regional food systems can enhance environmental and societal benefits {17.2.5}.

The food and financial sectors are central to funding the proposed food system transformation (*well established*). Access to financial capital is key for investment in alternative technologies, infrastructure, practices, and business models. Increased actions are required from the food industry to change practices, e.g., responsible sourcing, marketing, choice editing, portion sizes, labelling and reformulation to encourage healthier and more sustainable consumer behaviours {17.2.1; 17.2.2; 17.2.3}.

Shifting societal norms and consumer behaviour can be supported by community engagement and grassroots movements, including with Indigenous Peoples, along with education and awareness-raising targeted at changing preferences and values (*established but incomplete*). Public procurement of food can serve as a powerful tool to influence social norms and habits, promoting mindful, health-conscious and environmentally caring consumption {17.2.1; 17.2.2; 17.2.3}.

Expanding research and development and sharing of diverse forms of knowledge and data is necessary (*established but incomplete*). This includes advancing genetic research in crop, livestock, and aquatic systems, as well as strengthening the focus on Indigenous and local food systems, including locally adapted orphan and opportunity crops. Adopting locally adapted crop, livestock, and aquatic species helps in coping with environmental stresses while providing culturally appropriate food. Research and development of sustainable food systems, including novel technologies, data sharing, collaborative networks and partnerships, is necessary to accelerate innovation {17.2.2; 17.2.3; 17.2.4}.

Building skills and capacity across food systems is needed (*established but incomplete*). Public awareness and education on food, health, and environmental issues, as well as training and support for farmers, as well as veterinary and agricultural extension services, would support the required transformation. Retraining of displaced workers will also be needed with substantial shift away from livestock sector towards plant based foods or novel alternative proteins {17.2.2}.

Governance, policies and regulations set the conditions in which food systems operate, making policymakers and regulators critical to achieving the desired transformation (*very well established*). Key actions include reforming food and agricultural subsidies and taxation, removing perverse incentives and adjusting food prices to better reflect environmental and health externalities. They also should strengthen regulation of the food sector, including marketing (and especially marketing that targets children), choice editing, portion size and labelling; address market structure, including to control or breakup market power; and strengthen international regulatory coordination on transnational agri-food businesses and global food trade {17.2.1; 17.2.2; 17.2.3; 17.2.4; 17.2.5; 17.3}.

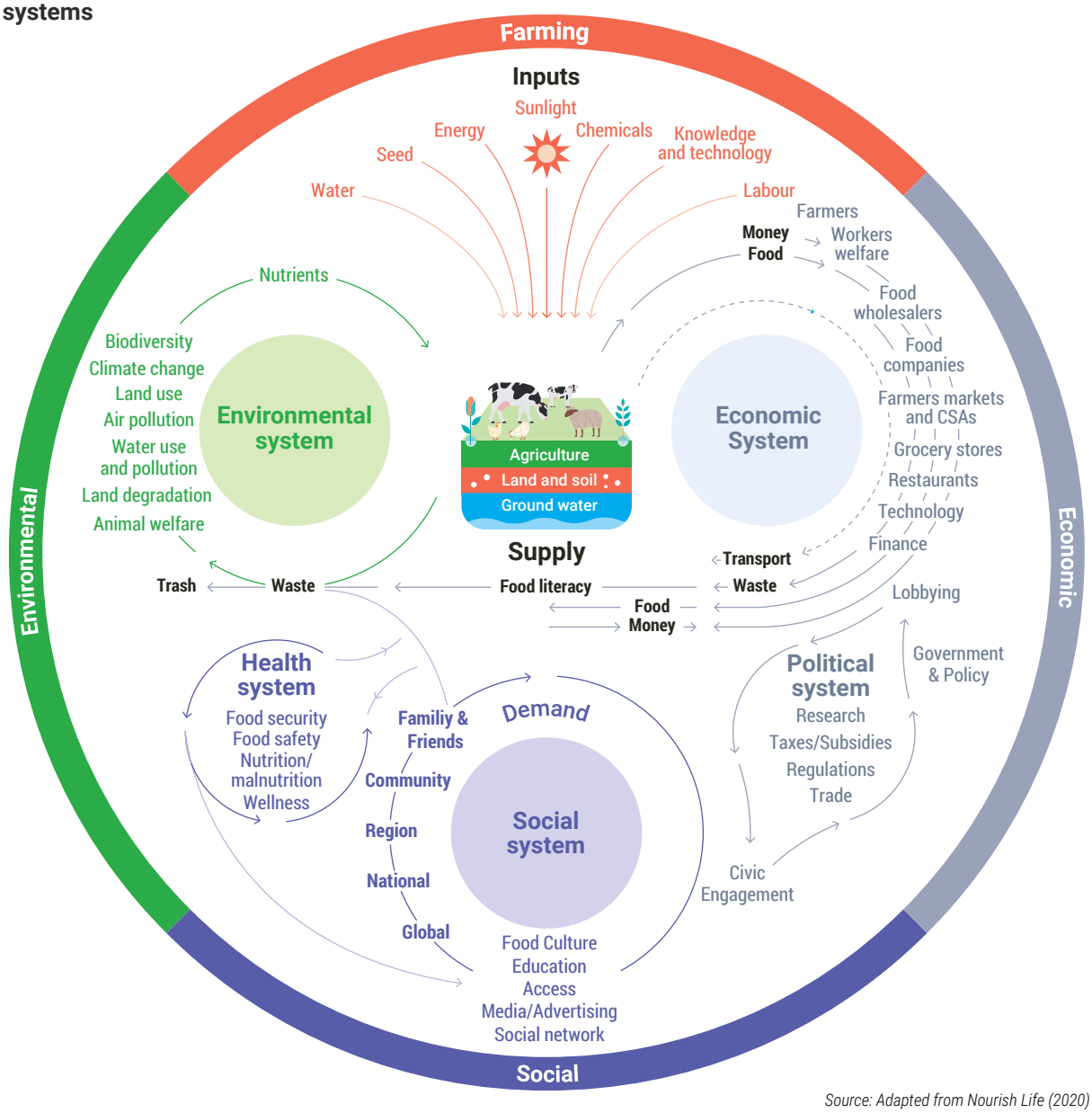
Connectivity among economic/finance, materials/waste, energy, environment and food systems means a successful transformation of all these systems can only be addressed together (*well established*). Changes to the economic system, including subsidy reform and pricing externalities, are central to achieving the food system transformation. Coordinated actions across systems is required due to competition for land with demands beyond food from renewable energy production, climate mitigation, biodiversity conservation and ecosystem functioning {17.4}.

17.1 Introduction

This chapter explores solution pathways for building a transformative food system, from food production to consumption, and back again, capturing the full cycle from "farm to fork". It examines necessary transformations – for crops, livestock, and fisheries – alongside dietary changes, including plant-based foods and novel alternative proteins. The chapter also highlights the key roles of governance, education, circular economic approaches, food distribution and marketing, all withing the context of adapting to environmental and social change.

The food system encompasses all the actors and activities related to the production, processing, distribution, trade, retail, preparation, consumption, and end of life management of foods and drinks, as well as the outcomes of these activities, including socioeconomic and environmental (High Level Panel of Experts [HLPE] 2017, p. 23) (**Figure 17.1**). Together, the activities undertaken by various actors across the food system give rise to the availability, access, affordability, utilization and stability of food with outcomes for food security (United Nations Environment Programme [UNEP] 2016). However, the current global food system fails to provide food security for all or end malnourishment in all forms, while creating substantial negative ecological and societal impacts that affect the achievement of many sustainable development goals (Willet et al. 2019).

Figure 17.1: Food System Map showing interactions between food consumption and supply, governed by the interactions of the social, political, economic and financial, and environmental systems



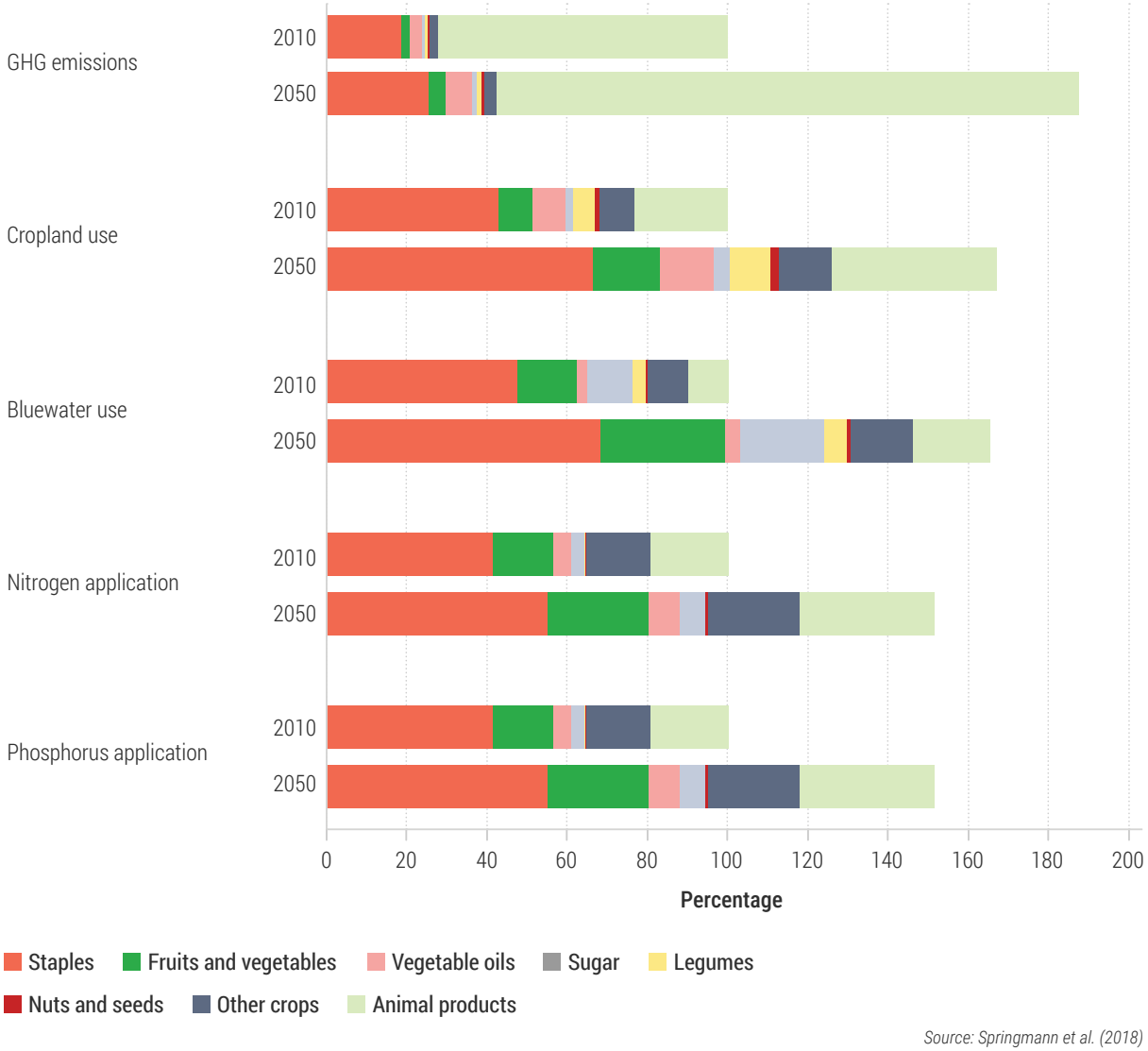
Source: Adapted from Nourish Life (2020)

The first quarter of the century has been characterized by lower food security, with four global food crises (2007-2008, 2011, 2020, 2022), albeit of varying intensity, reversing the long-term trend of hunger reduction (Webb et al. 2018).

The UN adopted the Sustainable Development Goals in September 2015, including SDG2: End hunger for all (Chapter 7). So far, there are few signs of meeting this goal, with 347 million adults globally underweight in 2022 (Phelps et al. 2024). In 2023, between 713 and 757 million people experienced hunger, approximately 152 million more than in 2019 (Food and Agriculture Organization [FAO], International Fund for Agricultural Development [IFAD], UNICEF, World Food Programme [WFP], World Health Organization [WHO] 2024), and 282 million people with acute food insecurity due to a combination of conflict, weather extremes and economic shocks (Global Network Against Food Crises 2024). The number of chronically undernourished people is projected to reach 582 million by 2030, with consequences including childhood stunting and wasting (FAO 2024). Additionally, 2 billion people worldwide suffer from micronutrient deficiencies – such as vitamin A, iron, iodine, and zinc – leading to various health problems.

All countries face at least one form of malnutrition. While undernutrition and hunger are most prevalent in low-income countries, particularly in South Asia and Sub-Saharan Africa, obesity and diet-related non-communicable diseases are rising globally (Popkin and Ng 2022). In 2022, 878 million adults were obese (Phelps et al. 2024). Diet-related non-communicable

Figure 17.2: Current (2010) and projected (2050) environmental pressures on five environmental domains by food group



Source: Springmann et al. (2018)

diseases, including cardiovascular heart disease, cancer and stroke, are increasing in nearly every country, with low- and middle-income countries experiencing rapid rises (Phelps et al. 2024). While many countries are still experiencing double burdens, this increase is largely driven by the rise in obesity. In 2017, malnutrition in different forms caused 11 million deaths and 255 million Disability Adjusted Life Years (Afshin et al. 2019).

While population pressure, environmental degradation, biodiversity loss and climate change directly affect food production and food systems, the way we manage our food systems also affects climate, environment, biodiversity and ecosystem functioning. Addressing these interconnected challenges and creating more sustainable and equitable food systems requires a fundamental transformation to the way food is produced, processed, distributed and consumed (Intergovernmental Panel on Climate Change [IPCC] 2022a; Rosenzweig et al. 2020).

Each environmental pressure is indexed to a score of 100 in 2010. Animal product impacts include feed requirements, and the 2050 projections are based on a business-as-usual socioeconomic development pathway (SSP2). Source: Springmann et al. (2018).

Livestock and aquaculture production contribute to a range of environmental problems, including habitat destruction, deforestation, land-use change, greenhouse gas (GHG) emissions, pollution, marine ecosystem degradation, zoonotic, animal and foodborne diseases and antimicrobial resistance (**Figure 17.2**) (see 8.2.2; 8.3.3) (Zhang 2024; UNEP 2020). The production of animal source food (ASF) accounts for 57 per cent of food production emissions (Xu 2021) and 38.5 per cent of global deforestation (FAO 2022). Around 70-80 billion terrestrial animals and 110 billion fish are raised and slaughtered annually, mostly in intensive systems (Ritchie 2024). ASFs provide an important source of energy and essential nutrients, such as protein, fatty acids, and some vitamins and minerals, especially in areas with low potential for crop production (Beal et al. 2023) and are important for meeting nutritional needs. They therefore provide important component of livelihoods in many subsistence agricultural communities, and hold cultural significance, including to Indigenous communities. However, the scale of the environmental harm associated with ASF production systems means that reducing their impact is essential to achieving sustainability goals (Chapters 10 & 11).

Globalization of food production, distribution, and consumption has resulted in an interconnected and interdependent network of countries and institutions (Greenville et al. 2019; Davis et al. 2021). Between 2005 and 2022, global agricultural trade has nearly tripled in value, rising to $US1.9 trillion (FAO 2022), with emerging market and developing country exports already accounting for more than a third of the global total (FAO 2022). Farmers receive less than 27 per cent of consumer food expenditure (Yi et al. 2021), and food production has become increasingly concentrated. 80-90 per cent of the world's daily calorie and protein needs are currently covered by 12-20 species, and 50 per cent of our diet comes from three crops: wheat, maize and rice (Akinola et al. 2020). In contrast, local and traditional food crops encompass 7000 species, with diverse nutritional and cultural uses (Balinga 2005; Zuza et al. 2024).

Environmental and health outcomes for which there are no markets, i.e., that are economic externalities, including, undernutrition and obesity, GHG emissions, and biodiversity loss, are pervasive in the food system (Faccioli et al. 2022). These unaccounted costs are estimated to be US$15-20 trillion annually, roughly double the US$9 trillion cost of food consumed globally (Hendriks et al. 2023; Ruggeri et al. 2024). These include externality costs comprise $US7 trillion (with a range of 3-11), health-related costs of $US11 trillion (with a range of 3-39), and socio-economic costs of $US1 trillion (with a range of 0.2–1.7) (Hendriks et al. 2023; Ruggeri et al. 2024).

Building on the Sustainable Development Goals (SDGs) and other internationally agreed-upon objectives, **Table 17.1** presents a set of overall goals for environmentally sustainable, socially just, and nutritionally healthy food systems.

If current trends in food production, trade and consumption across the food system continue, outcomes for the environment and society will deteriorate further. Under the modelled reference scenario, which assumes the continuation of current trends (10.3), total food demands and production are projected to increase by 35 per cent globally between 2020 and 2050. This growth is driven by

Table 17.1: Overall goals of the food system transformation

Area	Issue	Goal
Sustainable terrestrial and aquatic ecosystems	Biodiversity loss	Halt biodiversity loss and maintain ecosystem functions in terrestrial and marine ecosystems. Close to zero loss of areas of high biodiversity importance by 2030, and the extinction rate and risk of all species are reduced tenfold by 2050 (Convention on Biological Diversity [CBD] 2022).
	Land degradation and soil health	Maintain existing and restore degraded soil health, including by increasing soil organic carbon and microbial diversity, and reduce soil erosion. Achieve land degradation-neutrality by 2030 (SDG target 15.3). Restore 30 per cent of degraded land by 2030 (United Nations Convention on Combatting Desertification [UNCCD] and CBD 2023). Increase soil carbon by 12 per cent by 2050 (FAO 2023).
	Water pollution and unsustainable use	Increase water-use-efficiency by reducing unsustainable water use by 25 per cent by 2050 (Rosegrant et al. 2009), assuming 15-35 per cent of unsustainable water withdrawal can be eliminated by improving water-use-efficiency. Reduce nitrogen pollution from agriculture and food systems by 30 per cent by 2050, assuming an increase in nitrogen use efficiency to above 50 per cent by 2050 in areas where current efficiency remains below 50 per cent (Snapp et al. 2023).
	Air pollution	Reduce food systems related air pollution including $PM_{2.5}$ and ammonia by 30 per cent by 2050 (Montes, Sapkota and Singh 2022; Leon et al. 2022; Ahmed et al. 2024), assuming 30 per cent increase in nitrogen use efficiency and reduction in crop residue burning.
Climate change mitigation	GHG emissions from food system	Achieve a carbon neutral food system by 2040 and become a net-carbon sink by 2050 (FAO 2023). Cut food system methane emissions by 30 per cent by 2030 and halve by 2040, compared to 2020 (Global Methane Pledge 2021; FAO 2023). Halve food systems N2O emissions by 2040 compared to 2020 (FAO 2023; UNEP 2024 and FAO). Achieve food system net climate neutrality by 2050.
	Space for land-based climate mitigation measures, including bioenergy, reforestation, and afforestation	Allow land area for large-scale renewable energy adoption, such as bioenergy and solar energy, as well as other land-based climate mitigation measures, including, reforestation and afforestation, with area requirements defined by associated chapters. No expansion of agricultural land.
Human health and wellbeing	Undernutrition	Provide availability and access to sufficient, healthy, safe, and affordable food for all to end hunger by 2030 and reduce childhood stunting by 40 per cent and halve the 2018 rate of stunting in children of under 5 years by 2030 (Global Nutrition Report 2022).
	Overweigh and obesity	Halt the rise in obesity, diabetes and associated diet-related non-communicable diseases by 2030 (WHO NCD Target 7). This includes a 30 per cent reduction in mean population sodium intake (Target 4) and a 25 per cent relative reduction in the prevalence of raised blood pressure (Target 6), as well as ensuring there is no increase in childhood obesity by 2025.
	Micronutrient deficiencies	End all forms of malnutrition including micronutrient deficiencies by 2030. This includes achieving the World Health Assembly target of a 50 per cent reduction of anaemia among women of reproductive age by 2025.
	One health, including zoonotic diseases and anti-microbial resistance	By 2030, reduce deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination (SDG 3, Target 3.9). End epidemics of tuberculosis, malaria and neglected tropical diseases and combat hepatitis, water-borne diseases and other communicable diseases (SDG 3, Target 3.3). Promote One Health by balancing human, animal and environmental health, including at least 30-50 per cent reduction of antimicrobial use in the agri-food system by 2030.

population expansion and rising per capita food consumption, including higher consumption rates of animal-sourced foods, particularly in Africa. Consequently, in this scenario global cropland area is projected to expand by 8 per cent, accompanied by more intensive agricultural production practices. For example, nitrogen fertilizer use is projected to increase by 49 per cent, and water abstraction for irrigation by 10 per cent from 2020 to 2050. These changes are projected to boost yields by 28 per cent, but at the cost of further biodiversity loss and GHG emissions. Avoiding the adverse

Table 17.1: Overall goals of the food system transformation (cont.)

Area	Issue	Goal
Equitable livelihood	Fair treatment of workers throughout the food system	Eliminate exploitation and unfair practices in the food industry by 2030. Ensure all farmers and workers receive fair income, safe working conditions, protection of rights and access to social protection measures.
	Social justice	Achieve gender equality in access and ownership of land and other productive resources for agriculture. Ensure gender equality in education, training, capability building and technology transfer. End sociocultural and economic discrimination, including against women and girls, along food system value chain by 2030. Achieve personal security, including, ending gender-based violence, and access to gender responsive workspaces by 2030.
	Inclusion of Indigenous rights and knowledge as well as local knowledge in decision-making	Recognize, integrate and protect Indigenous rights as well as Indigenous Knowledge and Local Knowledge in decision-making processes, policy development, and research. Promote fair sharing and use of genetic resources and diverse knowledge among stakeholders and Indigenous communities.
	Diversity food cultures	Support the significance of food within diverse cultural and religious settings.
Resilience to shocks and stress	Adaptation of the food system to climate change	Adopt climate-smart agricultural practices to adapt to climate change and extreme weather events.
	Resilient to range of shocks and stresses	Build resilient food systems capable of withstanding and recovering from shocks and stresses, while providing sustainable and equitable access to nutritious food.

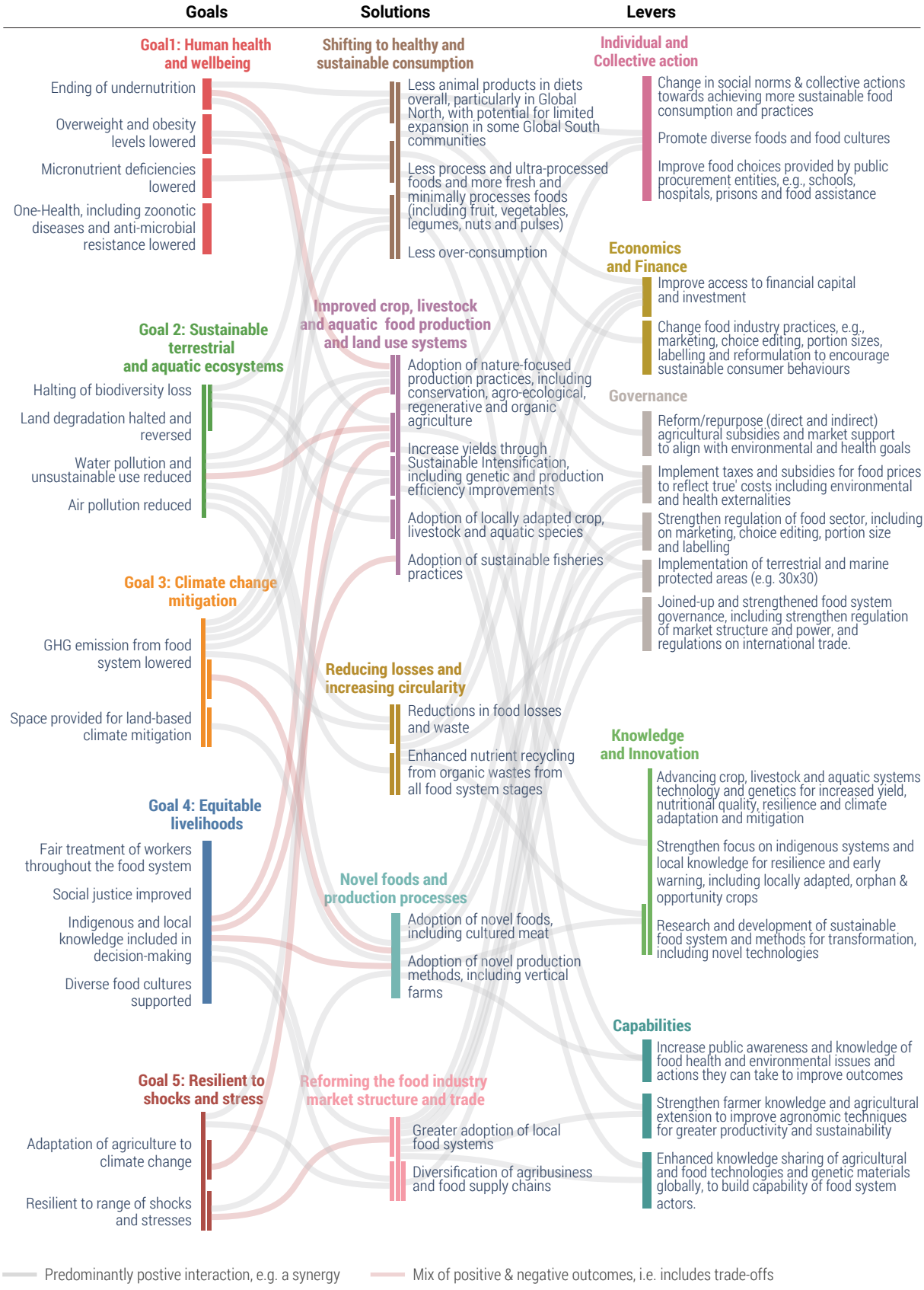
outcomes and achieving the sustainability goals requires a transformation of the food system.

This transformation must minimize the impact on biodiversity, the environment and the climate while delivering nourishment for all and equitable livelihoods. It requires fundamental changes in the behaviour of all the actors across the food system (Chapter 12), isolated changes or silver-bullet technical innovations will not be sufficient. Key elements of food systems transformation include sustainable intensification of the production system to ensure the long-term productivity, while maintaining environmental functions (Cassman and Grassini 2020); transitioning to more sustainable and healthy diets (Fanzo et al. 2021); minimizing food loss and waste (Galford et al. 2020; Read et al. 2020); and promoting local food systems and circular economy approaches (Hamam et al. 2021). These shifts can be achieved through a combination of appropriate technology and innovation, finance and business opportunity, awareness and education, and collaboration and partnership, all facilitated and incentivised by appropriate policies and regulatory frameworks.

The methodology from Chapter 13 and governance principles from Chapter 12 have been applied to identify the food system goals, the solutions to achieve them, and the underpinning actions required to establish these solutions (**Figure 17.3**). Achieving these goals (**Table 17.1**) requires multiple system changes in the form of multiple solutions (Alexander et al. 2019; Springmann et al. 2018), with each solution involving actions from a range of actors. While solution pathways improve outcomes for one or more desired goals, they may also create trade-offs with unintended or undesirable outcomes, hindering progress towards other goals. Complementary and integrated actions are needed to mitigate trade-offs and leverage synergies to achieve all goals, as is also highlighted in Chapter 11.

The remainder of this chapter outlines five solution pathways for food system transformation to meet the desired goals (17.2). For each solution pathway, a set of actions is identified for actors to take to enable the transformation, along with the associated benefits and trade-offs. Also discussed are the necessary conditions for implementation, including barriers and how they can be overcome. Section 17.3 examines how solutions can be combined to achieve the goals collectively. Section 17.4 discusses cross-system implications and places the solutions within the broader context.

Figure 17.3: Interactions between overall goals, solutions and levers in the food system, showing both synergies and trade-offs



Note: For Goals, Solution Pathways and Levers, the interactions are shown to or from an individual item, e.g., "end undernutrition". Interactions between goals are not shown. Interactions identified as high or medium in strength are shown; therefore, all possible interactions are not depicted. Only intended and positive interactions are shown between actions and solution pathways. The authors identified these interactions based on the chapter synthesis and cited literature; a fuller methodology is provided in Chapter 13.

Figure 17.4: Food System Transformation

Reduce food losses, waste, and increase circularity

Objective: Minimize waste and maximize resource efficiency throughout the food system.

Supply chain improvements: Optimize processes to reduce food spoilage from production to consumption.

Consumer education: Raise awareness of waste reduction practices and the importance of circularity.

Nutrient recycling: Enhance recycling of nutrients and by-products within the food system.

Sustainable packaging: Develop biodegradable and protective packaging to extend food shelf life.

Inclusivity in solutions: Engage diverse actors to ensure that circular approaches are widely adopted.

Develop and integrate novel foods and production processes

Objective: Support alternatives to conventional animal based foods to reduce environmental footprints.

Regulatory adaptation: Adjust regulations to enable safe, widespread use of novel foods.

Research and development: Invest in alternative proteins, such as plant-based, cultivated, and fermentation-derived products.

Sustainable production methods: Use renewable energy and advanced tech to lower the environmental impact of novel food production.

Public-private partnerships: Foster collaboration between governments and businesses to support innovation.

Market acceptance: Work on enhancing taste, texture, and affordability to encourage consumer adoption.

Restructure food industry market and trade

Objective: Create a fair and resilient food system that aligns market practices with environmental and social goals.

Subsidy reform: Redirect agricultural subsidies to promote sustainable practices over harmful ones.

Transparency and accountability: Increase industry accountability for environmental and social impacts through stricter regulations.

Local food systems: Support shorter supply chains and local markets to reduce environmental costs.

Enhanced governance: Strengthen regulatory frameworks to align food industry practices with sustainability targets.

Supply chain diversity: Encourage small-scale producers to participate in the market for more resilient and diverse supply chains.

17.2 Solution pathways for food system transformation

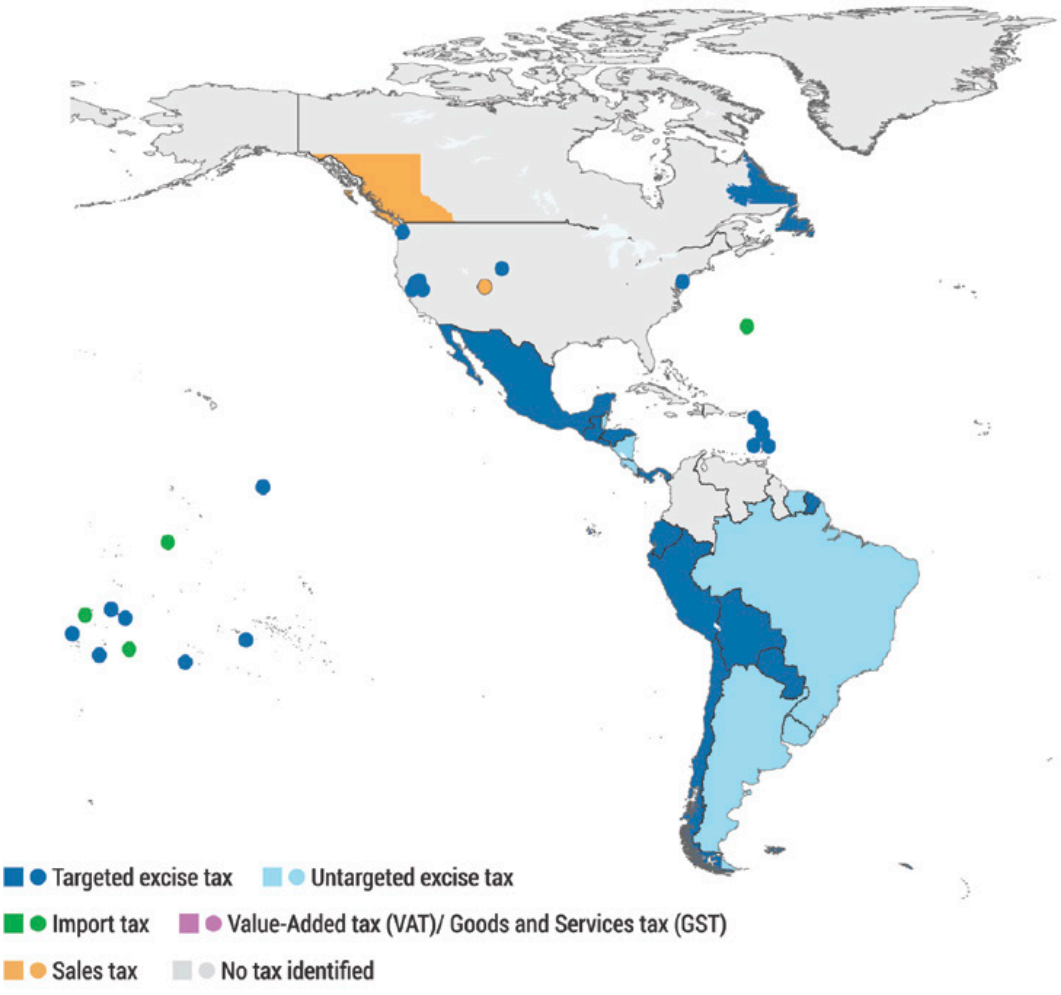
This section describes the five solution pathways (**Figure 17.4**), each accompanied by a set of actions that food system actors can take to advance one or more of the goals. A combination of solution pathways is essential to achieve the required transformation; no solution is sufficient alone to achieve the goals (17.3).

17.2.1 Solution pathway 1: Shifting to environmentally sustainable and healthy diets

Changing diets is a powerful driver for transforming the food system (Vermeulen et al. 2020). Reducing overall consumption of red meat, particularly in high beef-consuming countries, consumption in excess of nutrition requirements and consumption of highly processed foods, as well as reducing food waste at the household and retail levels, can deliver major environmental sustainability and human health benefits (Willett et al. 2019). Reducing food losses and waste and increasing circularity in the food system more broadly is dealt with in Solution Pathway 3 (17.2.3), while this pathway's focus is with consumers' behaviours and diet.

More sustainable consumption is associated with healthier diets (Springmann et al. 2020). Achieving these outcomes requires improving physical, economic and social access to nutritious and minimally processed foods (Schneider et al. 2023), while reducing consumption of unhealthy, highly processed foods (Phelps et al. 2024). The change in diet includes increased intake of whole grains, vegetables, fruits, legumes and pulses, nuts, healthy oils, low-carbon animal-sourced foods and seafood, and, where appropriate and sustainable, novel protein alternatives (Willett et al.2019). Considering food waste as part of consumer behaviours, minimizing food waste at the household and retail levels, is also essential (17.2.3).

Figure 17.5: Current sugar-sweetened beverage (SSB) taxes implemented around the world



While the evidence on the role of dietary changes for improving food systems outcomes is abundant, changing individual food patterns is complex, challenging and requires a range of tools and incentives that respect personal autonomy, culture, social norms, and traditions (Reisch et al. 2017). Nevertheless, various policy innovations and solutions are available to guide, support and encourage healthier and more sustainable dietary choices in all populations (Hawkes et al. 2020).

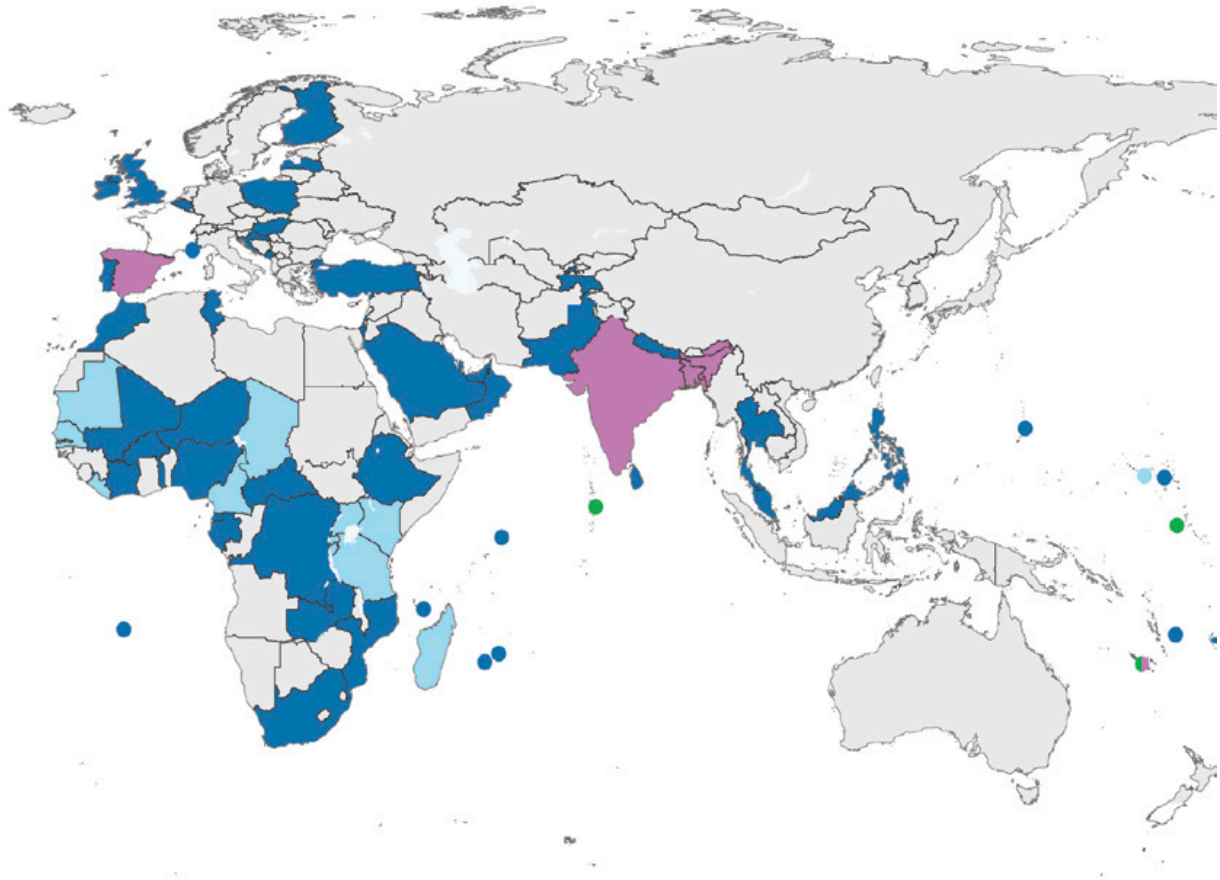
Influencing behaviours towards healthier and sustainable diet access and choices cut across five lever categories (12.5), as described below.

17.2.1.1 Taxes and subsidies for food prices to reflect true costs, including environmental and health externalities

Consumer food prices that better reflect the true cost of food – including health, environment and social consequences that are unaccounted for in current food prices – would be a strong signal to consumers and be an important step for changing consumption behaviours and advancing food system transformation (Faccioli et al. 2022; Latka et al. 2023; Hendriks et al. 2023). These impacts are typically not accounted for by the market and not reflected in food prices; that is, they are economic externalities (Master and Finaret 2024). If true costs were accounted for, food with high environmental or health burdens, such as red meat, would be more expensive, and food associated with positive health or environmental outcomes, such as legumes, fresh fruit and vegetable, would be less expensive (Funke et al. 2021). Chapter 14 discusses internalizing externalities across the economy (14.3).

While challenging, various methods are being developed to measure, trace, and account for hidden health, environmental, and social costs throughout the food supply chain (Hendricks et al. 2023). Improved accounting

Figure 17.5: Current sugar-sweetened beverage (SSB) taxes implemented around the world (cont.)



can support evidence-based policymaking and help public and private sector actors lower the overall cost of the food system to society.

Government measures could ensure that consumer food prices reflect the true cost of the food (Ruggeri et al. 2024). These policy instruments could include economic measures such as carbon taxes, targeted taxes on high-impact foods like meat, and subsidies for healthier, lower-impact options like fruits and vegetables, or, most likely, a combination of these measures to account for a wide range of externalities.

Many governments have implemented consumer taxes on sugar-sweetened beverages and some ultra-processed foods (Kiesel et al. 2023; Hattersly and Mandeville 2023) (**Figure 17.5**). However, taxation of high-carbon foods, such as ruminant meat, has faced political and social resistance, likely due to vested interests, potentially being regressive, and cultural values.

Reforming or reorienting agricultural subsidies is another government action to better align food prices with environmental and health outcomes (17.2.2). Such reforms, combined with consumer price taxation, could trigger substantive changes to both supply and demand. For example, industrialized nations could redirect subsidies from all forms of industrial-scale animal farming toward plant-based food production (Willett et al. 2019).

However, higher consumer food prices can be regressive, disproportionately affecting poorer populations who spend a greater share of their income on food. Currently, 2.8 billion people cannot afford a healthy diet that meets nutrient requirements and reduces the risk of non-communicable diseases. Such a diet is not affordable for over 75 per cent of the population in sub-Saharan Africa (FAO, IFAD, UNICEF, WHO 2024). Therefore, policies that internalize the externalities of food should be paired with social protection measures to offset potential adverse effects. Funds raised through taxes and saved from subsidy reforms could support those who would otherwise be adversely affected by increasing welfare payments and stronger safety nets, including providing a universal basic income (Beck et al. 2023). The potential impact on those with the lowest incomes should not justify inaction; viable mitigation options for these consequences exist and the urgency for food system transformation is clear.

Changes to a true cost of food pricing would likely substantially affect the livestock industry, due to the associated GHG emissions and biodiversity loss environmental externalities (Ruggeri et al. 2024; FAO 2024). Implementing such a change would require higher net taxation rate for meat and other animal-sourced products (Funke et al. 2021). Some private sector actors oppose such changes as they would increase consumer prices, with the explicit intention of reducing production and consumption of those foods (Sherrington, Carlile and Healy 2023). Greater controls and higher transparency are needed to limit lobbying power to reduce the impacts of vested interests (WHO 2024; 17.2.4.1).

Higher food prices and policies, such as consumer taxation on meat, are seen as publicly unacceptable in many countries (Amaglobeli et al. 2023; Ejelöv et al. 2025). To increase public acceptance and support for true-cost food prices, complementary efforts would be beneficial to shift social norms around food consumption (17.2.1.5), enhance education (17.2.1.4), and reform public procurement (17.2.1.7).

17.2.1.2 Voluntary food industry practices to encourage sustainable consumption

The food industry, including food processors and retailers, holds substantial power to influence consumer behaviours and diet, and can use this to promote sustainable consumption. Industry players influence consumption decisions through various means, such as formulation of foods, advertising and marketing, labelling and choice architecture – small changes to the environments where food choices are made (Bauer et al. 2022). Voluntary changes in industry practices, including marketing and retail food environments, could steer consumer choices towards better environmental and health outcomes. However, a combination of voluntary and regulatory measures is likely needed across various consumer interaction points (Russo et al. 2023).

Marketing and advertising of some food products influence consumer dietary choices and could be used to drive positive change. Examples include advertising in print, television, radio, and social media, engaging with schools such as the sponsoring of events or activities, directing products to children such as including toys or games, and altering product placement in food environments (Smith et al. 2019).

Choice architecture can support the consumption of healthy and sustainable foods (Reisch and Sunstein 2021) by modifying how food is presented and accessed (Lindstrom, Tucker and McVay 2023). This includes placing healthier items at eye level, using them as default on menus, adjusting portion sizes and simplifying preparation and serving (Bucher et al. 2016; Ensaff 2021). The same applies to digital choice architecture, such as the design of food delivery apps (Lohmann et al. 2024). These behavioural interventions, sometimes termed nudging, can be used to influence consumer food choice behaviours and promote positive change (Vecchio and Cavallo 2019).

The food industry has deep expertise in influencing consumer choices, but these efforts are primarily geared to private interests such as maximizing shareholder returns, rather than societal benefits. While voluntary industry actions are possible, it is likely that for sufficiently substantive changes to be made, the incentives for private sector actors need to be aligned to environmental and health outcomes either through policies and regulations (17.2.1.3; 17.2.2.1; 17.2.5) or through commercial benefits arising from a transformation in consumer preferences towards sustainability and health (17.2.1.4; 17.2.1.6).

17.2.1.3 Food sector regulation, including on marketing, choice editing, portion size and labelling

Stronger regulation of the retail food environment and food marketing could be used to align the industry's actions with environmental and public health goals. Rule on how foods can be advertised need to be improved – particularly unhealthy foods marketing directed at children. While information, knowledge, awareness, and guidelines are available across a range of platforms, their reach is overshadowed by pervasive and harmful advertising and cues in the choice architecture by food and beverage companies. The marketing of unhealthy foods has limited controls, particularly on social media platforms (Gerritsen et al. 2021; Kucharczuk et al. 2022; Friedman et al. 2022). Improved regulation in these areas, particularly governing social media and advertising unhealthy foods to young children and teenagers, would be highly beneficial (Hawkes and WHO 2004).

Labelling regulation is another valuable tool for guiding consumer choices. Labelling on the back, and more recently, on the front of food packages is increasingly regulated by state actors and used to alert consumers to unhealthy ingredients or to rate foods on their healthfulness (Shangguan et al. 2019). For example, introducing warning labels about high sugar and salt content in Chile led to a 27 per cent decline in sugar and a 37 per cent decline in salt purchased (Taillie et al. 2021). Regulation and standardization of labelling by governments have incentivized food industry players to reformulate their food products to avoid warning labels or to garner healthier ratings (Fanzo et al. 2023). Another example is the Nutri-Score tool that can inform consumers about healthier choices (Temmerman et al. 2021).

Greater regulation is also required for retailers who sell primarily unhealthy food products. Governments can provide tax incentives for retailers whose sales meet dietary guidelines or change the choice architecture to assist consumers in making healthier and sustainable choices (Rose et al. 2022). Industry resistance and lobbying against the need for greater regulation will likely occur and should be resisted (WHO 2024; 17.2.4.1).

17.2.1.4 Increase public awareness and education on food, health and environmental issues

Providing clear, accessible and trusted information on health and environment aspects of diets helps guide populations towards more informed choices. This information could be delivered in food markets and on labels, front and back of packages, mass media and advertising in public spaces, school cafeterias and curricula, and national food-based dietary guidelines. In low- and middle-income contexts, interventions that prioritize marginalized populations, tailored to their culture, language and relevance to their daily routines, have been shown to improve healthy eating, especially when combined with interventions such as social protection mechanisms (Ruel et al. 2013; Mayen et al. 2016), and when the information is targeted to the group regarding language, food culture, and relevance for their daily lives.

Public awareness and education campaigns can influence consumer attitudes and behaviour. Some examples of such efforts include nutrition education or dietary guidelines (Springmann et al. 2020, James-Martin et al. 2022), having meat-free days (Semba et al. 2024), mass media campaigns such as world hunger day and the National Farmers Day campaign,

food labels (Wolfson et al. 2022, Arrazat et al. 2023), and social marketing (Kenny et al. 2023). However, while these interventions increase awareness (Afshin et al. 2019), they sometimes do not translate into positive long-term sustainable dietary changes (Bailey and Harper 2015), especially when focused solely on individuals, as opposed to changing places and situational contexts where behaviours occur (McGowan et al. 2021).

National food-based dietary guidelines (FBDGs) are science-based, government recommendations and guidelines for healthy eating, aligned with the World Health Organization's guidance on healthy diets. These guidelines serve as a reference for the public, providing recommendations on healthy food, dietary patterns and strategies for a healthy diet (Herforth et al. 2019). FBDGs can also inform or set a standard for public procurement programs, such as school meals, federal food assistance programs, hospitals, and workplaces. As of 2022, 97 countries have FBDGs, but only 27 incorporated environmental sustainability goals and guidance (James-Martin et al. 2022). Aligning FBDGs with environmental sustainability, such as in the EAT-Lancet diet guidance, could increase environmental and health benefits, supporting One-Health goals (Springmann et al. 2020; Bui et al. 2024). However, public compliance with diet guidelines is currently low. To be more effective, the communication of guidelines needs to resonate strongly with consumers. Simplification is often an important step, and guidelines should avoid too technical presentation, but seek messages that are realistic, positive, straightforward, and actionable, without requiring consumers to forego their favourite foods (Webb and Byrd-Bredbenner 2015).

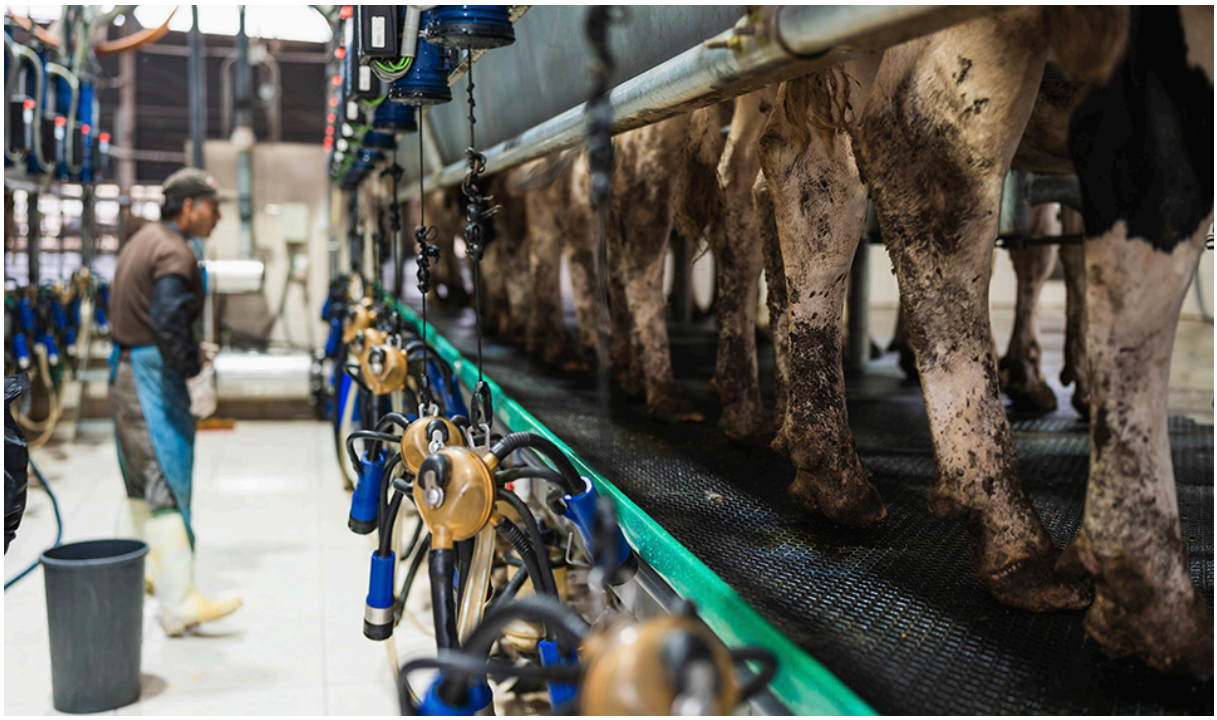
Improving cooking skills and food literacy, for example through cooking classes, increases adoption of healthier and sustainable diets while boosting confidence and positive attitudes (Hasan et al. 2019). However, many people lack access to kitchens, equipment, time, and financial resources (Garcia et al. 2016). Addressing the lack of knowledge and facilities would remove a major barrier to healthy eating (Wolfson et al. 2019) that can encourage people to opt out of more affordable, but less nutritious and sustainable dietary choices, particularly within high-risk vulnerable populations (Hawley et al. 2021).

School gardens can contribute to healthier consumption from an early age (Rico-Sapena et al. 2019, Davis et al. 2015), strengthening links with local biodiversity (Fischer et al. 2019), fostering knowledge about sustainable farming (Ferguson et al. 2019) and preserving biocultural knowledge (Robles-Piñeros et al. 2019). However, integration and maintenance of school gardens in both high and low-income settings often face a lack of funding, inadequate staff and space, low teacher interest and training, and difficulties including activities in the curriculum (Burt et al. 2018).

17.2.1.5 Changes in social norms & collective actions towards achieving more sustainable food consumption and practices

Changing social norms and food cultures could influence the perceptions of the value of food and the acceptability of food waste (Ranganathan et al. 2016; Çoker et al. 2022). Promoting pro-environmental norms and sustainable food consumption behaviours can be supported and sustained by well-targeted media campaigns, including social media (Sarkar et al. 2023). These campaigns could highlight the importance of choosing ethically sourced products, packaged sustainably, and produced with minimal environmental damage, while promoting and normalizing healthy food choices and behaviours among broad audiences (Rini et al. 2024). Partnering with influencers, like chefs and public figures, to endorse and share content on plant-based diets and the importance of choosing sustainably produced and packaged products could further amplify the message and reach a wider audience (Yidirim 2021).

Greater municipal and community engagement, local leadership and grassroots movements can foster connections with local food sources and encourage sustainable practices. These movements can educate about and implement practices like composting and the cultivation of local, seasonal produce through community gardens to larger-scale urban farms. They can also advocate for and support sustainable farming practices at a regional level (Motta 2021). Collective action of consumers and farmers in concert with health and environmental advocates can encourage the food industry to create more sustainable food supply chains, promote local and seasonal produce and reduce food waste (United Nations Environment Programme [UNEP] 2024).



Credit: GSR-PhotoStudio/Envato

17.2.1.6 Promote diverse foods and food cultures.

Integrating a wider variety of foods into people's diets – including locally adapted, Indigenous and underutilized "orphaned" crops – and embracing diverse food cultures, offers multiple benefits for nutrition, environmental sustainability, resilience, and economic opportunities (Talabi et al. 2022; Mabhaudhi et al. 2019; Zuza et al. 2024). Traditional foods contribute to diversified diets and enhance food and nutrition security (Akinola et al. 2020). Actions to support the integration of traditional foods in people's diets are discussed below, while measures to support their production are described in Section 17.2.2.5.

Education initiatives could be explicitly tailored to local food cultures to enhance public understanding and appreciation of benefits, celebrating diverse locally adapted foods. Educational programs can help widen the palate of children and youth, teaching them to appreciate the taste and flavour of new foods and the diversity of diets, including minimally processed and locally adapted foods (Hilimire et al. 2014). Policy interventions that facilitate the inclusion of diverse crops in school meals and public institutions boost their acceptance and normalize their consumption, supported through public procurement guidance or regulation (17.2.1.7).

Greater community engagement would foster local food cultures that supports food diversity. Local governments and community leaders can organize forums, town halls, and food expos to involve residents in sustainable food practices and to celebrate local cuisines. Community-driven projects such as local food co-ops or community-supported agriculture programs strengthen local food systems (Egli et al. 2023), while collaborative events like farmers markets and food festivals connect consumers with local producers, benefiting local economies.

Valuing traditional foods and cuisines through cultural festivals (Kuhnlein 2015), education and tourism (Kalenjuk et al. 2024) can enhance recognition of Indigenous and local food systems and their contributions to sustainability (Lopes et al. 2023). Women, often primary caregivers and food producers, face unique challenges. It is crucial to reduce gender inequalities by recognizing women's unpaid work, closing the gender gap in access to education, financial resources, extension services and technology, and transforming restrictive social norms (FAO 2023 & 2025; Marianne Gadeberg 2023).

17.2.1.7 Design and implement improved public food procurement and distribution

Public procurement in sectors such as schools, hospitals, the military, prisons, and food assistance programs can drive meaningful, albeit incremental, shifts in the food system that accumulate over time

(Parsons and Barling 2021). Public procurement can enhance nutritional quality and promote sustainable eating habits (WHO 2021). Strategically designed procurement policies can stimulate the supply of healthy foods and influence social norms and habits, supporting broader food system transformations (WHO 2021; Swensson et al. 2021; Sidaner, Baladan and Burlandy 2012; Privitera et al. 2024). To improve public procurement, the following key actions are key: set and monitor clear nutritional and environmental criteria that align with national guidelines (i.e., FBDGs), equip procurement professionals with adequate knowledge and training, addressing logistical and ensuring economic feasibility.

Nutrition and environmental sustainability criteria for public food provisioning should be established and monitored, aligning with national FBDGs and ensuring FBDGs incorporate environmental sustainability (Wood et al. 2023). Nutrition and environmental sustainability information for foods and meals needs to be readily available to consumers.

Those involved in designing or working in public procurement food service need sufficient knowledge and training to understand and assess what foods are healthy and sustainable (Guillaumie 2020). Logistical challenges, especially those related to preparing and distributing fresh and perishable healthy foods, must be addressed to facilitate smoother implementation. Solutions include new operating modes such as advanced supply chain software, decentralized food hubs and new recipes. For example, in Brazil and India, engagement with small- and medium-scale processors to supply food to school meal programmes has supported healthier diets, while providing a stable market for local enterprises (Swensson et al. 2020). Brazil's Public Food Procurement program, which supports family farmers faces challenges, including seasonal production gaps, inadequate infrastructure for food storage and processing, and limited technical assistance to farmers (Soares et al. 2024).

17.2.1.8 Synergies, trade-offs, and the need for social protection

While animal-sourced foods are typically more environmentally intensive to produce than plant-based foods, they are also important sources

Credit: seventyfourimages/Envato

of nutrients, including calcium, iron, vitamin B12 and zinc, particularly for people who consume them infrequently. In resource-constrained settings, diets often lack quality and diversity, which includes limited access to animal-sourced foods, increasing risk for nutrient deficiency (Allen et al. 2011; Parikh et al. 2022).

Livestock also contributes to livelihoods and resilience, especially in low-income rural communities. A reduction in animal-sourced food consumption among those vulnerable populations could be detrimental to growth, development, and health. In contrast, in high-income countries, where animal-sourced food consumption is high, shifting towards more plant-based diets could provide health and climate action gains.

Global efforts to reduce consumption of animal-sourced foods must not exacerbate existing injustices and inequities in access to healthy diets. Governments could establish social protection measures, such as welfare and food assistance, to support marginalized and vulnerable individuals and resource-constrained households (Kumar et al. 2021). Incorporating environmental and health externalities into food prices need to be implemented with caution and include protection for vulnerable low-income households (17.2.1.1 and 17.3.4).

Nevertheless, the substantial and essential benefits of these actions are indispensable for achieving the food system goals outlined in **Table 17.1**. Without dietary shifts, there isn't enough land or other resources to produce the necessary food, while protecting biodiversity and meeting climate targets.

17.2.2 Solution pathway 2: Improved crop, livestock and aquatic food production and land use systems

Sustainably increasing productivity is essential for enhancing food security while also freeing up land for ecosystem services and climate change mitigation (IPCC 2019; Tittonell and Giller 2013; Godfray and Garnett 2014; Keating et al. 2014; Pradhan et al. 2015). However, intensifying crop, livestock and aquatic systems without modifying current production models can further harm the environment and ecosystem (Raj et al. 2022; Clay et al. 2020). Expanding agricultural land to produce more food has substantial climate implications, biodiversity loss and environmental degradation (Maeda et al. 2021). In contrast, restoring degraded land and bringing it into agricultural production may improve production and carbon sequestration (Jat et al. 2019; Sapkota et al. 2019).

Sustainable intensification combines genetic improvement in crop, livestock and aquaculture with a range of locally adapted sustainable production practices to increase food production while minimizing environmental harm (Garnett et al. 2013; Eyhorn et al. 2019). Sustainable transformation of terrestrial and aquatic food production requires a balance between sustainable intensification and nature-based practices (Chapter 18). This means that productivity gains need to be aligned with the preservation of ecosystem services, social responsibility, animal welfare, and resilience to shocks (Vanlauwe et al. 2014).

Development and promotion of high-yielding crop varieties and breeds of livestock and aquatic species have historically increased yields and helped reduce hunger (Ricciardi et al. 2018) and continue to drive productivity gains (Avana-Tientcheu and Tiambo 2020). Genetic improvements could be further enhanced through integrated breeding strategies, combining conventional, marker-assisted, and genomic breeding and unlocking favourable genetic variations, locally adapted traits, precise envirotyping, to heighten selection intensity and to shorten selection cycle (Xu et al. 2017). Breeding for biotic and abiotic stress tolerance, better root systems, higher feed conversion ratio, and improved nutrient-use efficiency can substantially increase production, while increasing resilience against shocks and reducing GHG emissions. However, these genetic breakthroughs should be combined with a range of transformative management practices, such as agroecological approaches, resource-efficient technologies, soil health restoration, and climate-resilient farming systems to ensure long-term productivity, environmental sustainability, and food security.

Various management practices have been developed, tested, and validated to enhance the sustainable production of crops, livestock, and aquaculture systems, contributing to food security and environmental goals. Some examples include conservation tillage and crop establishment (Aryal et al. 2015; Jat et al. 2020; Sapkota et al. 2022), diversified crop rotation

Credit: Sebastian_Studio/Envato

and cropping system management (Ladha et al. 2016), precision nutrient and water management (Jat et al. 2015; Sapkota et al. 2021; Snapp et al. 2023), and improved livestock feeding strategies, including grazing rotation, animal welfare enhancements, and manure management (Herrero et al. 2016).

In India, implementing just three sustainable intensification technologies - efficient fertilizer use, conservation agriculture and rice water management - could reduce agricultural emissions by approximately 10 per cent, without compromising production (Sapkota et al. 2019). Although increasing food production through intensification may result in greater absolute GHG emissions, maintaining the same level of yield through precision nutrient and water management could contribute to long-term food and nutrition security and climate change mitigation, while also improving soil health.

A holistic approach is needed in livestock production systems, combining improved husbandry practices, strengthened biosecurity, alternative health interventions like vaccination and probiotics, responsible antibiotic stewardship, sustainable waste management, and policy-driven incentives.

Implementing recirculation systems and enhanced feed management practices in aquaculture improves water, nutrient, and energy use efficiency (Verdegem et al. 2022). Mariculture can use ocean space to build aquaculture farms (Schubel and Thompson 2019), reducing competition for land. Climate-adaptive fisheries reforms minimize negative impacts on wild-caught fisheries and increase their resilience to the effects of climate change (Beckensteiner et al. 2023).

Regenerative and agroecological practices, such as conservation tillage, crop residue recycling, production system diversification (Snapp et al. 2021), cover cropping, agroforestry (Niether et al. 2020), and mix crop-livestock (Bezner Kerr et al. 2021), as well as crop-livestock-fish (Keating et al. 2014) farming system, enhance biodiversity (Pettorelli et al. 2021; Dunlop et al. 2024), nutrient cycling (Giller et al. 2021), productivity and farmers' income. The practices also contribute to climate change adaptation and mitigation efforts by enhancing and functioning the root systems, increasing soil organic matter (van Groenigen et al. 2017) and reducing fossil fuel dependence (Aguilera et al. 2020).

Sustainable soil and water management are essential for sustainable food production, ensuring

efficient resource use, enhanced ecosystem services, and climate resilience. Integrated approaches, including precision water technologies from farm to watershed scale (Sikka, Alam, and Mandave 2022; Cofie and Amede 2015), renewable energy for irrigation (Fraunhofer ISE 2024), and soil-health enhancing practices, like residue recycling, optimize nutrient cycling, water retention, and carbon storage, supporting long-term agricultural sustainability (Jat et al. 2015; Kumar et al. 2023; Hiranmai et al. 2023).

Achieving long-term food security and environmental sustainability through the use of beneficial technologies for production of crop, livestock, and aquatic species requires a coordinated set of actions. These include advancing technology and genetics (17.2.2.1), leveraging Indigenous Knowledge (17.2.2), reforming agricultural subsidies (17.2.2.4), implementing protected areas (17.2.2.7), changing food industry practices (17.2.2.5), improving financial access (17.2.2.2), and enhancing farmer education and extension services (17.2.2.3).

17.2.2.1 Drive advanced research and innovation in crop, livestock and aquatic production systems

Cutting-edge research and innovation in genetic improvements and production systems management tailored to specific production circumstances are needed. This requires fundamental and applied research to unlock the genetic potential of crop, livestock, and aquaculture to develop varieties and breeds with improved biotic and abiotic stress resistance, including adverse environmental conditions, improved resource-use efficiency, increased productivity and enhanced nutritional quality (Jamir et al. 2024; Rojas-Downing et al. 2017; Lu and Luo 2020; Gratacap et al. 2019; UNEP and FAO 2024). Some aquatic species possess high fecundity and external fertilization (Gratacap et al. 2019) that can facilitate genome editing to produce favourable production traits, such as disease resistance.

Genetic breakthroughs should consider traditional and Indigenous Knowledge systems and leverage precision technologies to optimize resource use, monitor crop, livestock and aquatic species health, enhance overall productivity, and promote sustainability and resilience. Collaboration between national and international research institutions, universities and advanced research institutes, and the private sector can develop and validate advanced breeding techniques, build robust phenotyping platforms and high-throughput screening capabilities (Araus and Cairns 2014), providing training, advisory services and establishing effective distribution channels (Mangeni 2020).

Genetic innovations should be combined with sustainable production practices, such as precision agriculture or aquaculture, diversified cropping or species production, conservation agriculture or restorative aquaculture, or crop-livestock-aquaculture integration, to optimize nutrient cycling, enhance soil health, biodiversity and overall productivity.

National Agriculture Research and Extension Systems, universities and international research organizations should invest in sensors, satellite, big data analytics and artificial intelligence to understand soil, environment and climatic conditions. Integrating these data streams with farm management and decision support systems will generate site-specific management recommendations (Snapp et al. 2023). Application of advanced knowledge on symbiotic nitrogen-fixing mechanisms and nutrient cycling is needed to develop and grow self-fertilizing cereal crops (Guo et al. 2023), including those regulating nutrient cycling processes through nitrification inhibition (Leon et al. 2022). Another emerging research area is developing an integrated multi-trophic aquaculture system that combine finfish culture with lower-trophic-level species, such as seaweeds or bivalves, to recycle nutrients and allow for maximizing resource utilization, while minimizing environmental impacts (Ren et al. 2010; Edwards 2015).

Understanding the ability of agroecology and other innovative approaches to address climate risks, enhance the resilience of farming systems, and improve the flow of resources from diverse ecosystem services (Sinclair et al. 2019) is also critical. Disseminating such knowledge available to all value-chain actors, such as farmers, input and output dealers, policymakers and public (Kaufmann et al. 2023) is often lacking. This is particularly important in low-income countries as they often lack adequate knowledge from a system perspective (Mockshell and Villarino 2019).

Sustainable fisheries can be supported through small-scale, low-impact fishing methods that

Credit: Cookelma/Envato

use socially innovative, locally adapted practices (Akinsete et al. 2022). Improving fisheries governance through innovative community-based schemes can help develop new distribution systems, support local communities through employment, initiate new networks, and facilitate collaborative actions across fishers. Adequate monitoring, data analysis, and improving processes at all levels can drive transformation in fisheries management (Moe Føre et al. 2024).

Moreover, research efforts can also focus on designing future crops, animals and production systems to develop resilient, resource-efficient and climate-adapted crop varieties and livestock and fish breeds, together with innovative production systems such as urban agriculture, vertical farming (Oh and Lu 2023) or integrated aquaculture-agriculture models (Sekaran et al. 2021) to intensify production sustainably. Several sustainable fisheries management measures, approaches, and practices exist to minimize negative impacts from wild-caught fisheries operations and increase their resilience to climate change impacts, such as through climate-adaptive fisheries reforms that incorporate ecological and industry management responses (Beckensteiner et al. 2023).

Beyond sustainable intensification at the farm and landscape levels, food system transformation requires research and innovation on governance, power dynamics, political economy, inclusiveness, market instruments and finance. Scientific and professional bodies such as CGIAR (Govaerts et al. 2021), Global Alliance for Climate-Smart Agriculture, Sustainable Agriculture Initiative Platform, Global Forum on Agricultural Research and Innovation, Africa Food System Forum, National Agricultural Research and Extension Systems, farmers' group and civil society organizations play a crucial role in this transition by supporting research, providing educational resources, and building capacity for scientists, educators, managers, and businesses. These organizations should also help develop, harmonize, and standardize protocols and metrics for monitoring the effectiveness of transformational technologies for food security and environmental safeguards. National governments are responsible for creating enabling institutional mechanisms and

policy environments that catalyze greater international cooperation, knowledge sharing and scaled implementation of sustainable farming practices.

Private sector players can drive advancements in environmental sustainability by investing in cutting-edge research and technology development, such as genetic innovation, precision agriculture, water-efficient irrigation systems, renewable energy, greener cattle initiatives for enteric methane reduction, environmentally sound fertilizers, such as green ammonia, among others. Through public-private partnerships, businesses can accelerate the development and implementation of sustainable practices, such as organic fertilizers, biopesticides, and sustainable feed options, while advancing clean energy integration to reduce the reliance on harmful chemicals and fossil fuels, reducing the carbon footprint and improving soil health and biodiversity.

17.2.2.2 Improve access to financial capital and investment

Government and international organizations could commit to long-term efforts to design, develop, test and deploy agricultural and aquaculture technologies and approaches, allocating funding and resources to support such research and development. Strategies and policies that increase investments in sustainable production practices and nature-based solutions, including those that enhance soil health and ecosystem services, are crucial for the long-term sustainability and profitability of food production systems. More funding can be mobilized by linking transformative approaches with Sustainable Development Goals and leveraging financial support through international institutions, like the World Bank, multi-national development banks, and global financial institutions (Mukherji et al. 2023). High interest rates, currency instability, and inflation in developing countries often make finance costly and inaccessible for farmers and innovators. Targeted solutions such as subsidies, credit guarantees, stable monetary policies, and concessional lending from international institutions can help lower financial barriers and improve access to sustainable investment.

Leveraging a suite of financial mechanisms, stakeholders across the public, private, and philanthropic sectors can help overcome barriers and accelerate the transition towards more resilient and equitable food production systems.

Public-private partnerships can unlock investments in sustainable production systems through blended finance models, combining public, private and philanthropic capital. Payment for ecosystem services and well-designed carbon credit schemes can compensate farmers and landowners for providing environmental services, like carbon sequestration and biodiversity conservation, creating new revenue streams (Pagiola et al. 2020; Wunder et al. 2020; Wongpiyabovorn et al. 2023).

The private sector can support a sustainable food system by adopting responsible sourcing (Kamgang et al. 2023), ensuring fair compensation to producers, and optimizing supply chains, including investing in cold storage and efficient logistics to reduce food losses. Agricultural input companies should invest in precision farming technologies, including GPS-guided equipment and data analytics, to improve resource-use efficiency.

Private sector groups can also develop and provide sustainable feed options for livestock and aquaculture that eventually help reduce the environmental impact of livestock and fish farming, promoting healthier production systems. For example, Cargill and InnovaFeed are developing insect-based protein feed (Cargill 2024). Similarly, start-ups can provide renewable energy solutions for farm machinery, water pumping and irrigation systems, nutrient management, drying agricultural products, and heating and cooling solutions (Gorjian et al. 2022). Platforms like the World Intellectual Property Organization can facilitate access to finance and capital investment by connecting technology providers, seekers, and investors.

While private investment is crucial for advancing sustainable food systems, it raises concerns about ownership of knowledge, data, and intellectual property, potentially restricting access for smaller producers and public institutions. Additionally, conflicts of interest may arise if mixed investment portfolios prioritize short-term financial gains over long-term sustainability, undermining public oversight and resource allocation.

Developing innovative financial instruments, such as sustainability-linked loans or green bonds, can attract private capital (Flammer 2021). National and international organizations can deploy de-risking mechanisms, such as loan guarantees and risk-sharing facilities, to mitigate investment risk and incentivize private-sector funding in projects with environmental or social benefits. Similarly, microfinance institutions and agricultural development programs could offer farmer-tailored financial products, including affordable credit, savings, and insurance schemes, to enable smallholder investments in sustainable farming, building their economic resilience (Meyer 2014).

17.2.2.3 Enhance knowledge sharing for food producers through education and knowledge extension programs

Increased knowledge sharing and capacity building of farmers, extension agents, and other food value chain actors strengthen institutional capacity and improve knowledge, skills, and confidence for widespread adoption of sustainable production practices. This, in turn, enhances food security, producer livelihoods, and long-term environmental and economic resilience of the agricultural, aquaculture, and fisheries (Humphries 2018; Akpoviri et al. 2023; Kommey 2023). Effective capacity building can be supported by establishing comprehensive data and knowledge sharing platforms that harness the capabilities of big data analytics, machine learning and artificial intelligence (Delgado et al. 2019; Jimenez et al. 2019). Farmer-to-farmer learning networks and information and communication technologies for knowledge sharing can increase the speed of dissemination and accelerate the spread of best practices, empowering farmers with efficiency and productivity (Capponi 2023; Pandey 2021). For example, various CGIAR centres have established data platforms that collect data from satellite imagery, farm surveys, climate models and provide producers with real-time weather updates and agroadvisories, helping farmers select appropriate crops and management practices to enhance crop yields, improving soil health and managing climate risks. Education and knowledge dissemination facilitate interaction among farmers and various stakeholders, fostering behaviour change and better utilization of funds and competencies (Nyaplue-Daywhea et al. 2021; Kirkwood et al. 2022; Kabir and Islam 2023).

Government extension systems need to incorporate digital advisories and pluralistic extension models, involving non-government organizations, private agribusinesses and farmers' organizations to provide technical assistance, agroadvisories and market access. To be effective, these systems require adequate financing and effective channelling to extension services (Food and Land Coalition 2019). Local institutional capacities of grassroots-level organizations can be strengthened through collaboration with universities, advanced research institutes and vocational training centres.

Farmer education initiatives should aim to promote gender equality and inclusion by prioritizing the adoption of inclusive agricultural tools and technologies, such as lightweight farming tools, mobile-based agricultural advisory services, and solar-powered irrigation systems, and mainstreaming Indigenous Knowledge as well as local knowledge (Sitachew, Jeyabalasing and Debela 2018). Promoting gender and social inclusion along the supply chain is also essential (Frangoudes and Gerrard 2019).

Achieving inclusive and equitable outcomes requires cross-sector collaboration among public education and research committees, finance and development agencies, farmer network representatives, community leaders, civil society organizations, and local authorities. Technical schools and universities can also participate by incorporating non-environmental or non-agronomic disciplines, such as law, engineering, architecture, economics, or business. Together, these stakeholders can develop gender-responsive funding and appropriate financial support for farmers, design curricula for farmer education and extension services to support the uptake of sustainable farming and harvesting practices (Davis 2022; Vafadarnikjoo et al. 2023; Vieira et al. 2023).

17.2.2.4 Reform/repurpose agricultural subsidies

Subsidies are policy tools to provide financial incentives that encourage environmentally sound practices among producers. Subsidies can take various forms, such as direct payments for ecosystem services, minimum price support, price premiums for sustainably produced food, and technical assistance for adopting sustainable farming techniques.

These can promote producing and marketing more environmentally sound, humane and sustainable products or systems.

In most OECD countries, most subsidies are directed towards intensively grown commodities, such as rice, sugar and a range of livestock products, which account for about 80 per cent of GHG emissions from agriculture (Mamun et al. 2019), disproportionately favouring large corporations over small and medium-sized enterprises, which benefit local communities and food systems. This approach tends to promote monoculture and input-intensive production systems, discouraging the production of more nutritious foods, such as vegetables, fruits, legumes, eggs, and fish that follow integrated production systems (Mamun et al. 2019).

Reforming agricultural subsidies is essential to drive the transition toward sustainable and resilient food systems. This involves phasing out support for environmentally harmful practices and redirecting financial incentives toward sustainable inputs, agroecological methods, and innovative technologies that enhance both productivity and ecological integrity (Piñeiro et al. 2020). Governments can reinforce these incentives with penalties for unsustainable practices (Nordhaus 2017), creating a balanced system of rewards and deterrents. A comprehensive review of existing subsidy programs is needed to identify and correct biases that prioritize input-intensive, yield-maximization approaches at the cost of environmental and public health. Effective reform requires inclusive engagement with policymakers, farmer organizations, and stakeholders to ensure that subsidy policies align with broader goals such as food security, climate resilience, biodiversity conservation, and human well-being.

One prominent example is revising fertilizer subsidy policies in India to phase out subsidies on urea and increase support for phosphorus and potassium fertilizers. This can promote balanced fertilization, leading to increased yield, reduced cost of production, and reduced environmental pollution (Sapkota et al. 2021). Other examples of repurposing subsidies include shifting to output-based payments, providing transition support for farmers moving to agroecological methods, and integrating subsidies with other financial incentives, such as payment for ecosystem services and price premiums for sustainable products. In fisheries, subsidies can also be repurposed to encourage sustainable aquaculture practices, such as integrated multi-trophic aquaculture (Knowler et al. 2020) or modernize the aquaculture sector for improved yields and environmental outcomes (Guillen et al. 2019).

However, reforming agricultural subsidies may face strong resistance from policymakers, agribusinesses, and industry lobbies that benefit from existing production-focused incentives. Policymakers often fear political backlash from farmers and rural communities reliant on existing subsidies. Therefore, the transition must be phased and inclusive, requiring financial restructuring, strong political will, and stakeholder consensus to maintain food security and stability of rural economies throughout the process.

17.2.2.5 Change food industry practices to encourage sustainable production

The food industries play a pivotal role in food system transformation, with the potential to either exacerbate negative consequences (Slater et al. 2024) or drive positive change (Prasanna et al. 2024). While the influence of food industry practice on consumer behaviours and diet is discussed in Section 17.2.1.2, this section focuses on how food industry action can generate positive systemic change by creating powerful incentives and market signals that drive the widespread adoption of sustainable production practices. For example, companies can commit to sourcing raw materials from suppliers who adhere to sustainable practices, requiring suppliers to meet sustainability benchmarks. At the same time, third-party certification and traceability systems (e.g. blockchain) can improve transparency and consumer trust.

Mandatory sustainability labelling and certification schemes can boost consumer awareness and demand for nature-focused products. Government-supported market linkage and procurement programs should prioritize sustainable food products, while providing marketing and branding support to private enterprises to promote their environmentally responsible products and services.

Consumers play vital role to a sustainable and resilient food system by making informed choices and prioritizing traceable, locally produced food. Strengthening connections between local producers

Credit: DC_Studio/Envato

and urban markets, along with widespread adoption of eco-labels and carbon labelling, can enhance transparency and shift preferences toward sustainably produced goods (Miranda-Ackerman and Azzaro-Pantel 2017). These consumer-focused strategies are most impactful when embedded in evidence-informed, holistic food system governance (Costello et al. 2020; Melnychuk et al. 2021; Boyd et al. 2020; Delabre et al. 2021; Farmery et al. 2022).

Indigenous and traditional crops – well-adapted to degraded soils, harsh climates, and a range of biotic and abiotic stresses – are vital for enhancing local climate resilience and restoring fragile landscapes (Tadele 2019), yet they remain marginalized in policy, with limited research investment, poor market access, and underdeveloped value chains (McMullin et al. 2021). Strengthening these diverse, locally adapted crops, livestock, and aquatic species can boost biodiversity, food security, and climate resilience (Chivenge et al. 2015; Akinola et al. 2020). To unlock the potential of Indigenous crops, targeted policies, increased research investment, and stronger market integration are crucial.

Preserving traditional agricultural knowledge, including the use of medicinal plants, community shrines, and living libraries, sustains biodiversity and supports diversified, nutritious diets (Moghaddam et al. 2017; Aniah and Yelfaanibe 2016; Sraku-Lartey 2021; Kruger et al. 2018; Mensah et al. 2021). This requires improving seed availability, integrating Indigenous Knowledge and Local Knowledge holders and their insights into public service, and treating conservation and cultural preservation of Indigenous Knowledge and Local Knowledge as a priority. Research and policy should enhance community seed banks and promote farmer-managed seed systems (Zuza et al. 2024).

17.2.2.6 Implement terrestrial and marine protected areas

Effectively implementing and managing terrestrial and marine protected areas promotes environmental sustainability through preserving biodiversity, protecting critical ecosystems, and mitigating climate change impacts. For more details, see chapter 18.3.1 on environmental system transformation pathways.

17.2.3 Solution pathway 3: Reducing loss and waste and increasing circularity

This solution pathway focuses on reducing food loss and waste along the food system and enhancing circularity, where losses cannot be eliminated. Food system losses, including food waste, occur at all stages of the food

system and account for 30-40 per cent of agricultural production, representing more than US$1 trillion worth of food, with losses contributing to food insecurity and environmental degradation (UNEP 2024; Surdulescui et al. 2023; de Sousa et al. 2024; Alexander et al. 2017a). Food waste is a loss that occurs at the retail, food service or household level (Gustavsson, Cederberg and Sonesson 2011), and accounts for 19 per cent of available food (UNEP 2024). Additional losses occur earlier in the supply chain from post-harvest handling through to processing and distribution. Consumption exceeding nutrient requirements can also be considered a loss (Alexander et al. 2017b; Franco et al. 2022).

Food system waste and by-product streams, including human waste, are often not handled in a circular manner. Currently, over 80 per cent of wastewater, 95 per cent in low- and middle-income countries, is discharged without treatment or to capture nutrients, leading to environmental damage and lost opportunities for nutrient recovery (UN Water 2017). Reducing food losses at source, including, reductions in consumer waste, overconsumption, spoilage, transport and on-farm losses, along with increasing circularity at every stage of the food system would reduce environmental harms and improve food availability (Manzoor et al. 2024; Ellen MacArthur Foundation 2021; Franco et al. 2022) (15.4).

Losses can be reduced by better understanding what and where losses occur, limiting damages during processing and handling, increasing shelf-life through packaging and developing new foods that reduce losses. Behaviour changes to prevent food loss and waste can be initiated by ensuring a positive attitude and better food choices among consumers and using food-saving technologies (UNEP 2024). Actions to improve circularity include recovering on-farm nutrients, including through composting and anaerobic digestion, empowering producers with knowledge and skills on circularity, leveraging technology to convert waste or by-product streams into higher value products, promoting nature-based circular approaches, and ensuring inclusivity and collaboration. As with other solution pathways, progress depends on research and development (17.2.4.1), and targeted investments (17.2.2.2).

17.2.3.1 Value chain actions to reduces loss and waste

Improved measurement of food loss and waste rates through the value chain would help to prioritize actions and employ sustainable operations to prevent the losses (Dora 2021). Identifying and addressing inappropriate systems and poor storage and packing during processing and handling can reduce food damage (Karanth et al. 2023). Extending shelf-life through digital, practical, user-friendly tools is an effective strategy to reduce food waste (Reyes, Cahill and Solval 2024). Packaging plays a key role in extending shelf-life and protects products from contamination or mechanical damage, contributing to reduced food losses during transportation, retail and in households. However, evaluating environmental impact of packaging is essential to identify and manage trade-offs (Paiva and Ugaya 2024). For example, fruits and vegetables should be sold loose unless it can be shown that plastic packaging reduces overall food waste. Biodegradable packaging materials (e.g. derived from onion solid waste) can serve as indicators of bioactive components, displaying the freshness in real-time (Thivya et al. 2023). Natural, edible and nature-based preservative material, such as chitosan, have been shown to increase shelf-life, maintain quality and reduce food losses of perishable foods (Chaudhary2024). Spoilage losses can be reduced by improving storage facilities, including maintaining and monitoring for appropriate moisture levels and controlling pests (Bradford et al. 2018). Solar-powered cold storage units in regions with limited infrastructure can enhance food preservation (Amjad et al. 2023). Smart systems that optimise storage conditions based on real-time data can also extend the shelf life of perishable products (Mustafa et al. 2024).

17.2.3.2 Leverage consumer attitude toward circularity

Positive attitudes among consumers to prevent food waste can reduce losses and promote circularity (Prestes Floriano 2024; Veselá, Králiková and Kubíčková 2023). Measurement of food waste can trigger behavioural change encouraging better planning in cooking and purchasing (Ramos et al. 2024), while food-saving applications can promote ecologically conscious behaviors (Balińska, Werenowska, and Jaska 2024). An example is the TooGoodToGo app which increased acceptance of buying leftover food in many countries. Surplus food re-distribution through charitable initiatives can help reduce food loss and waste (Kenny and Sage 2021), while increased transparency and consumer knowledge on date labels, such as the difference of “best-before”

versus "use-by" dates, can cut food waste (World Resources Institute 2022).

Another method for reducing food losses include novel practices for setting smart distribution, use of machine learning algorithms, which can help to classify, identify and predict contamination levels of leftover cooked food (Matera and Genovese 2024; Azman, Azir and Khairuddin 2024). Innovative applications for sorting and weighting "pay-as-you-throw" food waste schemes, or other financial or taxation-based incentives, can help reduce household and canteen food waste, as shown in the Republic of Korea (Kim and Lee 2020; Broad Leib et al. 2023). Higher food prices (17.2.1.1) may also influence to adopt consumer waste-reducing behavior (Veselá, Králiková and Kubíčková 2023).

Eating more of the edible parts of plants and animals, like offal and commonly discarded vegetable leaves and stems, makes the food system more efficient and circular (Font 2023). Widespread adoption of such changes may require intervention to encourage changes to social norms (17.2.1.5-7) (Llauger et al. 2021). Enhancing the direct connections between producers and consumers, for example with agroecological systems, urban and peri-urban agricultural and school food gardens, can also strengthen circularity and reduce losses (Voge et al. 2023).

17.2.3.3 Increasing circularity and nutrient recycling across the food system

The production of some waste and by-product streams is inevitably associated with the food system. Circular approaches can make fuller use of these resource streams, including greater recycling of on-farm and food industry by-products and wastes, and nutrient recycling from human wastewater. When poorly managed, the decomposition of organic materials generates methane, a potent greenhouse gas (Karakurt et al. 2021).

Farm-level by-products can be used converting agricultural residues into biofuels or biomaterials, reducing reliance on non-renewable resources and lowering environmental harms (Kumar, Sasikumar and Dhilipkumar 2024; Ginni et al. 2021; Riseh et al. 2024). Composting and anaerobic digestion of food system waste and by-products, including municipal food waste, can help close nutrient loops and reduce GHG emissions (Le Pera et al. 2022; Yaser et al. 2022; Murphy and Power 2006). Insects can recycle nutrients from food waste or by-products into feed suitable for livestock and aquaculture (Ojha, Bußler, Schlüter 2020; Lalander Nordberg and Vinnerås 2018).

Nutrients – such as nitrogen, phosphorus, and potassium – should be recovered from human wastewater, turning waste disposal challenges into resource recovery opportunities (Sniatala et al. 2023; Browlie et al. 2024). Capturing and recycling nutrients from human waste reduces the need for chemical fertilizers, a major user of natural gas and GHG emitter, that drives demand for mining of phosphorus and potassium ores (Macura et al. 2021; Day, Alexander and Maslin 2023; Browlie et al. 2024). However, potential risks for soil contamination with pharmaceuticals, heavy metals or persistent organic pollutants must be carefully addressed through appropriate measures, treatment and regulation (Buta et al. 2021; van der Broek et al. 2024).

Nature-based approaches, including Indigenous food production systems, should be promoted, as these typically minimize waste by using each product and by-product. For example, animal products are used for food, clothing, housing, and other materials. Integrated systems, such as combining fish farming with aquaponics vegetable production, reusing waste from the fish to nourish the plants. These systems improve resource efficiency and productivity (Limbu et al. 2017).

17.2.3.4 Engage actors and ensure inclusivity and networking

Inclusivity and collaboration across the food system would help to increase circularity and reduce losses (Somlai 2022), transitioning toward a Circular Society (e.g., Jaeger-Erben et al. 2021; Frojan et al. 2023). Small-scale farmers remain under-represented in food system governance (Avikal et al. 2023). Involving them, including updating infrastructure and farming equipment, supports circularity. Effective waste management policies, technologies, and targeted incentives are key enablers (Sahoo et al. 2023; Shukla, Pullabhotla and Baylis 2023; Gitau et al. 2024). Collaboration between governments, the private sector, educational institutions, researchers, and consumers can provide insight on new co-products and better handling of waste

(Bechir et al. 2023) (14.4 & 15.2.3), while supporting suitable business models and financing (17.2.2.2). Additionally, such collaborations can encourage industries to use more recycled materials and waste streams (Shafqat et al. 2023).

17.2.4 Solution pathway 4: Novel foods and production processes

Novel foods, including alternative proteins, such as cultivated meat (i.e. cellular agriculture), novel plant-based foods and fermentation-derived products, can potentially displace conventional ASFs. Cultivated meat, also known as lab-grown, cultured, or cell-based meat, is produced directly from cultivated animal cells, bypassing animal rearing and slaughter. Instead, the cultured cells are differentiated into muscle, fat and other tissues to replicate the properties of meat. Novel plant-based foods are formulated to mimic the taste and texture of animal products, and do not include traditional plant-based foods, such as tofu, tempeh or seitan. Fermentation-derived proteins use microorganisms, such as yeast and fungi, to produce biomass or specific animal proteins, including dairy and eggs.

These products could potentially provide nutritious foods with lower GHG emissions, land and water use, and biodiversity loss, compared to conventional animal-sourced food production (UNEP 2023; Alexander et al. 2017b), and also reduce the risk of zoonotic diseases (Santo et al. 2020) and antimicrobial resistance, and animal welfare concerns (van der Weele and Driessen 2013; Sexton 2019; Heidemann et al. 2020). However, the human healthimplications from these foods are uncertain (Hadi and Brightwell 2021; Cellura et al. 2021; Holmes et al. 2022), including allergenicity (Dong et al. 2024; Malila et al. 2024), and need further investigation.

The scale and the timeline of the adoption of alternative proteins remain uncertain, and widespread uptake is unlikely before 2030. Meanwhile, novel production methods and innovative technologies, such as vertical farming, precision sensing and monitoring technologies, agricultural robotics, on-farm automation and artificial intelligence, can increase the efficiency and sustainability of conventional food production (Poore and Nemecek 2018; Rubio, Xiang and Kaplan 2020; Javaid et al. 2023; van Delden et al. 2024).

The economic cost of producing cultivated meat and subsequent consumer prices are currently higher than conventional meat products (Chen et al. 2022; Kantor and Kantor 2021; Guan et al. 2021). While alternative protein prices in the medium term may approach parity with conventional meat, they are unlikely to compete with traditional plant-based proteins, due to the high costs associated with the construction and operation of production facilities. Lifecycle emissions may also be higher than plant-based foods due to embodied emissions in the infrastructure and the direct energy requirements, though likely lower than conventional ruminant meat (Alexander et al. 2017b). Using renewable energy for their production and processing could reduce their footprint. A key benefit over plant-based foods is that cultivated meats may be more acceptable to some consumers as a substitute for conventional meats (Sinke et al. 2023; Rombach 2022).

Multiple advanced technologies with potential to increase the sustainability and efficiency of food production are in development (De Clercq, Vats and Biel 2018; Popkova and Sergi 2023; McGrath et al. 2023; Haddad 2020; Rose et al. 2021). Vertical agriculture, using controlled-environment agriculture technologies to grow fruits, vegetables and crops indoors in vertically stacked layers, is producing foods commercially (Jaeger 2024). Artificial lighting, climate control, precision monitoring technologies, and automation are utilized to optimize plant growth, providing increased yield and requiring lower land use, natural resources, and agrichemical inputs. Other innovative production methods include hydroponics, aeroponics, and aquaponics, which all involve growing plants without soil and can be located in urban areas, reducing transportation emissions, distances, costs, and time. Other innovations are discussed in the agricultural efficiency solution pathway section (17.2.2), including remote monitoring and sensing technologies, livestock biosensing devices, farm automation technologies, agricultural robotics, and biotechnology.

To realize the potential of these technologies, greater investment in research and development is needed from national and international governments and the private sector. This includes more research into consumer acceptance (17.2.4.1) and financial support to scale up production facilities, establish supply chains, and facilitate commercialization (17.2.2.2). Regulatory regimes need to change to

Credit: JuiceFlair/Envato

enable widespread uptake of these novel foods and technologies (17.2.4.2). Changes to the financial incentives of the conventional meat industry, including educing subsidies for livestock production or taxing environmental externalities (17.2.1.1) could make conventional meat less price-competitive, and help novel foods and technologies to be price competitive. Socio-economic impacts should be considered to ensure equitable and inclusive benefits from novel alternative proteins, including supporting sectors that may be negatively affected by the shift from conventional ASFs (UNEP 2023). Widespread consumer adoption will depend on behaviour change, that could be supported by action contained in dietary change solution pathway (17.2.1), including trusted and tailored information, changes to social norms, and improvements in convenience and availability.

17.2.4.1 Drive advanced research and development in novel foods and production processes

While promising, the environmental and health impacts of many of these technologies are currently uncertain, with substantial development and research required to improve the technologies and understand their consequences fully. Internationally coordinated research programmes are needed to enhance flavour and nutritional value, reduce production costs, and evaluate the potential sociocultural impacts (Stephens et al. 2018; UNEP 2023). Both public and private investments are required to support this work. Research and development also need to address and mitigate associated trade-offs, such as the high energy demand of certain production processes (Sillman et al. 2020; Järviö et al. 2021; Odegard and Sinke 2021).

Widespread consumer acceptance will require integrating novel foods into global diets (Wilks et al. 2019; Kantor and Kantor 2021). Food neophobia, the reluctance to try unfamiliar foods, is a barrier, particularly for foods produced using new technologies that are often perceived as less natural than conventionally produced foods (Bryant et al. 2019). More research is required to understand consumer attitudes, including marketing strategies to achieve greater and rapid adoption post-commercialization, and identifying actions to inform (17.2.1.4) and shift social norms (17.2.1.5).

17.2.4.2 Changes to the regulation of novel foods

Efficient regulatory pathways are needed to enable the market entry of novel alternative proteins while upholding safety standards (UNEP 2023; Lanzoni et al. 2024). Integrating independent and transparent safety assessments is crucial, as similarities between novel and traditional products might not equate to identical safety or nutritional profiles (Holmes et al. 2022). Existing novel food approval frameworks may take considerable time to evaluate such products, and changes that reduce uncertainty in timeframes would support faster industry development (Good Food Institute 2022). Regulatory clarity around labelling and terminology would build consumer understanding and acceptance. This includes decisive positions on whether terms like "meat" and "milk" can be used for plant-based, fermentation-derived and cultivated products, with some evidence indicating these terms can help consumers understand the taste and use of these products (Gleckel 2020; Taylor 2020; Demartini et al. 2022). Finally, harmonizing international standards would facilitate global distribution of novel foods, helping producers create larger markets and attain economies of scale.

17.2.5 Solution pathway 5: Restructuring the food industry market structure and trade

A small number of transnational institutions dominate segments of the food system, such as agricultural commodity trading, intellectual property rights of animal and plant genetics, fertilizer production, and crop protection agrochemicals, which creates power asymmetries, and environmental and social costs (Wood et al. 2021; Sievert et al. 2024). Archer-Daniels-Midland, Bunge, Cargill and Louis Dreyfus control 70-90 per cent of the global grain trade. Bayer-Monsanto, Corteva Agriscience and Syngenta-ChemChina control around 50 per cent of the global seed market (United Nations Conference on Trade and Development [UNCTAD] 2023). The lack of institutional diversity raises potential concerns about the resilience of the food system to shocks (Davis et al. 2021; Moran 2020; Merkle et al. 2021), concerns of about excess profits (WHO 2024; IATP 2023; UNCTAD 2023) and the role of market power in unhealthy food consumption (Wood et al. 2021). Consolidation continues with dominant firms seeking leading positions in emerging digital platforms for agriculture, seed and agrichemicals, and vertically integrated supply chains. These transnational agri-food corporations are driving globalization of the food system, though the extent of an appropriate level of globalization in the food system remains contested.

Proposed solutions span the full range from returning to more local approaches (European Commission 2020) to maintaining or increasing globalization (Greenville, Kawasaki and Jouanjean 2019). Local food systems can promote biodiversity conservation, enhance soil health and water quality by supporting small-scale farmers to adopt more diverse and agroecological or traditional farming practices that preserve local crop varieties and protect ecosystems and support climate adaptation. But conversely, a globalized food system is better able to take advantage of the most efficient locations to produce foods and thereby achieve a greater overall efficiency. By specializing in the production of agricultural commodities based on their comparative advantages, countries can improve resource allocation and reduce overall environmental damage. Climate change adaption may reinforce globalization by changing the locations of areas where crops are grown (Alexander et al. 2018). Achieving self-sufficiency in all food categories within each region is often impractical, especially for countries with less suitable climates or limited arable land. Only a small proportion, between 11 and 28 per cent, of the global population could fulfil their food demands within a 100 km-radius (Kinnunen et al. 2020).

Reducing food miles can lower GHG emissions. However, transport accounts for only 4.8 per cent of food system GHG emissions, while 81 per cent comes from local to regional road transport (Crippa et al. 2021). While airfreight has the highest emissions on a per unit of mass and distance, emitting approximately 10 times more emissions for each tonne and kilometre of food transported than marine shipping, in total it contributes only 0.4 per cent of food transport emissions (Crippa et al. 2021). Local food systems are also promoted as a way to reduce the vulnerability from food supply chain disruptions originating in other locations. However, a reliance on local food is likely to increase exposure to local risks, such as crop failures, extreme weather, pests, or diseases. Additionally, prices for food commodities

produced and consumed locally are still influenced by global commodity prices (Hadachek, Ma and Sexton 2022). International trade typically enhances food system resilience to shocks, except when trade is directly impacted, such as during armed conflicts (Hamilton et al. 2020).

A balance between localized and globalized food system is likely to be most beneficial (Bajaj et al. 2025). However, current market structures often create lock-ins that hinder transformative change, with smaller actors being constrained by larger corporations, which may lobby policymakers against change. Despite these challenges, the power of these corporations could be leveraged to provide pathways for rapid transformations if aligned with consumer pressure (17.2.1.4-7), market incentives, subsidy changes (17.2.1.1-2; 17.2.3.4), and regulations (17.2.1.1; 17.2.4.1). However, socially beneficial transformations are less likely if corporate influence on policymaking goes unchecked, for example in an attempt to avoid damages to the vested interests of these corporations (Clapp 2021; WHO 2023; Wood et al. 2021). Greater transparency and accountability are required, alongside measures to foster a more equitable distribution of market power (Clapp 2021; UNCTAD 2023).

17.2.5.1 Joined-up and strengthened food system governance

Coordinated multinational policymaking is needed to regulate the transnational corporations operating in the global food system and ensure greater transparency (UNCTAD 2023). Inadequate regulation of corporate political involvement, such as lobbying, has allowed agribusinesses to partially capture of the regulatory processes in defence of their vested interests (WHO 2024). Governments need to strengthen regulations to curb corporate influence on political processes, including the need for greater regulatory coverage to prevent revolving-door practices, mandating disclosure of lobbying activities by industry associations, and requiring shareholder approval for corporate lobbying.

Incorporating environmental considerations into competition law can ensure that unsustainable practices, such as blocking collaborative sustainable initiatives, are face appropriate scrutiny, including being subject to competition law (Holmes and Meagher 2022). Governments can enhance and standardize corporate disclosure mandates, especially on environmental and social impacts. There is a need for greater global alignment, extending beyond climate reporting, to include nature-related disclosure, enabling meaningful and comparable transparency across jurisdictions.

Tariff and non-tariff barriers to international trade increase costs across the food system. While neither a localized nor a globalized food system is intrinsically more environmentally sustainable or healthier, trade in agricultural goods remains essential to the food system today. Protectionist measures, such as export bans, especially during food price shocks, often worsen price volatility (Alexander et al. 2023), and trigger retaliatory restrictions, leading to the same disruptions they were meant to avoid (Glauber and Laborde 2022).

Aligning trade policies with environmental and social objectives, using import regulations and customs duties, would promote international markets for sustainably produced goods and help uphold domestic policy targets. Adopting consumption-based accounting of emissions, rather than the current dominate approach which attributes emissions solely to producing countries, would reduce offshoring of emissions and avoid unintended consequences (Nielsen et al. 2021; Foong et al. 2022). Incorporating sustainable production and minimum food standards into bilateral or regional trade agreements can stimulate demand for healthier and more environmentally sound products. More broadly, greater governance integration is needed, aligning agriculture, health, environmental, and trade policies, supported by inclusivity measures and multi-stakeholder collaboration (Nicolini et al. 2023; UNEP, FAO, and UNDP 2023).

17.3 Combination of solutions to achieve the desired goals

This section outlines how each of the goals (Table 17.1) could be achieved through combinations of solution pathways (17.2). Combinations of pathways are essential to achieve the scale of the required transformation, while minimizing trade-offs and maximizing benefits.

17.3.1 Sustainable terrestrial and marine ecosystems

Achieving biodiversity and ecosystem goals (Table 17.1) while ensuring food security requires a multi-faceted,

holistic approach across food systems, employing a combination of solution pathways (17.2) and targeted actions. Transforming food systems through these pathways can halt biodiversity loss, prevent or reverse land degradation and improve soil health.

17.3.1.1 Halt biodiversity loss

Achieving the ambitious goals of reducing biodiversity loss to near zero in areas of high biodiversity by 2030 and cutting the extinction rates and risks tenfold by 2050 (**Table 17.1**), while ensuring food security, requires all of the solution pathways and their actions (17.2) to work in synergy. A holistic approach is essential, as different pathways and actions tackles different aspects of integrating biodiversity into the food system. Such holistic approaches will combine a multitude of approaches from production systems (17.2.2), market reforms to consumption patterns (17.2.1) creating the foundation for a sustainable food system that not only meets human needs but also conserves biodiversity and prevents mass extinctions. For example, shifting consumption patterns to sustainably sourced food (17.2.1) and improving food production efficiency (17.2.2), reduces the need for further land conversion, helping to maintain high-biodiversity areas and avoid habitat loss. Fisheries management approaches, such as modified fishing gear helps to minimize impacts on other marine species by reducing by-catch (Hilborn et al. 2023). Reducing production and consumption of animal-sourced foods and shifting to plant-based diets would lower agricultural land demand and reduce production intensity Henry et al. 2019; Harwatt et al. 2022). Protection and restoration of non-productive farmland, such as field margin, buffer strips, wetlands, peatlands, and permanent grassland, offers biodiversity and ecosystem service benefits (Pe'er et al. 2022).

Promoting sustainable healthy diets (17.2.1) through tax and subsidy reforms, combined with public awareness and education, alongside the development of novel foods (17.2.4), can steer consumer choices toward foods that balance nutritional requirements with biodiversity and environment protection (Delabre et al. 2021).

Promoting diverse foods and food cultures (17.2.1.6) helps preserve the genetic diversity of crops, livestock and fisheries cultivated for generations, supporting agroecological production systems that are closely tied to the environment and support the ecosystems underpinning agricultural productivity. For example, promoting millet in India, which is drought-resistant and requires less inputs, enhances grain diversity and reduces dependence on water- and fertilizer-intensive crops, like rice and wheat (Fischer et al. 2016). Similarly, encouraging consumption of food produced through traditional systems, such as milpa in Central America, which involves intercropping maize, beans, and squash, helps maintaining soil fertility and reduces the need for chemical inputs and sustains biodiversity (Romero-Natale, Acevedo-Sandoval and Sanchez-Porras 2024; Gonzalez Alvarez, Koohafkhan and Ahagarodsky 2023).

Strengthening the focus on Indigenous and local food systems and knowledge (17.2.3.4) can help preserve agrobiodiversity and valuable ecosystems (Kennedy et al. 2022). This knowledge and these systems have evolved over centuries to manage and produce various crops, livestock and aquatic species. Agrobiodiversity enhances food, economic and climate resilience by diversifying income sources, stabilizing food supply, and improving adaptability to climate extremes (Altieri et al. 2015; Ickowitz et al. 2019). Local and Indigenous Knowledge and food systems often align with preserving natural ecosystems and landscapes. For example, in the Amazon rainforest, Indigenous agroforestry systems incorporate diverse crops and trees that mimic the natural forest structure, supporting soil health, biodiversity and maintaining ecosystem functions (Rodriguez et al. 2021).

Establishment of marine and terrestrial protected areas (17.2.2.6) can safeguard critical ecosystems and has historically contributed to biodiversity conservation (Pe'er et al. 2022: Harwatt et al. 2022). Protected areas, like national parks, wildlife reserves, and marine sanctuaries, protect species diversity, maintain ecological processes, and buffer against land-use changes that threaten species extinction. Circularity, nutrient recycling, and food waste reductions decrease the need for resource extraction and agricultural expansion, conserving biodiversity. Shifts in societal perceptions and market reforms that encourage the consumption of sustainably farmed fish or shellfish support food security by providing a reliable source of nutrition, while also reducing

Credit: ©UNEP

overfishing and minimizing ecosystem degradation (Smith et al. 2022).

Finally, strong governance, investments and incentive mechanisms are essential for overcoming social, economic and institutional barriers to mainstream biodiversity conservation in food systems. This includes aligning food market and trade policies with zero-deforestation goals, particularly in sectors like soy, palm oil and beef (Ortiz et al. 2021). Investment in nature-based solutions, such as the sustainable farming incentives (Harwatt et al. 2022) and the EU's Farm to Fork Strategy (Pe'er et al. 2022; Harwatt et al. 2022), offer financial support for farmers who adopt biodiversity-friendly practices. In fisheries, area-based management, such as seasonal, temporal or permanent closures of specific fish species, can help address trade-offs between sustainable fishing and biodiversity conservation (Hilborn et al. 2021).

17.3.1.2 Prevent and reverse land degradation and improve soil health

Many solution pathways and actions explained above (17.2) can help prevent land degradation and improve soil health, including enhancing soil carbon sequestration. When integrated in a cohesive strategy, these solution pathways and actions can support land degradation and soil health goals (**Table 17.1**) to maintain and restore soil health by increasing soil organic carbon and microbial diversity, to achieve land degradation neutrality by 2030, restore 30 per cent of degraded land by 2030, and increase soil carbon levels by 12 per cent by 2050.

Advancing research and innovation for sustainable intensification of crop, livestock and fisheries production systems (17.2.2.1) helps generate the practices that restore degraded soils, enhance soil organic matter and improve overall soil health. For example, conservation agriculture based on the principles of no-till farming, permanent soil cover and appropriate crop rotation improves soil health, increases carbon sequestration (Sapkota et al. 2017), reduces erosion, and increases water retention (Lal 2015). Similarly regenerative production practices such as agroecology and permaculture, help restore soil health, increase biodiversity, and enhance ecosystem resilience

Indigenous communities often possess a deep understanding of their local ecosystems, which have developed over generations. Increased focus on such systems and knowledge preserves these valuable knowledge systems and promotes long-term soil conservation and stress resilience. For example, the traditional *Zai* technique, used by farmers in the Sahel region, involves digging small pits to capture

rainwater and concentrate organic matter, which enhances soil moisture and nutrient availability in otherwise arid environments (Tamagnone et al. 2020). Similarly, pastoralists in Eastern Africa use water pans and well excavation during droughts to ensure water availability for their livestock (Nkuba et al. 2019).

Adopting a systems-thinking approach enhances the interconnections between food systems, land management, and soil health, enabling the development of more holistic solutions. Nature-based solutions, including reforestation, wetland restoration, and the establishment of protected areas (17.2.2.6), can safeguard critical ecosystem services. At the same time, transitioning to circular and regenerative agriculture (17.2.3) can restore degraded soils, improve soil organic matter, and enhance carbon sequestration.

Redirecting financial support (17.2.2.2; 17.2.2.4) away from agrochemical-intensive production systems towards practices that encourage regenerative agriculture (Giller et al. 2021), crop rotation, and reduced chemical inputs can help improve soil health (Peeters et al. 2020). Healthier soil improves water retention and nutrient cycling, which are essential for ecosystem services, biodiversity, and long-term agricultural productivity (Peeters et al. 2020). Such reforms would benefit the environment and offer farmers long-term economic gains by reducing their dependency on expensive chemical inputs and improving crop resilience to climate variability.

17.3.2 Climate change mitigation

The solution pathways and actions detailed in section 17.2 support the transformation of food systems in ways that contribute directly to the climate mitigation goals (**Table 17.1**), including achieving net CO_2 neutrality, reducing CH_4 and N_2O emissions, and enabling land-based mitigation strategies. As bioenergy, afforestation, reforestation, and other land-based mitigation options compete for land with agricultural production (Muscat et al. 2020; Perkins et al. 2023), increasing productivity on existing farmland through sustainable practices, reducing waste, and shifting towards plant-based diets can reduce pressure on land and free up space for land-based mitigation solutions, turning the food system into a carbon sink (Cost Jr et al. 2022; IPCC 2019; Poore and Nemecek 2018). Studies estimate that plant-based diets alone could reduce agricultural land use by up to 76 per cent (Poore and Nemecek 2018).

Reducing the intensity of meat and dairy consumption, especially in high-income countries, and promoting plant-based diets rich in coarse grains, pulses, fruits, vegetables, nuts, and seeds can cut GHG emissions from the food system by up to 49 per cent (Poore and Nemecek 2018). These changes can be achieved through changes in food industry practices and regulations (17.2.1.2, 17.2.2.5), taxes and subsidies to reflect true environmental costs of food (17.2.1.1), producer and consumer awareness campaigns (17.2.1.4), and promotion of local and traditional food systems. The global mitigation potential of such dietary shifts is estimated to be 0.7-8.0 $GtCO_2$-e annually by 2050 (IPCC 2019).

Similarly, investing in agricultural innovation for improved crop management, optimized fertilizer and water use can reduce nitrous oxide and methane emissions. Sustainable intensification of crop, livestock and aquatic production systems through advanced research and innovation in genetic improvement and management systems (17.2.2.1) helps reach the climate change mitigation goals by increasing carbon sequestration and reducing GHG emissions (Herrero et al. 2016; Campbell et al. 2016; Carlson et al. 2017). Circular and closed-loop production systems, which recycle resources and reduce reliance on external inputs, such as synthetic fertilizers and energy-intensive production processes, further lower GHG emissions. Similarly, promoting local food systems can reduce long-haul transportation and refrigeration emissions.

Reforming finance and policy mechanisms is essential to transforming food systems toward low-emission pathways and achieving climate goals. Shifting agricultural subsidies (17.2.2.4) away from input-intensive practices, such as fertilizer subsidies in high-intensity production systems, toward sustainable practices, and strengthening Indigenous systems (17.2.2.6), can foster more carbon-efficient farming, reducing agricultural emissions. Financial mechanisms, like payments for ecosystem services, low-interest loans, green and blended finance, and carbon credits, can accelerate the adoption of clean technologies, including precision agriculture, renewable energy, and low-emission innovative mechanization. Similarly, flexible, scalable, and accessible financing mechanisms, such as Pay-As-You-Go and pay-for-service models, help

overcome upfront cost, enabling greater adoption of sustainable practices in low-income regions. The application of these financial mechanisms in food systems is still limited, but they have the potential to grow (Wattel et al. 2024).

Policy reforms and incentives, such as subsidies for sustainably sourced products and taxes on carbon-intensive goods, can drive market transformation, supporting climate mitigation.

Finally, tackling food loss and waste—which contribute 8–10 per cent of total anthropogenic GHG emissions (IPCC 2019)—can reduce emissions and improve food security. This can be achieved by improving harvesting and storage, raising awareness, and promoting behavioural change to support greater circularity (17.2.3).

17.3.3 Human health and wellbeing

The lack of progress on eliminating global hunger (SDG2) and malnutrition (7.2.2, 17.1), can only be addressed by making healthy and environmentally sustainable food accessible and affordable for all. Currently, largely affordable and accessible around the world are too often ultra-processed foods. These foods are high in sugar, salt, unhealthy fats, industrial additives, and preservatives, contributing to poor health, including obesity (Valicente et al. 2023; Askari et al. 2020). Poor global nutritional outcomes have multiple causes and exacerbating factors, including climate change and conflict (FAO 2023a). However, the key challenge lies in misaligned incentives for food system actors to deliver healthy, safe and diverse, accessible and affordable diets for all (Herforth et al. 2021; Wood et al. 2021).

Lower food prices can appear to be a solution to malnutrition, but evidence from the past 60 years suggests otherwise. Despite food productivity outpacing population growth, with 34 per cent more cereal per person in 2022 than in 1961 (FAO 2024) and decreasing real terms food prices, the rate of undernutrition remains high and is now coupled with a rapid rise in obesity. Increasing food production and declining prices have led to unhealthy overconsumption and environmental degradation, a form of Jevons Paradox (Alcott 2005). A continued focus on lowering food prices through increased productivity is likely to see these damaging trends persist (Hendriks et al. 2023).

Consumer practices and food production changes are required, leveraging all five solution pathways. Agriculture and fishery policies and research must shift from being focused on increasing the yield and providing consumers with low nutrient density calories to being focused on providing nutritious and more sustainable foods (solution pathway 2). This includes diversifying food production and minimizing environmental harm from agricultural expansion and input-intensive production (17.2.2).

Consumption preferences need to shift away from diets high in meat and processed foods, using a mix of education, market reforms and pricing policies (17.3.1). Reducing demand for environmentally intensive food will also require cutting food system losses and waste, including lowering losses across the supply chain, and achieving greater nutrient circularity (17.2.3). Alternative proteins, novel plant-based foods, cultivated meat, and fermentation-derived products may also play a role in addressing the high demand for ASFs (Sexton et al. 2019) (17.2.4). The food industry will play a principal role in facilitating healthier consumption patterns, calling for realignment of industry incentives (17.3.4) and voluntary industry actions (17.3.5).

Food prices that reflect health and environmental costs and benefits will be central to achieving the transformation. Reforming agricultural taxes and subsidies to prioritize public good and discourage the production of environmentally damaging foods is necessary (17.2.2.4). This alone is unlikely to be sufficient. Therefore, consumer taxes and subsidies on foods are needed to reflect their true food costs (17.2.1.1). Such changes would make many foods, and especially animal-sourced foods, more expensive. Stronger social protection and security nets, including welfare payments or other supports for the poorest, will be essential to avoid damaging vulnerable households and ensuring that their nutritional needs are met. In combination, these reforms could be pro-poor and reduce inequalities. Ultimately, to make healthy food affordable for all, we need to address poverty, rather than making the current, often unhealthy food, cheaper.

17.3.4 Equitable livelihoods

Equitable livelihood goals (**Table 17.1**) require fair treatment of workers across the food systems,

improved social justice, recognition of Indigenous rights and knowledge, as well as local knowledge, and support for diverse food cultures. Good working conditions, dignity and fair wages for food system workers contribute to productivity and safety at the farm and industry level (Ramos et al. 2021). Empowering communities to produce their food can be beneficial. In addition, farmer organizations should amplify the community's voices on various platforms to eliminate social injustices and promote inclusion. Social security, higher wages, healthy living, safety nets and gender equality are all critical to ensure equitable livelihoods and food system transformation (Reynolds et al. 2016).

Sustainability and justice in food systems are also reinforced by the realization of human rights (e.g., the right to a clean, healthy and sustainable environment, UNGA A/RES/76/300), Indigenous rights (e.g., the collective rights to lands, territories and resources, UNDRIP), the rights of peasants and rural workers (e.g., the right to determine their food and agriculture systems, and to participate in decision-making processes on food and agriculture policy, UNDROP).

Sustainable and just food systems also require supporting local food production and consumption, integrating lived experiences to inform food production, and recognizing consumer-led local food initiatives. Indigenous Knowledge forecasts enhance the adaptive capacity of arable farmers (Nkuba et al. 2020) and pastoralists (Nkuba et al. 2019). Investing in education and work opportunities in rural communities, many of which suffer from youth outmigration, can encourage younger farmers to stay in these regions, thus preserving generational knowledge and traditions.

Local and diverse foods can offer healthy, affordable and nutrient-dense options, while promoting more sustainable and lower-impact harvest and production methods (including fisheries and aquaculture) that are rooted in traditional, Indigenous, or small-scale practices, would help to reduce negative environmental impacts while also supporting socioeconomic objectives (17.2.2). These can methods create jobs, enhance the interconnections and knowledge exchange among local food producers, improving sustainability outcomes (Ajayi et al. 2021; Soma et al. 202). However, local food systems often face limited market access, inadequate social capital, unfavourable government policies, restricted funding, and minimal access to appropriate technology. Government support, prioritization of local foods as part of an adaptation strategy and strengthening of farmer networks can help address these challenges (Carter 2022).

Restructuring the global food system requires actors to adopt innovative tools, embrace sustainable practices, organize sustainable supply chains, revamp marketing, and create shared value along the food value chain. Collaboration between the public and private sectors is crucial for promoting agroecological practices, sustainable procurement, and the empowerment of local food producers (Stahlbrand 2017). Education can help spread best practices, raise awareness on causes and impacts of inequalities, share success stories, and identify future areas for development, while farmers' narratives can inform decision-making (Breen and Muller 2020).

17.3.5 Resilient to shocks and stresses

A resilient food system can withstand and recover from disruptions, while maintaining functionality and providing sustainable and equitable access to nutritious food (de Steenhuijsen et al. 2021; Zurek 2022) (**Table 17.1**). This is one of the food system goals. Disease outbreaks (including the COVID-19 pandemic (Moran et al. 2020), climate changes, weather extremes, and geopolitical events have affected the food system, and will likely do so more severely in the future (Hamilton et al. 2020; Jones 2023). These disruptions range from sudden shocks to gradual long-term stressors, like pollution and climate change. Progress towards the Sustainable Development Goals has been slowed, if not reversed, by recent events such as the global financial crisis in 2008-2009, 2011-2012, the Covid-19 pandemic, and Russia's invasion of Ukraine (FAO et al. 2024; UNDESA 2023).

When food system operations are disrupted, whether through damage to agricultural production or constraints on international trade, food prices rise, leading to disproportionate harms for the poorest, including increased malnutrition and associated mortality (Alexander et al. 2023). This highlights the need to provide social safety nets that ensure sufficient income for a healthy diet (Fan 2021) (17.2.1.1). To

increase food system resilience a level of supply chain redundancy and elimination of single sources of failure across the supply chain is needed. Local or national self-sufficiency does not necessarily increase resilience and still exposes consumers to global market price shocks. So, maintaining a combination of domestic production with open access to international markets is likely be beneficial (17.2.4.1). Diversity in food industry structure and supply sources enhances food system resilience (17.2.5). This includes avoiding harmful policy responses, such as export bans and restrictions in response to trade shocks or price fluctuations (Fan 2021).

Resilience in the food system can only be achieved with climate-resilient production, capable of withstanding weather extremes, pests and diseases (FAO 2021). While adaptation of agriculture to future climate and weather extremes is essential, climate-smart agriculture and fisheries approaches (African Union Development Agency 2021), should go hand-in-hand with agroecological approaches that build resilience (17.2.2). While some events are likely to reduce productivity for some crops and locations, the risks to the food system more widely can be mitigated by having a diverse system, at all levels (Nicholson et al. 2021; Eisenhauer 2023). Diversity in production includes increasing the diversity of species, crop varieties and animal breeds. Current trends are moving in the opposite direction, with a homogenization in crop varieties and animal breeds (Khoury 2014; McCouch 2023; Gruber 2017). Actions are needed to increase the diversity of food produced, including expanding the use of orphan or opportunity crops and Indigenous or locally adapted species (Renard and Tilman 2019; Talabi 2022; Zuza et al. 2024) (17.2.1.6).

17.4 Implications of the solution pathways on the other systems

There are strong interconnections between energy (Chapter 16), environmental (Chapter 18) and food systems due to shared demand for land and other resources (IPCC 2022b). Land use is key to the energy transition and climate change mitigation, with large areas being projected for carbon dioxide removal using bioenergy with carbon capture and storage in many scenarios (Chapter 16) (Perkinset al. 2023). At the same time, transformations in the food system place additional demands on the energy system. For example, large-scale adoption of some novel foods or novel production processes, including cultured meat, will likely require cheap, low-carbon energy for net positive environmental outcomes (UNEP 2023). Land protection and use for biodiversity conservation is also increasing, with targets for 30 per cent of land to be protected by 2030 (Convention on Biological Diversity 2022) and support for the Half-Earth Project, advocating for 50 per cent of the planet being protected for nature (Chapter 18), with implication for the food system (Henry et al. 2022).

Competition for water is also intensifying, increasing linkages between energy, environment and food systems (Chapters 6, 10, 11). Climate change is reducing water availability while increasing demand for agricultural use. Irrigation is an effective adaptation approach in agriculture and can be used to increase productivity (IPCC 2022a). Additionally, water demands continue to increase for industrial use and as populations grow and urbanize (Chapter 2). Resulting unsustainable water extraction and pollution leads to biodiversity loss and impaired freshwater and marine ecosystems functioning. The food system is central to solving these issues, with 70 per cent of water withdrawals used for agriculture today as well as fertilizers and animal waste being a key source of nutrient runoff, leading to eutrophication. However, agricultural adaptation and the transformation of the food system are also heavily constrained by sustainable water availability. Coordinated actions and adoption of technologies that improve irrigation and water use efficiency are needed to reducepollution of aquatic ecosystems and help preserve water stocks (17.2.2).

Agrochemicals production and use add further cross-system interactions. For example, fertilizer production heavily relies on fossil fuels, with over 100 million ton of inorganic nitrogen fertilizers produced annually. While some reductions in total fertilizer use may be possible through the solution pathways described here, providing sufficient food will still require inorganic fertilizers. Therefore, green ammonia and other renewable and low-carbon fertilizers will be required, increasing demands for renewable energy (Ch16). Phosphate fertilizers production also relies on fossil fuel derivatives, like sulphur (Day, Alexander and Maslin 2024). Both potassium for potash and phosphate fertilizer

production cause substantial environmental damage (Chapter 18).

Changes in the economic system (Chapter 14) and materials/waste (Chapter 15) are critical to achieving the transformation of the food system. Internalizing externalities (14.3.1) to achieve prices that reflect the true cost across the economy is vital, and this applies strongly to the food system, where both environmental and health outcomes from foods should be reflected in their pricing (17.3.1.1). Reforming subsidies and financial mechanisms is also essential to enable the transformation (14.3.2; 17.2.2.4). Similarly, the transformation must reduce losses and increase circularity at all stages of the food system, from production, transport, processing, retail and at the consumer (15.2.1; 15.2.4; 17.3.3).

The need for cross-system coordination between food and other systems, particularly the energy system, is made clear by the results of the modelled transformation pathways (Chapter 11). Achieving climate mitigation targets in these scenarios heavily relies on bioenergy, with energy crop production projected to be 3-5 times larger than in the current trend scenario. In these scenarios, energy crops account for 15 per cent of crop production in the Technology-focused Transformation pathway and 22 per cent in the Behaviour-focused Transformation pathway. Expansion of forests and other natural areas, for enhanced ecosystem functioning and to support biodiversity, further intensifies competition for land. On the current trends pathway, this area contracts, while it expands substantially by 2050 in both modelled transformation pathways – with an additional area of 670 million hectares in the Technology-focused Transformation pathway and 380 million hectares in the Behaviour-focused Transformation pathway.

Dietary change plays a key role in both the Behaviour-focused and Technology-focused Transformation pathways (Chapter 11). In the Behaviour-focused Transformation pathway, global per capita demand for ASFs drops by 44 per cent by 2050 due to shifts in preference (17.2.1), but even in the Technology-focused Transformation pathway, ASF consumption drops by 17 per cent due to pricing of externalities (17.2.2) and substitution with alternative proteins (17.2.4).

In both transformation pathways, agricultural yields increase, 41 per cent in the Behavioural-focused Transformation pathway and 46 per cent in the Technology-focused Transformation pathway, from 2020 to 2050 (17.2.2). This is accompanied by production methods using fewer inputs, lowering environmental harms. For example, by 2050 water withdrawal for irrigation drops by 20 per cent and 11 per cent, respectively, compared to the reference scenario. Additionally, food loss and waste are also substantially reduced, with 28 per cent and 32 per cent reductions in food waste rates, respectively, in these scenarios (17.2.3). These modelled scenarios underscore the need to transform food production and consumption and the need for cross-system changes.

Many policy requirements are seen as politically challenging. Measures like meat taxes and the true cost of food often face public resistance. While environmental awareness is rising, social acceptance is emerging too slowly relative to the urgency of the environmental crisis. Food is a sensitive subject, deeply embedded in culture, and there is a risk of backlash and resistance from citizens.

Chapters 12, 13 and 21 discuss addressing the interacting transformation challenges. In the specific context of the food system, education, awareness raising, and collective actions need to increase acceptance and demand for changes in governance of the food system, as well as to directly impact the food system through individual actions related to foods consumed. Implementing these solutions on a scale sufficient to address the issues and constraints faced by food systems is challenging. To move towards large-scale food system transformation, a high level of political commitment and tailored solutions adapted to specific regional needs and local socio-economic realities.

A successful transformation across energy, environmental and food systems require a coordinated and integrated approach. Part of this will be minimizing the land use of the food system, to allow enough space for ecosystem functioning, biodiversity conservation, and climate mitigation. This will require strategic implementation of the solution pathways and actions described in this chapter.

References

Acheampong, A.O. and Osei Opuko, E.E. (2023). Environmental degradation and economic growth: investigating linkages and potential pathways. Energy Economics 123. 106734. https://doi.org/10.1016/j.eneco.2023.106734

African Union Development Agency (2021). African common position on food systems.

Afshin, A., Sur, P.J., Fay, K.A., Cornaby, L., Ferrara, G., Salama, J.S. et al. (2019). Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. The Lancet 393(10184), 1958-1972. https://doi.org/10.1016/S0140-6736(19)30041-8

Aguilera, G., Roslin, T., Miller, K., Tamburini, G., Birkhofer, K., Caballero-Lopez, B. et al. (2020). Crop diversity benefits carabid and pollinator communities in landscapes with semi-natural habitats. Journal of Applied Ecology 57(11), 2170-2179. https://doi.org/10.1111/1365-2664.13712

Ahmed, H.S., Yahya, Z., Ali khan, W. and Faraz, A. (2024). Sustainable pathways to ammonia: a comprehensive review of green production approaches. Clean Energy 8(2), 60-72. https://doi.org/10.1093/ce/zkae002

Ajayi, A.I., Mudefi, E. and Owolabi, E.O. (2021). Prevalence and correlates of sexual violence among adolescent girls and young women: findings from a cross-sectional study in a South African university. BMC Women's Health 21(1), 299. https://doi.org/10.1186/s12905-021-01445-8

Akinola, R., Pereira, L.M., Mabhaudhi, T., de Bruin, F.-M. and Rusch, L. (2020). A Review of Indigenous Food Crops in Africa and the Implications for more Sustainable and Healthy Food Systems. Sustainability, 8. https://doi.org/10.3390/su12083493

Akinsete, E., Vassilopoulos, A., Secco, L., Pisani, E., Nijnik, M., Marini-Govigli, V. et al. (2022). Social innovation for developing sustainable solutions in a fisheries sector. Environmental Policy and Governance 32(6), 504-519. https://doi.org/10.1002/eet.2022

Akpoviri, F.I., Baharum, S.N. and Zainol, Z.A. (2023). Digital Sequence Information and the Access and Benefit-Sharing Obligation of the Convention on Biological Diversity. NanoEthics 17(1), 1. https://doi.org/10.1007/s11569-023-00436-3

Alcott, B. (2005). Jevons' paradox. Ecological Economics 54(1), 9-21. https://doi.org/10.1016/j.ecolecon.2005.03.020

Alejandro González Álvarez, P.K., Tomás Shagarodsky (2023). The conuco in Cuban agricultural systems and its contribution to agrobiodiversity. https://www.taylorfrancis.com/chapters/edit/10.4324/9781315183886-13/conuco-cuban-agricultural-systems-contribution-agrobiodiversity-alejandro-gonz%C3%A1lez-%C3%A1lvarez-parviz-koohafkhan-tom%C3%A1s-shagarodsky

Alexander, P., Arneth, A., Henry, R., Maire, J., Rabin, S. and Rounsevell, M.D.A. (2023). High energy and fertilizer prices are more damaging than food export curtailment from Ukraine and Russia for food prices, health and the environment. Nature Food 4(1), 84-95. https://doi.org/10.1038/s43016-022-00659-9

Alexander, P., Brown, C., Arneth, A., Dias, C., Finnigan, J., Moran, D. et al. (2017). Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? Global Food Security 15, 22-32. https://doi.org/10.1016/j.gfs.2017.04.001

Alexander, P., Brown, C., Arneth, A., Finnigan, J., Moran, D. and Rounsevell, M.D.A. (2017). Losses, inefficiencies and waste in the global food system. Agricultural Systems 153, 190-200. https://doi.org/10.1016/j.agsy.2017.01.014

Alexander, P. and Moran, D. (2017). Rethinking food waste for a healthier planet. The Lancet Planetary Health 1(5), e170-e171. https://doi.org/10.1016/S2542-5196(17)30077-3

Alexander, P., Rabin, S., Anthoni, P., Henry, R., Pugh, T.A.M., Rounsevell, M.D.A. et al. (2018). Adaptation of global land use and management intensity to changes in climate and atmospheric carbon dioxide. Global Change Biology 24(7), 2791-2809. https://doi.org/10.1111/gcb.14110

Alexander, P., Reddy, A., Brown, C., Henry, R.C. and Rounsevell, M.D.A. (2019). Transforming agricultural land use through marginal gains in the food system. Global Environmental Change 57, 101932. https://doi.org/10.1016/j.gloenvcha.2019.101932

Allen, L.H. and Dror, D.K. 67 (2011). Effects of Animal Source Foods, with Emphasis on Milk, in the Diet of Children in Low-Income Countries Milk and Milk Products in Human Nutrition. 67th Nestlé Nutrition Institute Workshop, Pediatric Program, Marrakech, March 2010. S.Karger AG, 0 https://doi.org/10.1159/000325579. Accessed on 22 October 2024

Alleway, H.K., Waters, T.J., Brummett, R., Cai, J., Cao, L., Cayten, M.R. et al. (2023). Global principles for restorative aquaculture to foster aquaculture practices that benefit the environment. Conservation Science and Practice 5(8), e12982. https://doi.org/10.1111/csp2.12982

Altieri, M.A., Nicholls, C.I., Henao, A. and Lana, M.A. (2015). Agroecology and the design of climate change-resilient farming systems. Agronomy for Sustainable Development 35(3), 869-890. https://doi.org/10.1007/s13593-015-0285-2

Amaglobeli, D., Gu, M., Hanedar, E., Hong, G.H. and Thevenot, C. (2023). Policy Responses to High Energy and Food Prices. IMF Working Papers 2023(074), A001. https://www.imf.org/en/Publications/WP/Issues/2023/03/24/Policy-Responses-to-High-Energy-and-Food-Prices-531343

Amjad, W., Munir, A., Akram, F., Parmar, A., Precoppe, M., Asghar, F. et al. (2023). Decentralized solar-powered cooling systems for fresh fruit and vegetables to reduce post-harvest losses in developing regions: a review. Clean Energy 7(3), https://doi.org/10.1093/ce/zkad015

Andreyeva, T., Marple, K., Marinello, S., Moore, T.E. and Powell, L.M. (2022). Outcomes Following Taxation of Sugar-Sweetened Beverages: A Systematic Review and Meta-analysis. JAMA Network Open 5(6), e2215276-e2215276. https://doi.org/10.1001/jamanetworkopen.2022.15276

Aniah, P. and Yelfaanibe, A. (2016). Learning from the past: the role of sacred groves and shrines in environmental management in the Bongo District of Ghana. Environmental Earth Sciences 75(10), 916. https://doi.org/10.1007/s12665-016-5706-2

Araus, J.L. and Cairns, J.E. (2014). Field high-throughput phenotyping: the new crop breeding frontier. Trends in Plant Science 19(1), 52-61. https://doi.org/10.1016/j.tplants.2013.09.008

Arrazat, L., Chambaron, S., Arvisenet, G., Goisbault, I., Charrier, J.C., Nicklaus, S. et al. (2023). Traffic-light front-of-pack environmental labelling across food categories triggers more environmentally friendly food choices: a randomised controlled trial in virtual reality supermarket. Int J Behav Nutr Phys Act 20(1), 7. https://doi.org/10.1186/s12966-023-01410-8

Aryal, J.P., Sapkota, T.B., Jat, M.L. and Bishnoi, D.K. (2015). On-farm economic and environmental impact of zero-tillage wheat: A case of North-West India. Experimental Agriculture 51(1), 1-16. https://doi.org/10.1017/S001447971400012X

Askari, M., Heshmati, J., Shahinfar, H., Tripathi, N. and Daneshzad, E. (2020). Ultra-processed food and the risk of overweight and obesity: a systematic review and meta-analysis of observational studies. International Journal of Obesity 44(10), 2080-2091. https://doi.org/10.1038/s41366-020-00650-z

Avana-Tientcheu, M.L., & Tiambo, C. K. (2020). Breeding and Productivity in Ending Hunger and Achieving Food Security and Nutrition. https://doi.org/10.1007/978-3-319-69626-3_59-1

Avikal, S., Pant, R., Barthwal, A., Ram, M. and Upadhyay, R.K. (2023). Factors implementing sustainable circular economy in agro-produce supply chain:

DEMATEL-DANP-based approach. Management of Environmental Quality: An International Journal 34(4), 1158-1173. https://www.emerald.com/insight/content/doi/10.1108/meq-03-2022-0088/full/html

Bagnall, D.K., Shanahan, J.F., Flanders, A., Morgan, C.L.S. and Honeycutt, C.W. (2021). Soil health considerations for global food security. Agronomy Journal 113(6), 4581-4589. https://doi.org/10.1002/agj2.20783.

Bailey, R., Harper, David (2015). Reviewing interventions for healthy and sustainable diets. Chatham House. https://www.chathamhouse.org/sites/default/files/field/field_document/20150529HealthySustainableDietsBaileyHarperFinal.pdf

Bajaj, K., Mehrabi, Z., Kastner, T., Jägermeyr, J., Müller, C., Schwarzmüller, F. et al. (2025). Current food trade helps mitigate future climate change impacts in lower-income nations. PLoS One 20(1), e0314722. https://doi.org/10.1371/journal.pone.0314722

Baker, P., Machado, P., Santos, T., Sievert, K., Backholer, K., Hadjikakou, M. et al. (2020). Ultra-processed foods and the nutrition transition: Global, regional and national trends, food systems transformations and political economy drivers. Obesity Reviews 21(12), e13126. https://doi.org/10.1111/obr.13126

Balinga, S. (2005). Comparative uses of wildlife in west and Central Africa. Unasylva 32(120), 24-27

Balińska, A., Werenowska, A. and Jaska, E. (2024). The importance of mobile applications in reducing food waste - the example of the TooGoodToGo application. Journal of Modern Science 56(2), 190-214. https://doi.org/10.13166/jms/188723

Barling, K.P.a.D. (2021). Food systems transformation: What's in the policy toolbox? University of Hertfordshire. https://ukfoodsystems.ukri.org/food-systems-transformation-whats-in-the-policy-toolbox/

Bart de Steenhuijsen Piters, E.T., Deborah Bakker, Hubert Fonteijn and Herman Brouwer, (2021). Food system resilience Towards a joint understanding and implications for policy. https://edepot.wur.nl/549244

Bauer, J.M., Aarestrup, S.C., Hansen, P.G. and Reisch, L.A. (2022). Nudging more sustainable grocery purchases: Behavioural innovations in a supermarket setting. Technological Forecasting and Social Change 179, 121605. https://doi.org/10.1016/j.techfore.2022.121605

Beal, T., Gardner, C.D., Herrero, M., Iannotti, L.L., Merbold, L., Nordhagen, S. et al. (2023). Friend or Foe? The Role of Animal-Source Foods in Healthy and Environmentally Sustainable Diets. The Journal of Nutrition 153(2), 409-425. https://doi.org/10.1016/j.tjnut.2022.10.016

Bechir, S., Lachi, Oualid, Taouzinet, Lamia, Messaoudene, Lynda, Allam, Ayoub, Madani, Khodir (2023). Exploring the environmental economic impact of Fruits and vegetable loss quantification in the food industry. Environmental Science and Pollution Research. http://dx.doi.org/10.1007/s11356-023-31311-z

Beck, D., Peters, R., Poitier, F., Pearson, B. and Bridge, G. (2023). Could a Universal Basic Income reduce food insecurity and assist with the transition to a sustainable food system? http://dx.doi.org/10.13140/RG.2.2.29393.10081

Beckensteiner, J., Boschetti, F. and Thébaud, O. (2023). Adaptive fisheries responses may lead to climate maladaptation in the absence of access regulations. npj Ocean Sustainability 2(1), 3. https://doi.org/10.1038/s44183-023-00010-0

Bello-Bravo, J., Namatsi Lutomia, Anne, Abbott, Eric,Mazur, Robert, Mocumbe, Sostino, R. Pittendrigh, Barry (2017). Making Agricultural Learning Accessible: Examining Gender in the Use of Animations via Mobile Phones. Empowering Learners With Mobile Open-Access Learning Initiatives, 47-73. https://www.igi-global.com/gateway/chapter/174895

Bello-Bravo, J., Medendorp, J., Lutomia, A.N., Peter Reeves, N., Sal y Rosas Celi, V.G., Tamò, M. et al. (2022). Dramatically increased accessibility and decreased cost-per-person impacts are needed for scaling IPM in Africa. Current Opinion in Insect Science 54, 100971. https://doi.org/10.1016/j.cois.2022.100971

Bezner Kerr, R., Madsen, S., Stüber, M., Liebert, J., Enloe, S., Borghino, N. et al. (2021). Can agroecology improve food security and nutrition? A review. Global Food Security 29, 100540. https://doi.org/10.1016/j.gfs.2021.100540

Birch, I. (2018). Agricultural productivity in Kenya: barriers and opportunities. https://assets.publishing.service.gov.uk/media/5c70028ee5274a0ecbe9a1c2/483_Agricultural_Productivity_in_Kenya_Barriers_and_Opportunities.pdf

Boyd, C.E., D'Abramo, L.R., Glencross, B.D., Huyben, D.C., Juarez, L.M., Lockwood, G.S. et al. (2020). Achieving sustainable aquaculture: Historical and current perspectives and future needs and challenges. Journal of the World Aquaculture Society 51(3), 578-633. https://doi.org/10.1111/jwas.12714

Bradford, K.J., Dahal, P., Van Asbrouck, J., Kunusoth, K., Bello, P., Thompson, J. et al. (2018). The dry chain: Reducing postharvest losses and improving food safety in humid climates. Trends in Food Science & Technology 71, 84-93. https://doi.org/10.1016/j.tifs.2017.11.002

Breen and Muller (2020). Education and Intergenerational Social Mobility in Europe and the United States. Müller, R.B.a.W. (ed.). http://ora.ox.ac.uk/objects/uuid:414c8e81-df3c-4fe0-b7b0-a57fded9535b/files/mead82164e70898b3a1e0163828841040

Bridge, G., Lomazzi, M. and Bedi, R. (2020). Implementation of a sugar-sweetened beverage tax in low- and middle-income countries: recommendations for policymakers. J Public Health Policy 41(1), 84-97. https://doi.org/10.1057/s41271-019-00196-z

Brownlie, W.J., Alexander, P., Maslin, M., Cañedo-Argüelles, M., Sutton, M.A. and Spears, B.M. (2024). Global food security threatened by potassium neglect. Nature Food 5(2), 111-115. https://doi.org/10.1038/s43016-024-00929-8

Bryant, C., Szejda, K., Parekh, N., Deshpande, V. and Tse, B. (2019). A Survey of Consumer Perceptions of Plant-Based and Clean Meat in the USA, India, and China. Frontiers in Sustainable Food Systems 3. https://doi.org/10.3389/fsufs.2019.00011

Bucher, T., Collins, C., Rollo, M., McCaffrey, T., Vlieger, N., Bend, D. et al. (2016). Nudging consumers towards healthier choices: A systematic review of positional influences on food choice. British Journal of Nutrition -1, 1-12. https://doi.org/10.1017/s0007114516001653

Bui, L.P., Pham, T.T., Wang, F., Chai, B., Sun, Q., Hu, F.B. et al. (2024). Planetary Health Diet Index and risk of total and cause-specific mortality in three prospective cohorts. The American Journal of Clinical Nutrition 120(1), 80-91. https://doi.org/10.1016/j.ajcnut.2024.03.019

Buta, M., Hubeny, J., Zieliński, W., Harnisz, M. and Korzeniewska, E. (2021). Sewage sludge in agriculture – the effects of selected chemical pollutants and emerging genetic resistance determinants on the quality of soil and crops – a review. Ecotoxicology and Environmental Safety 214, 112070. https://doi.org/10.1016/j.ecoenv.2021.112070

C, K.R., Jamir, M., Theunuo, S., T, B., Verma, H. and Chandora, R. (2024). On the Road to a Sustainable and Climate-Smart Future: Recent Advancements in Genetics and Genomics of Pulse Crops in the Hills BT. In Genetics and Genomics of High-Altitude Crops. Gahlaut, V. and Jaiswal, V. (eds.). Singapore: Springer Nature Singapore. 1-45. https://doi.org/10.1007/978-981-99-9175-4_1

C., P.D.S.A.Z. (2024). Beyond social agriculture: rehabilitation and sustainable practices in penitentiary contexts. https://www.iris.unict.it/handle/20.500.11769/646031

Campbell, B.M., Vermeulen, S.J., Aggarwal, P.K., Corner-Dolloff, C., Girvetz, E., Loboguerrero, A.M. et al. (2016). Reducing risks to food security from climate change. Global Food Security 11, 34-43. https://doi.org/10.1016/j.gfs.2016.06.002

Capponi, S. and Daniels, K.G. (2023). Harnessing the power of artificial intelligence to advance cell therapy. Immunological Reviews 320(1), 147-165. https://doi.org/10.1111/imr.13236

Carlson, K.M., Gerber, J.S., Mueller, N.D., Herrero, M., MacDonald, G.K., Brauman, K.A. et al. (2017). Greenhouse gas emissions intensity of global croplands. Nature Climate Change 7(1), 63-68. 10.1038/nclimate3158. https://doi.org/10.1038/nclimate3158

Carter, J. and Hollinsworth, D. (2022). Governing extension and extending governance for Pacific organic farming. Geographical Research 60(3), 498-510. https://doi.org/10.1111/1745-5871.12542

Cassman, K.G. and Grassini, P. (2020). A global perspective on sustainable intensification research. Nature Sustainability 3(4), 262-268. 10.1038/s41893-020-0507-8. https://doi.org/10.1038/s41893-020-0507-8

Cellura, M., Cusenza, M.A., Longo, S., Luu, L.Q. and Skurk, T. (2022). Life Cycle Environmental Impacts and Health Effects of Protein-Rich Food as Meat Alternatives: A Review. Sustainability, 2. https://doi.org/10.3390/su14020979

Chaudhary, S. and Singh, B. (2024). Pineapple by-products utilization: Progress towards the circular economy. Food and Humanity 2, 100243. https://doi.org/10.1016/j.foohum.2024.100243

Chen, L., Guttieres, D., Koenigsberg, A., Barone, P.W., Sinskey, A.J. and Springs, S.L. (2022). Large-scale cultured meat production: Trends, challenges and promising biomanufacturing technologies. Biomaterials 280, 121274. https://doi.org/10.1016/j.biomaterials.2021.121274

Chivenge, P., Mabhaudhi, T., Modi, A.T. and Mafongoya, P. (2015). The Potential Role of Neglected and Underutilised Crop Species as Future Crops under Water Scarce Conditions in Sub-Saharan Africa. International Journal of Environmental Research and Public Health, 6. https://doi.org/10.1038/s41893-020-0507-8

Clapp, J. (2021). The problem with growing corporate concentration and power in the global food system. Nature Food 2(6), 404-408. 10. https://doi.org/10.1038/s43016-021-00297-7

Clay, N. and Yurco, K. (2020). Political ecology of milk: Contested futures of a lively food. Geography Compass 14(8), e12497. https://doi.org/10.1111/gec3.12497

Cofie, O. and Amede, T. (2015). Water management for sustainable agricultural intensification and smallholder resilience in sub-Saharan Africa. Water Resources and Rural Development 6, 3-11. https://doi.org/10.1016/j.wrr.2015.10.001

Çoker, E.N., Pechey, R., Frie, K., Jebb, S.A., Stewart, C., Higgs, S. et al. (2022). A dynamic social norm messaging intervention to reduce meat consumption: A randomized cross-over trial in retail store restaurants. Appetite 169, 105824. https://doi.org/10.1016/j.appet.2021.105824

Convention on Biological Diversity (2022). Kunming-Montreal Global Biodiversity Framework. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf

Costa, C., Wollenberg, E., Benitez, M., Newman, R., Gardner, N. and Bellone, F. (2022). Roadmap for achieving net-zero emissions in global food systems by 2050. Scientific Reports 12(1), 15064. https://doi.org/10.1038/s41598-022-18601-1

Costello, C., Cao, L., Gelcich, S., Cisneros-Mata, M.Á., Free, C.M., Froehlich, H.E. et al. (2020). The future of food from the sea. Nature 588(7836), 95-100. https://doi.org/10.1038/s41586-020-2616-y

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N. and Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food 2(3), 198-209. https://doi.org/10.1038/s43016-021-00225-9

Global Network Against Food Crises (2024). 2024 Global Report on Food Crises – Joint analysis for better decisions. https://www.fsinplatform.org/report/global-report-food-crises-2024/

Davis, A.G., Huggins, D.R. and Reganold, J.P. (2023). Linking soil health and ecological resilience to achieve agricultural sustainability. Frontiers in Ecology and the Environment 21(3), 131-139. https://doi.org/10.1002/fee.2594

Davis, J.N., Spaniol, M.R. and Somerset, S. (2015). Sustenance and sustainability: maximizing the impact of school gardens on health outcomes. Public Health Nutrition 18(13), 2358-2367. https://doi.org/10.1017/s1368980015000221

Davis, K., Gammmelgaard, J., Preissing, J., Gilbert, R. and Ngwenya, H. (2022). Investing in Farmers: Agriculture Human Capital Investment Strategie. Rome: FAO and IFPRI. https://openknowledge.fao.org/items/c696769f-b37b-4ce8-a669-da2b7450db69

Davis, K.F., Downs, S. and Gephart, J.A. (2021). Towards food supply chain resilience to environmental shocks. Nature Food 2(1), 54-65. https://doi.org/10.1038/s43016-020-00196-3

Day, S., Alexander, P. and Maslin, M. (2023). Energy decarbonization threatens food security by reducing the availability of cheap sulfur. Nature Food 4(6), 442-444. 10. https://doi.org/10.1038/s43016-023-00782-1

De Clercq, M., Vats, Anshu, Biel, Alvaro (2018). Agriculture 4.0: The future of farming technology. World Government Summit. https://www.bollettinoadapt.it/wp-content/uploads/2019/12/OliverWyman-Report_English-LOW.pdf

De Temmerman, J., Heeremans, E., Slabbinck, H. and Vermeir, I. (2021). The impact of the Nutri-Score nutrition label on perceived healthiness and purchase intentions. Appetite 157, 104995. https://doi.org/10.1016/j.appet.2020.104995

Delabre, I., Rodriguez, L.O., Smallwood, J.M., Scharlemann, J.P.W., Alcamo, J., Antonarakis, A.S. et al. (2021). Actions on sustainable food production and consumption for the post-2020 global biodiversity framework. Sci Adv 7(12). https://doi.org/10.1126/sciadv.abc8259

Delgado JA, S.N.J., Roberts DP and Vandenberg B (2019). Big Data Analysis for Sustainable Agriculture on a Geospatial Cloud Framework. Fronties in Sustainable Food Systems 3. https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2019.00054/full

Demartini, E., Vecchiato, D., Finos, L., Mattavelli, S. and Gaviglio, A. (2022). Would you buy vegan meatballs? The policy issues around vegan and meat-sounding labelling of plant-based meat alternatives. Food Policy 111, 102310. https://doi.org/10.1016/j.foodpol.2022.102310

Development, U.N.C.o.T.a. (2023). Trade and Development Report: Growth, debt, and climate: Realigning the global financialm architecture. https://unctad.org/system/files/official-document/tdr2023_en.pdf

Dong, G., Hinds, L.M., Soro, A.B., Hu, Z., Sun, D.-W. and Tiwari, B.K. (2024). Non-Thermal Processing Technologies for Allergen Control in Alternative Protein Sources for Food Industry Applications. Food Engineering Reviews 16(4), 595-617. https://doi.org/10.1007/s12393-024-09378-2

Dora, M., Biswas, S., Choudhary, S., Nayak, R. and Irani, Z. (2021). A system-wide interdisciplinary conceptual framework for food loss and waste mitigation strategies in the supply chain. Industrial Marketing Management 93, 492-508. https://doi.org/10.1016/j.indmarman.2020.10.013

Dunlop, T., Khojasteh, D., Cohen-Shacham, E., Glamore, W., Haghani, M., van den Bosch, M. et al. (2024). The evolution and future of research on Nature-based Solutions to address societal challenges. Communications Earth & Environment 5(1), 132. https://doi.org/10.1038/s43247-024-01308-8

Edwards, P. (2015). Aquaculture environment interactions: Past, present and likely future trends. Aquaculture 447, 2-14. https://doi.org/10.1016/j.aquaculture.2015.02.001

Egli, L., Rüschhoff, J. and Priess, J. (2023). A systematic review of the ecological, social and economic sustainability effects of community-supported agriculture. Frontiers in Sustainable Food Systems 7. https://doi.org/10.3389/fsufs.2023.1136866

Ejelöv, E., Nässén, J., Matti, S., Elinder, L.S. and Larsson, J. (2025). Public and political acceptability of a food tax shift – An experiment with policy framing and revenue use. Food Policy 130, 102772. https://doi.org/10.1016/j.foodpol.2024.102772

Ellen McArthur Foundation (2021). The Nature imperative: How the circular economy tackles biodiversity loss. https://www.ellenmacarthurfoundation.org/biodiversity-report

Emeana, E.M., Trenchard, L. and Dehnen-Schmutz, K. (2020). The Revolution of Mobile Phone-Enabled Services for Agricultural Development (m-Agri Services) in Africa: The Challenges for Sustainability. Sustainability, 2. https://doi.org/10.3390/su12020485

Ensaff, H. (2021). A nudge in the right direction: the role of food choice architecture in changing populations' diets. Proceedings of the Nutrition Society 80(2), 195-206. https://doi.org/10.1017/s0029665120007983

European Commission (2020). Farm to Fork Strategy. Council of the European Union, General Secretariat, Brussels, Belgium. https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en

Eyhorn, F., Muller, A., Reganold, J.P., Frison, E., Herren, H.R., Luttikholt, L. et al. (2019). Sustainability in global agriculture driven by organic farming. Nature Sustainability 2(4), 253-255. https://doi.org/10.1038/s41893-019-0266-6

Faccioli, M., Law, C., Caine, C.A., Berger, N., Yan, X., Weninger, F. et al. (2022). Combined carbon and health taxes outperform single-purpose information or fiscal measures in designing sustainable food policies. Nature Food 3(5), 331-340. https://doi.org/10.1038/s43016-022-00482-2

Fan, H. (2021). Tariff Structure, Intermediate Goods, and China–U.S. Trade Friction. London: Routledge.

Fan, S., Cho, E.E., Meng, T. and Rue, C. (2021). How to Prevent and Cope with Coincidence of Risks to the Global Food System. Annual Review of Environment and Resources 46(Volume 46, 2021), 601-623. https://doi.org/10.1146/annurev-environ-012220-020844

Fanzo, J., Bellows, A.L., Spiker, M.L., Thorne-Lyman, A.L. and Bloem, M.W. (2021). The importance of food systems and the environment for nutrition. Am J Clin Nutr 113(1), 7-16. https://doi.org/10.1093/ajcn/nqaa313

Fanzo, J., McLaren, R., Bellows, A. and Carducci, B. (2023). Challenges and opportunities for increasing the effectiveness of food reformulation and fortification to improve dietary and nutrition outcomes. Food Policy 119, 102515. https://doi.org/10.1016/j.foodpol.2023.102515

Farmery, A.K., Alexander, K., Anderson, K., Blanchard, J.L., Carter, C.G., Evans, K. et al. (2022). Food for all: designing sustainable and secure future seafood systems. Reviews in Fish Biology and Fisheries 32(1), 101-121. 10.1007/s11160-021-09663-x. https://doi.org/10.1007/s11160-021-09663-x

Ferguson, B.G., Morales, H., Chung, K. and Nigh, R. (2019). Scaling out agroecology from the school garden: the importance of culture, food, and place. Agroecology and Sustainable Food Systems 43(7-8), 724-743. https://doi.org/10.1080/21683565.2019.1591565

Fischer, H.W., Reddy, N.L.N. and Rao, M.L.S. (2016). Can more drought resistant crops promote more climate secure agriculture? Prospects and challenges of millet cultivation in Ananthapur, Andhra Pradesh. World Development Perspectives 2, 5-10. https://doi.org/10.1016/j.wdp.2016.06.005

Flammer, C. (2021). Corporate green bonds. Journal of Financial Economics 142(2), 499-516. https://doi.org/10.1016/j.jfineco.2021.01.010

Font-i-Furnols, M. (2023). Meat Consumption, Sustainability and Alternatives: An Overview of Motives and Barriers. Foods 12(11). https://doi.org/10.3390/foods12112144

Food and Agriculture Organization of the United Nations (2021). The impact of disasters and crises on agriculture and food security: 2021. https://openknowledge.fao.org/server/api/core/bitstreams/30c0d98d-1c21-48ef-b5d9-8d988e6fa6f2/content

Food and Agriculture Organization of the United Nations (2022). The State of the World's Forests 2022. Forest pathways for green recovery and building inclusive, resilient and sustainable economies. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/70248d2a-4340-4b7a-983a-8eea18a575a6/content

Food and Agriculture Organization of the United Nations (2022). Trade of agricultural commodities, 2005 - 2022. FAOSTAT Analytical brief 80. https://openknowledge.fao.org/server/api/core/bitstreams/b32f9ee9-a721-4e2a-95f9-e60922b3e546/content

Food and Agriculture Organization of the United Nations (2023). Achieving SDG2 without breaching the 1.5C threshold: A Global Roadmap. How Agrifood Systems Transformation Through Accelerated Climate Actions Will Help Achieving Food Security and Nutrition, Today and Tomorrow. https://openknowledge.fao.org/items/b86cd543-e8ca-4e95-b5d2-06ea6af23842

Food and Agriculture Organization of the United Nations (2023). Global assessment of soil carbon in grasslands – From current stock estimates to sequestration potential. FAO Animal Production and Health Paper No. 187. Dondini, M., Martin, M., De Camillis, C., Uwizeye, A., Soussana, J.-F., Robinson, T. & Steinfeld, H. (ed.). Rome, FAO. https://openknowledge.fao.org/items/29349846-3fec-4623-b5bc-0984a860ec43

Food and Agriculture Organization of the United Nations (2023). The status of women in agrifood systems. https://www.fao.org/gender/the-status-of-women-in-agrifood-systems/en

Food and Agriculture Organization of the United Nations (2024). The State of Food and Agriculture 2024 – Value-driven transformation of agrifood systems. Rome, Italy. https://openknowledge.fao.org/handle/20.500.14283/cd2616en

Food and Agriculture Organization of the United Nations (2025). Gender and inclusive food systems and value chains. https://www.fao.org/gender/learning-center/thematic-areas/gender-and-inclusive-food-systems-and-value-chains/en

Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, UNICEF, World Health Organization, (2024). The State of Food Security and Nutrition in the World 2024. https://doi.org/10.4060/cd1254en

Foong, A., Pradhan, P., Frör, O. and Kropp, J.P. (2022). Adjusting agricultural emissions for trade matters for climate change mitigation. Nature Communications 13(1), 3024. https://doi.org/10.1038/s41467-022-30607-x

Franco, S., Barbanera, M., Moscetti, R., Cicatiello, C., Secondi, L. and Massantini, R. (2022). Overnutrition is a significant component of food waste and has a large environmental impact. Scientific Reports 12(1), 8166. https://doi.org/10.1038/s41598-022-11813-5

Frangoudes, K. and Gerrard, S. (2019). Gender Perspective in Fisheries: Examples from the South and the North. In Transdisciplinarity for Small-Scale Fisheries Governance: Analysis and Practice. Chuenpagdee, R. and Jentoft, S. (eds.). Cham: Springer International Publishing. 119-140. https://doi.org/10.1007/978-3-319-94938-3_7

Fraunhofer Institute for Solar Energy Systems ISE (2024). Agrivoltaics: Opportunities for Agriculture and the Energy Transition. https://www.ise.fraunhofer.de/en/publications/studies/agrivoltaics-opportunities-for-agriculture-and-the-energy-transition.html

Friedman, V.J., Wright, C.J.C., Molenaar, A., McCaffrey, T., Brennan, L. and Lim, M.S.C. (2022). The Use of Social Media as a Persuasive Platform to Facilitate Nutrition and Health Behavior Change in Young Adults: Web-Based Conversation Study. J Med Internet Res 24(5), e28063. https://doi.org/10.2196/28063

Frojan, J., Bisquert, P., Buche, P., Gontard, N., Boone, L., Nhu Thuy, T. et al. (2023). Scoring methodology for comparing the environmental performance of food packaging. Packaging Technology and Science 36(6), 439-463. https://doi.org/10.1002/pts.2720

Funke, F.a.M., Linus and van den Bijgaart, Inge and Godfray, Charles and Hepburn, Cameron J. and Klenert, David and Springmann, Marco and Treich, Nicolas, (2021). Is meat too cheap? Towards optimal meat taxation. SSRN. http://dx.doi.org/10.2139/ssrn.3801702

G, G., S, K., R, Y.K., Bhatia, S.K., S, A.K., M, R. et al. (2021). Valorization of agricultural residues: Different biorefinery routes. Journal of Environmental Chemical Engineering 9(4), 105435. https://doi.org/10.1016/j.jece.2021.105435

Galford, G.L., Peña, O., Sullivan, A.K., Nash, J., Gurwick, N., Pirolli, G. et al. (2020). Agricultural development addresses food loss and waste while reducing greenhouse gas emissions. Science of The Total Environment 699, 134318. https://doi.org/10.1016/j.scitotenv.2019.134318

Garcia, A.L., Reardon, R., McDonald, M. and Vargas-Garcia, E.J. (2016). Community Interventions to Improve Cooking Skills and Their Effects on Confidence and Eating Behaviour. Curr Nutr Rep 5(4), 315-322. https://doi.org/10.1007/s13668-016-0185-3

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P. et al. (2013). Sustainable Intensification in Agriculture: Premises and Policies. Science 341(6141), 33-34. https://doi.org/10.1126/science.1234485

Gerritsen S, S.F., Lin K, Martino F, Backholer K, Culpin A and Mackay S (2021). The Timing, Nature and Extent of Social Media Marketing by Unhealthy Food and Drinks Brands During the COVID-19 Pandemic in New Zealand. Frontiers in Nutrition. http://frontiersin.org/journals/nutrition/articles/10.3389/fnut.2021.645349/full

Giller, K.E., Hijbeek, R., Andersson, J.A. and Sumberg, J. (2021). Regenerative Agriculture: An agronomic perspective. Outlook on Agriculture 50(1), 13-25. https://doi.org/10.1177/00307270211998063

Gitau, A., Kilalo, D., Nderitu, J., Mendesil, E. and Tefera, T. (2024). Grain handling and storage practices of grain traders in Kenya and its implications in reducing food losses. Cogent Food & Agriculture 10(1), 2306723. https://doi.org/10.1080/23311932.2024.2306723

Glauber, J., Laborde, David (2022). How will Russia's invasion of Ukraine affect global food security?. https://www.ifpri.org/blog/how-will-russias-invasion-ukraine-affect-global-food-security/. Accessed 10 April 2025

Gleckel, J. (2020). Are consumers really confused by plant-based food labels? An empirical study. University of Louisville, Louis D. Brandeis School of Law, Journal of Animal and Environmental Law. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3727710

Global Methane Pledge (2021). Global Methane Pledge. https://www.globalmethanepledge.org/

Global Nutrition Report (2022). 2022 Global Nutrition Report: Stronger commitments for greater action. Bristol, UK: Development Initiatives. https://media.globalnutritionreport.org/documents/2022_Global_Nutrition_Report.pdf

Godfray, H.C. and Garnett, T. (2014). Food security and sustainable intensification. Philos Trans R Soc Lond B Biol Sci 369(1639), 20120273. https://doi.org/10.1098/rstb.2012.0273

Gollakota, A. and Savage, P.E. (2020). Fast and Isothermal Hydrothermal Liquefaction of Polysaccharide Feedstocks. ACS Sustainable Chemistry & Engineering 8(9), 3762-3772. https://doi.org/10.1021/acssuschemeng.9b06873

Gorjian, S., Fakhraei, O., Gorjian, A., Sharafkhani, A. and Aziznejad, A. (2022). Sustainable Food and Agriculture: Employment of Renewable Energy Technologies. Current Robotics Reports 3(3), 153-163. https://doi.org/10.1007/s43154-022-00080-x

Govaerts B, N.C., Camacho Villa TC, Chavez Suarez X, Espinosa AD, Fonteyne S, et al. (2021). One CGIAR and the Integrated Agri-food Systems Initiative: From short-termism to transformation of the world's food systems. PLoS One 16(6). https://doi.org/10.1371/journal.pone.0252832

Gratacap, R.L., Wargelius, A., Edvardsen, R.B. and Houston, R.D. (2019). Potential of Genome Editing to Improve Aquaculture Breeding and Production. Trends Genet 35(9), 672-684. 10.1016/j.tig.2019.06.006

Greenville, J., Kawasaki, K. and Jouanjean, M.-A. (2019). Value Adding Pathways in Agriculture and Food Trade. https://doi.org/10.1787/bb8bb93d-en

Gruber, K. (2017). Agrobiodiversity: The living library. Nature 544(7651). https://doi.org/10.1038/544S8a

Guan, X., Lei, Q., Yan, Q., Li, X., Zhou, J., Du, G. et al. (2021). Trends and ideas in technology, regulation and public acceptance of cultured meat. Future Foods 3, 100032. https://doi.org/10.1016/j.fufo.2021.100032

Guillaumie, L., Boiral, O., Baghdadli, A. and Mercille, G. (2020). Integrating sustainable nutrition into health-related institutions: a systematic review of the literature. Canadian Journal of Public Health 111(6), 845-861. https://doi.org/10.17269/s41997-020-00394-3

Guillen, J., Asche, F., Carvalho, N., Fernández Polanco, J.M., Llorente, I., Nielsen, R. et al. (2019). Aquaculture subsidies in the European Union: Evolution, impact and future potential for growth. Marine Policy 104, 19-28. https://doi.org/10.1016/j.marpol.2019.02.045

Gulati, A. and Juneja, R. (2022). Transforming Indian Agriculture. In: Chand, R., Joshi, P., Khadka, S. (eds) Indian Agriculture Towards 2030. India Studies in Business and Economics. Springer, Singapore. https://doi.org/10.1007/978-981-19-0763-0_2

Guo, K., Yang, J., Yu, N., Luo, L. and Wang, E. (2023). Biological nitrogen fixation in cereal crops: Progress, strategies, and perspectives. Plant Communications 4(2). https://doi.org/10.1016/j.xplc.2022.100499

Gustavsson, J., Cederberg, Christel, Sonesson, Ulf (2011). Global food losses and food waste. Rome: FAO. https://www.fao.org/4/mb060e/mb060e00.pdf

Hadachek, J., Meilin, M. and Sexton, Richard J. (2022). Market Structure and Resilience of Food Supply Chains Under Extreme Events. https://dx.doi.org/10.2139/ssrn.4176350

Haddad, L. (2020). Viewpoint: A view on the key research issues that the CGIAR should lead on 2020–2030. Food Policy 91, 101824. https://doi.org/10.1016/j.foodpol.2020.101824

Hadi, J., Brightwell, Gale (2021). Safety of Alternative Proteins: Technological, Environmental and Regulatory Aspects of Cultured Meat, Plant-Based Meat, Insect Protein and Single-Cell Protein. Foods 10(6). https://doi.org/10.3390/foods10061226

Hamam, M., Chinnici, G., Di Vita, G., Pappalardo, G., Pecorino, B., Maesano, G. et al. (2021). Circular Economy Models in Agro-Food Systems: A Review. Sustainability, 6. https://doi.org/10.3390/su13063453

Hamilton, H., Henry, R., Rounsevell, M., Moran, D., Cossar, F., Allen, K. et al. (2020). Exploring global food system shocks, scenarios and outcomes. Futures 123, 102601. https://doi.org/10.1016/j.futures.2020.102601

Harwatt, H., Wetterberg, Klas, Giritharan, Arpana, Bengon, Tim G. (2022). Aligning food systems with climate and biodiversity targets: Assessing the suitability of policy action over the next decade Chatham House. https://www.chathamhouse.org/sites/default/files/2022-10/2022-10-14-food-systems-climate-biodiversity-harwatt-et-al.pdf

Hasan, B., Thompson, W.G., Almasri, J., Wang, Z., Lakis, S., Prokop, L.J. et al. (2019). The effect of culinary interventions (cooking classes) on dietary intake and behavioral change: a systematic review and evidence map. BMC Nutr 5, 29. https://doi.org/10.1186/s40795-019-0293-8

Hattersley, L. and Mandeville, K.L. (2023). Global Coverage and Design of Sugar-Sweetened Beverage Taxes. JAMA Network Open 6(3), e231412-e231412. https://jamanetwork.com/journals/jamanetworkopen/fullarticle/2802843

Hawkes, C. and World Health Organization (2004). Noncommunicable Diseases and Mental Health Cluster. Marketing food to children: the global regulatory environment. https://iris.who.int/bitstream/handle/10665/42937/9241591579.pdf

Hawkes, C. (2005). The role of foreign direct investment in the nutrition transition. Public Health Nutrition 8(4), 357-365. https://doi.org/10.1079/phn2004706

Hawkes, C., Walton, Stephanie, Haddad, Lawrence, Fanzo, Jessica (2020). 42 policies and actions to orient food systems towards healthier diets for all. Centre for Food Policy Research Brief, University of London. https://www.foodsystemsdashboard.org/resources/publication-42.pdf.

Hawkes, C. and Murphy, S. (2010). An overview of global food trade. Trade, Food, Diet and Health. Perspectives and Policy Options, 16-32. https://www.wiley.com/en-ae/Trade%2C+Food%2C+Diet+and+Health%3A+Perspectives+and+Policy+Options-p-9781444315400

Hawley, C.N., Huber, C.M., Best, L.G., Howard, B.V., Umans, J., Beresford, S.A.A. et al. (2021). Cooking for Health: a healthy food budgeting, purchasing, and cooking skills randomized controlled trial to improve diet among American Indians with type 2 diabetes. BMC Public Health 21(1), 356. https://doi.org/10.1186/s12889-021-10308-8

Heidemann, M.S., Molento, C.F.M., Reis, G.G. and Phillips, C.J.C. (2020). Uncoupling Meat From Animal Slaughter and Its Impacts on Human-Animal Relationships. Frontiers in Psychology 11. https://doi.org/10.3389/fpsyg.2020.01824

Hendriks, S., de Groot Ruiz, A., Acosta, M.H., Baumers, H., Galgani, P., Mason-D'Croz, D. et al. (2023). The True Cost of Food: A Preliminary Assessment. In Science and Innovations for Food Systems Transformation. von Braun, J., Afsana, K., Fresco, L.O. and Hassan, M.H.A. (eds.). Cham: Springer International Publishing. 581-601. https://doi.org/10.1007/978-3-031-15703-5_32

Henry, R.C., Alexander, P., Rabin, S., Anthoni, P., Rounsevell, M.D.A. and Arneth, A. (2019). The role of global dietary transitions for safeguarding biodiversity. Global Environmental Change 58, 101956. https://doi.org/10.1016/j.gloenvcha.2019.101956

Henry, R.C., Arneth, A., Jung, M., Rabin, S.S., Rounsevell, M.D., Warren, F. et al. (2022). Global and regional health and food security under strict conservation scenarios. Nature Sustainability 5(4), 303-310. https://doi.org/10.1038/s41893-021-00844-x

Herforth, A., Arimond, M., Álvarez-Sánchez, C., Coates, J., Christianson, K. and Muehlhoff, E. (2019). A Global Review of Food-Based Dietary Guidelines. Adv Nutr 10(4), 590-605. https://doi.org/10.1093/advances/nmy130

Herrero, M., Henderson, B., Havlík, P., Thornton, P.K., Conant, R.T., Smith, P. et al. (2016). Greenhouse gas mitigation potentials in the livestock sector. Nature Climate Change 6(5), 452-461. https://doi.org/10.1038/nclimate2925

Hilborn, R., Akselrud, C.A., Peterson, H. and Whitehouse, G.A. (2021). The trade-off between biodiversity and sustainable fish harvest with area-based management. ICES Journal of Marine Science 78(6), 2271-2279. https://doi.org/10.1093/icesjms/fsaa139

Hilborn, R., Amoroso, R., Collie, J., Hiddink, J.G., Kaiser, M.J., Mazor, T. et al. (2023). Evaluating the sustainability and environmental impacts of trawling compared to other food production systems. ICES Journal of Marine Science 80(6), 1567-1579. https://doi.org/10.1093/icesjms/fsad115

Hilimire, K., Gillon, S., McLaughlin, B.C., Dowd-Uribe, B. and Monsen, K.L. (2014). Food for Thought: Developing Curricula for Sustainable Food Systems Education Programs. Agroecology and Sustainable Food Systems 38(6), 722-743. https://doi.org/10.1080/21683565.2014.881456

Hiranmai, R.Y., Neeraj, A. and Vats, P. (2023). Improvement of soil health and crop production through utilization of organic wastes: A sustainable approach. International Journal of Recycling of Organic Waste in Agriculture 13(1). https://doi.org/10.57647/j.ijrowa.2024.1301.01

Holmes, D., Humbird, D., Dutkiewicz, J., Tejeda-Saldana, Y., Duffy, B. and Datar, I. (2022). Cultured meat needs a race to mission not a race to market. Nature Food 3(10), 785-787. https://doi.org/10.1038/s43016-022-00586-9

Holmes, S., Meagher, Michelle (2022). A sustainable future: how can control of monopoly power play a part? European Competition Law Review. https://www.balancedeconomy.org/latest/a-sustainable-future-how-can-control-of-monopoly-power-play-a-part#:~:text=This%20paper%20by%20Simon%20Holmes,use%20competition%20policy%20(particularly%20art

Humphries, A.T., Gorospe, K.D., Carvalho, P.G., Yulianto, I., Kartawijaya, T. and Campbell, S.J. (2019). Catch Composition and Selectivity of Fishing Gears in a Multi-Species Indonesian Coral Reef Fishery. Frontiers in Marine Science 6. https://doi.org/10.3389/fmars.2019.00378

Ickowitz, A., Powell, B., Rowland, D., Jones, A. and Sunderland, T. (2019). Agricultural intensification, dietary diversity, and markets in the global food security narrative. Global Food Security 20, 9-16. https://doi.org/10.1016/j.gfs.2018.11.002

Institute for Agriculture and Trade Policy and GRAIN (2023). A corporate cartel fertilizes food inflation. https://www.iatp.org/corporate-cartel-fertilises-food-inflation. Accessed 10 April 2025

Intergovernmental Panel on Climate Change (2019). Food Security, in: Climate Change and Land an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Mbow, C., Rosenzweig, C., Barioni, L.G., Benton, T.G., Herrero, M., Krishnapillai, M., Liwenga, E., Pradhan, P., Rivera-Ferre, M.G., Sapkota, T., Tubiello, F.N., Xu, Y. (ed.). https://doi.org/10.1017/9781009157988

Intergovernmental Panel on Climate Change (2022a). Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. H.-O. Pörtner, D.C.R., M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.) (ed.). Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009325844

IPCC (2022b). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926

Ishfaq, M., Farooq, Muhammad, Zulfiqar, Usman, Hussain, Saddam, Akbar, Nadeem, Nawaz, Ahmad, Anjum, Shakeel (2020). Alternate wetting and drying: A water-saving and ecofriendly rice production system. Agricultural Water Management 241. https://doi.org/10.1016/j.agwat.2020.106363

Islam, S., Islan, Shariful, Kabir, Humayun, Muhammad, Alam, Zamshed Mohammad, Nur-E-Alam (2019). Use of communication media by the bean farmers. International Journal of Science and Business, IJSAB International, 3(2), 126-137. https://ideas.repec.org/a/aif/journl/v3y2019i2p.html

Jacquet, J., Hocevar, John, Lai, Sherman, Majlif, Patricia, Pelletier, Nathan, Pitcher, Tony, Sala, Enric, Sumaila, Rashid and Pauly, Daniel (2010). Conserving wild fish in a sea of market-based efforts. The International Journal of Conservation - Oryx. https://jenniferjacquet.com/wp-content/uploads/2010/05/jacquetetal2010_oryx.pdf

Jaeger, S.R. (2024). Vertical farming (plant factory with artificial lighting) and its produce: consumer insights. Current Opinion in Food Science 56, 101145. https://doi.org/10.1016/j.cofs.2024.101145

Jaeger-Erben, M., Jensen, C., Hofmann, F. and Zwiers, J. (2021). There is no sustainable circular economy without a circular society. Resources, Conservation and Recycling 168, 105476. https://doi.org/10.1016/j.resconrec.2021.105476

James-Martin, G., Baird, D.L., Hendrie, G.A., Bogard, J., Anastasiou, K., Brooker, P.G. et al. (2022). Environmental sustainability in national food-based dietary guidelines: a global review. Lancet Planet Health 6(12), e977-e986. https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(22)00246-7/fulltext

Järviö, N., Parviainen, T., Maljanen, N.-L., Kobayashi, Y., Kujanpää, L., Ercili-Cura, D. et al. (2021). Ovalbumin production using Trichoderma reesei culture and low-carbon energy could mitigate the environmental impacts of chicken-egg-derived ovalbumin. Nature Food 2(12), 1005-1013. https://doi.org/10.1038/s43016-021-00418-2

Jat, H.S., Datta, A., Choudhary, M., Sharma, P.C., Yadav, A.K., Choudhary, V. et al. (2019). Climate Smart Agriculture practices improve soil organic carbon pools, biological properties and crop productivity in cereal-based systems of North-West India. CATENA 181, 104059. https://doi.org/10.1016/j.catena.2019.05.005

Jat, H.S., Jat, R.D., Nanwal, R.K., Lohan, S.K., Yadav, A.K., Poonia, T. et al. (2020). Energy use efficiency of crop residue management for sustainable energy and agriculture conservation in NW India. Renewable Energy 155, 1372-1382. https://doi.org/10.1016/j.renene.2020.04.046

Jat, K.L., Singh, Y.V., Santosh, Kumar Meena, Meena Kumari Sunnita, Manoj, Parihar, Jatav, H.S., Meena, Kumar Raj, Meena, Singh Vijay (2015). Does Integrated Nutrient Management, Enhance Agricultural Productivity? Journal of pure and applied microbiology 9(2). https://d1wqtxts1xzle7.cloudfront.net/38153510/JPAMVO9N2P1211-1221-libre.pdf?1436561468=&response-content-disposition=inline%3B+filename%3DDoes_Integrated_Nutrient_Management_Enha.pdf&Expires=1729776944&Signature=WiX3QmPc63VxYmnUjDLocOi9iJ~G0Hylei4iC1SkObTJ0owyK4Vb28HCUXadcF-8YwGz8j5GDhEWJnKB~BMcCpXMYC4Uq7n9LpGgNbvV9zrvs8kK~OLEdqgEpkF4l1l13~u-cglPF10tDyKlprUNVXv7W2HJWhg09b3Z0nK6EK83rORjhxrLjEnfi6L19aeM2RoE-zR6NTSMcSHCep1~zmHaxAs00ZJneJapnQ6ARIASW6leyD5S33ZC65SEoRZ4vlplNxtK1h4yNUA7EMdFWP0XH29w5POYmTSXj5tGbMzBx5IRrwKgEw5WLyPLnFwUZbsrzjL1N1CKPNGI-zUx9g__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA

Javaid, M., Haleem, A., Khan, I.H. and Suman, R. (2023). Understanding the potential applications of Artificial Intelligence in Agriculture Sector. Advanced Agrochem 2(1), 15-30. https://doi.org/10.1016/j.aac.2022.10.001

Jiménez, D., Delerce, S., Dorado, H., Cock, J., Muñoz, L.A., Agamez, A. et al. (2019). A scalable scheme to implement data-driven agriculture for small-scale farmers. Global Food Security 23, 256-266. https://doi.org/10.1016/j.gfs.2019.08.004

Jones, S.K., Sánchez, A.C., Beillouin, D., Juventia, S.D., Mosnier, A., Remans, R. et al. (2023). Achieving win-win outcomes for biodiversity and yield through diversified farming. Basic and Applied Ecology 67, 14-31. https://doi.org/10.1016/j.baae.2022.12.005

Kabir, M. and Islam, M.S. (2023). Effectiveness of Public and Private Extension Services in Building Capacity of the Farmers: A Case of Bangladesh. Sarhad Journal of Agriculture. https://researcherslinks.com/current-issues/Effectiveness-Public-and-Private-Extension-Services/14/1/5946/html

Kalenjuk Pivarski, B., Tešanović, D., Šmugović, S., Ivanović, V., Paunić, M., Vuković Vojnović, D. et al. (2024). Gastronomy as a Predictor of Tourism Development—Defining Food-Related Factors from the Perspective of Hospitality and Tourism Employees in Srem (A.P. Vojvodina, R. Serbia). Sustainability, 24. https://doi.org/10.3390/su162410834

Kamgang, S.E., Boiral, O., Guillaumie, L. and Brotherton, M.-C. (2024). Responsible sourcing in the food industry: a scoping review. Environment, Development and Sustainability 26(8), 19325-19349. http://dx.doi.org/10.1007/s10668-023-03509-1

Kantor, B.N. and Kantor, J. (2021). Public Attitudes and Willingness to Pay for Cultured Meat: A Cross-Sectional Experimental Study. Frontiers in Sustainable Food Systems 5. http://dx.doi.org/10.3389/fsufs.2021.594650

Karakurt, I., Aydin, G. and Aydiner, K. (2012). Sources and mitigation of methane emissions by sectors: A critical review. Renewable Energy 39(1), 40-48. https://doi.org/10.1016/j.renene.2011.09.006

Karanth, S., Feng, S., Patra, D. and Pradhan, A.K. (2023). Linking microbial contamination to food spoilage and food waste: the role of smart packaging, spoilage risk assessments, and date labeling. Front Microbiol 14, 1198124. https://doi.org/10.3389/fmicb.2023.1198124

Keating, B.A., Herrero, M., Carberry, P.S., Gardner, J. and Cole, M.B. (2014). Food wedges: Framing the global food demand and supply challenge towards 2050. Global Food Security 3(3), 125-132. https://doi.org/10.1016/j.gfs.2014.08.004

Kennedy, G., Hunter, Danny, Garret, James, Padulosi, Stefano (2022). A spotlight on the nutrition decade. Nutrition, U.N.S.S.C.o. (ed.). https://cgspace.cgiar.org/server/api/core/bitstreams/ad67e3cd-a38e-449d-88ec-027371cedd10/content

Kenny, T.a.S., Colini, (2021). Surplus food redistribution and healthy, sustainable diets: Exploring the contradictions of charitable food provisioning. International Journal of Sociology of Agriculture and Food 27, 71-86. https://doi.org/10.48416/ijsaf.v27i1.82

Khoury, C.K., Bjorkman, A.D., Dempewolf, H., Ramirez-Villegas, J., Guarino, L., Jarvis, A. et al. (2014). Increasing homogeneity in global food supplies and the implications for food security. Proceedings of the National Academy of Sciences 111(11), 4001-4006. https://doi.org/10.1073/pnas.1313490111

Kiesel, K., Lang, H. and Sexton, R.J. (2023). A New Wave of Sugar-Sweetened Beverage Taxes: Are They Meeting Policy Goals and Can We Do Better? Annual Review of Resource Economics 15(Volume 15, 2023), 407-432. https://doi.org/10.1146/annurev-resource-111522-111325

Kim, S. and Lee, S.H. (2020). Examining Household Food Waste Behaviors and the Determinants in Korea Using New Questions in a National Household Survey. Sustainability, 20. https://doi.org/10.3390/su12208484

Kinnunen, P., Guillaume, J.H.A., Taka, M., D'Odorico, P., Siebert, S., Puma, M.J. et al. (2020). Local food crop production can fulfil demand for less than one-third of the population. Nature Food 1(4), 229-237. https://doi.org/10.1038/s43016-020-0060-7

Kirkwood, H. (2022). Perspectives: Revisited 2022-2. Business Information Review 39(2), 62-64. https://doi.org/10.1177/02663821221102293

Knowler, D., Chopin, T., Martínez-Espiñeira, R., Neori, A., Nobre, A., Noce, A. et al. (2020). The economics of Integrated Multi-Trophic Aquaculture: where are we now and where do we need to go? Reviews in Aquaculture 12(3), 1579-1594. https://doi.org/10.1111/raq.12399

Kommey, R., Fombad, Madeleine (2023). Strategies for Knowledge Sharing Among Rice Farmers: A Ghanaian Perspective. The Electronic Journal of Knowledge Management (EJKM) 21(2). https://doi.org/10.34190/ejkm.21.2.2803

Kruger, C., Caiado, R.G.G., França, S.L.B. and Quelhas, O.L.G. (2018). A holistic model integrating value co-creation methodologies towards the sustainable development. Journal of Cleaner Production 191, 400-416. https://doi.org/10.1016/j.jclepro.2018.04.180

Kucharczuk, A.J., Oliver, T.L. and Dowdell, E.B. (2022). Social media's influence on adolescents' food choices: A mixed studies systematic literature review. Appetite 168, 105765. https://doi.org/10.1016/j.appet.2021.105765

Kuhnlein, H.V. (2015). Food system sustainability for health and well-being of Indigenous Peoples. Public Health Nutrition 18(13), 2415-2424. https://doi.org/10.1017/s1368980014002961

Kumar, A., Mishra, A.K., Saroj, S. and Rashid, S. (2022). Government transfers, COVID-19 shock, and food insecurity: Evidence from rural households in India. Agribusiness 38(3), 636-659. https://doi.org/10.1002/agr.21746

Kumar, N., Chaudhary, A., Ahlawat, O.P., Naorem, A., Upadhyay, G., Chhokar, R.S. et al. (2023). Crop residue management challenges, opportunities and way forward for sustainable food-energy security in India: A review. Soil and Tillage Research 228, 105641. https://doi.org/10.1016/j.still.2023.105641

Kumar, N.Q., Agnes R.; Gelli, Aulo; Gentilini, Ugo; and Shapleigh, Sara. (2021). Toward inclusive food systems: Pandemics, vulnerable groups, and the role of social protection. In 2021 Global food report: Transforming food systems after COVID-19.: International Food Policy Research Institute (IFPRI). https://ideas.repec.org/h/fpr/ifpric/9780896293991_05.html

Kuyah, S., Sileshi, G. W., luedeling, E., Akinnifesi, F. K., Whitney, C. W., Bayala, J., Kuntashula, E., Dimobe, K., Mafongoya, P. L. (2019). Potential of Agroforestry to Enhance Livelihood Security in Africa. Agroforestry for Degraded Landscapes. Recent Advances and Emerging Challenges - Vol. 1. https://doi.org/10.1007/978-981-15-4136-0_4%23DOI

Ladha, J.K., Tirol-Padre, A., Reddy, C.K., Cassman, K.G., Verma, S., Powlson, D.S. et al. (2016). Global nitrogen budgets in cereals: A 50-year assessment for maize, rice and wheat production systems. Scientific Reports 6(1), 19355. https://doi.org/10.1038/srep19355

Lal, R. (2015). Restoring Soil Quality to Mitigate Soil Degradation. Sustainability, 5. https://doi.org/10.3390/su7055875

Lalander, C., Nordberg, Å. and Vinnerås, B. (2018). A comparison in product-value potential in four treatment strategies for food waste and faeces – assessing composting, fly larvae composting and anaerobic digestion. GCB Bioenergy 10(2), 84-91. https://doi.org/10.1111/gcbb.12470

Lanzoni, D., Rebucci, R., Formici, G., Cheli, F., Ragone, G., Baldi, A. et al. (2024). Cultured meat in the European Union: Legislative context and food safety issues. Current Research in Food Science 8, 100722. https://doi.org/10.1016/j.crfs.2024.100722

Latka, C., Kuiper, M., Frank, S., Heckelei, T., Havlík, P., Witzke, H.-P. et al. (2021). Paying the price for environmentally sustainable and healthy EU diets. Global Food Security 28, 100437. https://doi.org/10.1016/j.gfs.2020.100437

Le Pera, A., Sellaro, M., Bencivenni, E. and D'Amico, F. (2022). Environmental sustainability of an integrate anaerobic digestion-composting treatment of food waste: Analysis of an Italian plant in the circular bioeconomy strategy. Waste Management 139, 341-351. https://doi.org/10.1016/j.wasman.2021.12.042

Lem, A., Castro de Souza, M., Toussaint, M.; Bhakti, A.; Mateos, A. (2023). The World Trade Organization Agreement on Fisheries Subsidies and the role of FAO. https://www.fao.org/fishery/en/publications/312229

Leon, A., Guntur V, S., Kishii, M., Matsumoto, N. and Kruseman, G. (2022). An ex ante life cycle assessment of wheat with high biological nitrification inhibition capacity. Environmental Science and Pollution Research 29(5), 7153-7169. https://doi.org/10.1007/s11356-021-16132-2

Limbu, S.M., Shoko, A.P., Lamtane, H.A., Kishe-Machumu, M.A., Joram, M.C., Mbonde, A.S. et al. (2017). Fish polyculture system integrated with vegetable farming improves yield and economic benefits of small-scale farmers. Aquaculture Research 48(7), 3631-3644. https://doi.org/10.1111/are.13188

Lindstrom, K.N., Tucker, J. A. and McVay, M (2023). Nudges and choice architecture to promote healthy food purchases in adults: A systematized review. Psychology of Addictive Behaviors 37(1), 87 - 103. https://doi.org/10.1037/adb0000892.

Llauger, M., Claret, A., Bou, R., López-Mas, L. and Guerrero, L. (2021). Consumer Attitudes toward Consumption of Meat Products Containing Offal and Offal Extracts. Foods 10(7). https://doi.org/10.3390/foods10071454

Lohmann, P.M., Gsottbauer, E., Farrington, J., Human, S. and Reisch, L.A. (2024). Choice architecture promotes sustainable choices in online food-delivery apps. PNAS Nexus 3(10), pgae422. https://academic.oup.com/pnasnexus/article/3/10/pgae422/7762134

Lopes, C.V., Mihrshahi, S., Ronto, R. and Hunter, J. (2023). Aboriginal Food Practices and Australian Native Plant-Based Foods: A Step toward Sustainable Food Systems. Sustainability, 15. https://doi.org/10.3390/su151511569

Lu, G. and Luo, M. (2020). Genomes of major fishes in world fisheries and aquaculture: Status, application and perspective. Aquaculture and Fisheries 5(4), 163-173. https://doi.org/10.1016/j.aaf.2020.05.004

Mabhaudhi, T., Chimonyo, V.G.P., Hlahla, S., Massawe, F., Mayes, S., Nhamo, L. et al. (2019). Prospects of orphan crops in climate change. Planta 250(3), 695-708. https://link.springer.com/article/10.1007/s00425-019-03129-y#citeas

Macura, B., Thomas, J., Metson, G.S., McConville, J.R., Johannesdottir, S.L., Seddon, D. et al. (2021). Technologies for recovery and reuse of plant nutrients from human excreta and domestic wastewater: a protocol for a systematic map and living evidence platform. Environmental Evidence 10(1), 20. https://doi.org/10.1186/s13750-021-00235-x

Madeleine Kaufmann, A.G.Á., Alberto Tarraza and Alessandra Giuliani (2024). Family farms as innovative living labs in agroecology and transfer of knowledge in Family Farms and the Conservation of Agrobiodiversity in Cuba. Urbano Fra Paleo, L.C. (ed.). https://doi.org/10.4324/9781315183886

Maeda, E., Eiji, Abera, Temesgen, Alemayehu, Siljander, Mika, Aragao, Luiz, E., Mendes de Moura, Yhasmin, Heiskanen, Janne (2021). Large-scale commodity agriculture exacerbates the climatic impacts of Amazonian deforestation. PNAS. https://doi.org/10.1073/pnas.2023787118

Malik, V.S. and Hu, F.B. (2022). The role of sugar-sweetened beverages in the global epidemics of obesity and chronic diseases. Nat Rev Endocrinol 18(4), 205-218. https://doi.org/10.1038/s41574-021-00627-6

Malila, Y., Owolabi, I.O., Chotanaphuti, T., Sakdibhornssup, N., Elliott, C.T., Visessanguan, W. et al. (2024). Current challenges of alternative proteins as future foods. npj Science of Food 8(1), 53. https://doi.org/10.1038/s41538-024-00291-w

Mamun, A., Martin, W. and Tokgoz, S. (2021). Reforming Agricultural Support for Improved Environmental Outcomes. Applied Economic Perspectives and Policy 43(4), 1520-1549. https://doi.org/10.1002/aepp.13141

Mana, A.A., Allouhi, A., Hamrani, A., Rehman, S., el Jamaoui, I. and Jayachandran, K. (2024). Sustainable AI-based production agriculture: Exploring AI applications and implications in agricultural practices. Smart Agricultural Technology 7, 100416. https://doi.org/10.1016/j.atech.2024.100416

Mangeni, B. (2020). The role of Public-Private Partnerships (PPPs) in ensuring technology access for farmers in sub-Saharan Africa. African Journal of Food, Agriculture and Development 19(1). https://doi.org/10.18697/ajfand.84.BLFB1018

Manzoor, S., Fayaz, U., Dar, A.H., Dash, K.K., Shams, R., Bashir, I. et al. (2024). Sustainable development goals through reducing food loss and food waste: A comprehensive review. Future Foods 9, 100362. https://doi.org/10.1016/j.fufo.2024.100362

Marianne Gadeberg, E.L. (2023). The status of women in agriculture and food systems: persistent gaps and promising solutions. CGIAR. https://gender.cgiar.org/news/status-women-agriculture-and-food-systems-persistent-gaps-and-promising-solutions. Accessed 10 April 2025

Masters, W.A. and Finaret, A.B. (2024). Social Welfare: Evaluating Change in Food Markets. In Food Economics: Agriculture, Nutrition, and Health. Masters, W.A. and Finaret, A.B. (eds.). Cham: Springer International Publishing. 101-148. https://doi.org/10.1007/978-3-031-53840-7_4

Matera, A.a.G., F. (2024). Innovative Technology in Food Analysis and Processing. Journal of Applied Sciences, Food Science adn Technology. https://www.mdpi.com/journal/applsci/special_issues/Food_Analysis_and_Processing#info

Mayén, A.-L., de Mestral, C., Zamora, G., Paccaud, F., Marques-Vidal, P., Bovet, P. et al. (2016). Interventions promoting healthy eating as a tool for reducing social inequalities in diet in low- and middle-income countries: a systematic review. International Journal for Equity in Health 15(1), 205. https://doi.org/10.1186/s12939-016-0489-3

McCouch, S., Baute, G.J., Bradeen, J., Bramel, P., Bretting, P.K., Buckler, E. et al. (2013). Feeding the future. Nature 499(7456), 23-24. https://doi.org/10.1038/499023a

McGowan, C. (2021). Care for some lunch? It's more than just food! Care, Commensality and Pedagogic Meals in Irish Primary Schools Level 3 15(3). https://arrow.tudublin.ie/level3/vol15/iss3/3?utm_source=arrow.tudublin.ie%2Flevel3%2Fvol15%2Fiss3%2F3&utm_medium=PDF&utm_campaign=PDFCoverPages

McGrath, K., Brown, C., Regan, Á. and Russell, T. (2023). Investigating narratives and trends in digital agriculture: A scoping study of social and behavioural science studies. Agricultural Systems 207, 103616. https://doi.org/10.1016/j.agsy.2023.103616

McMullin, S., Stadlmayr, B., Mausch, K., Revoredo-Giha, C., Burnett, F., Guarino, L. et al. (2021). Determining appropriate interventions to mainstream nutritious orphan crops into African food systems. Global Food Security 28, 100465. https://doi.org/10.1016/j.gfs.2020.100465

Melnychuk, M.C., Kurota, H., Mace, P.M., Pons, M., Minto, C., Osio, G.C. et al. (2021). Identifying management actions that promote sustainable fisheries. Nature Sustainability 4(5), 440-449. https://doi.org/10.1038/s41893-020-00668-1

Mensah, H., Ahadzie, D.K., Takyi, S.A. and Amponsah, O. (2021). Climate change resilience: lessons from local climate-smart agricultural practices in Ghana. Energy, Ecology and Environment 6(3), 271-284. https://doi.org/10.1007/s40974-020-00181-3

Merkle, M., Moran, D., Warren, F. and Alexander, P. (2021). How does market power affect the resilience of food supply? Global Food Security 30, 100556. https://doi.org/10.1016/j.gfs.2021.100556

Meyer, R.L. (2014). Innovative Microfinance: Potential for Serving Rural Markets Sustainably. In Finance for Food: Towards New Agricultural and Rural Finance. Köhn, D. (ed.). Berlin, Heidelberg: Springer Berlin Heidelberg. 89-113. https://doi.org/10.1007/978-3-642-54034-9_5

Micha, R., Peñalvo, J.L., Cudhea, F., Imamura, F., Rehm, C.D. and Mozaffarian, D. (2017). Association Between Dietary Factors and Mortality From Heart Disease, Stroke, and Type 2 Diabetes in the United States. Jama 317(9), 912-924. https://jamanetwork.com/journals/jama/fullarticle/2608221

Miranda-Ackerman, M.A. and Azzaro-Pantel, C. (2017). Extending the scope of eco-labelling in the food industry to drive change beyond sustainable agriculture practices. J Environ Manage 204(Pt 3), 814-824. https://doi.org/10.1016/j.jenvman.2017.05.027

Misra, M. (2023). Practicing ecological citizenship through community supported agriculture: Opportunities, challenges, and social justice concerns. Culture, Agriculture, Food and Environment 45(1), 21-33. https://doi.org/10.1111/cuag.12306

Mockshell, J. and Villarino, M.E.J. (2019). Agroecological Intensification: Potential and Limitations to Achieving Food Security and Sustainability. In Encyclopedia of Food Security and Sustainability. Ferranti, P., Berry, E.M. and Anderson, J.R. (eds.). Oxford: Elsevier. 64-70. https://www.sciencedirect.com/science/article/pii/B9780081005965222117

Moe Føre, H., Thorvaldsen, T., Folkedal, O., Holmen, I., Lona, E., Grøtli, E., Selvik, Ø., Fagertun, J., Endresen, P., Ohren, S., Slette, H., Gutsch, M., Mathisen, B., Hvas, M., and Klebert, P (2024). Safe, Robust, and Productive Exposed Aquaculture Operations: Challenges and Solutions

Montes, C., Sapkota, T. and Singh, B. (2022). Seasonal patterns in rice and wheat residue burning and surface $PM_{2.5}$ concentration in northern India. Atmospheric Environment: X 13, 100154. https://doi.org/10.1016/j.aeaoa.2022.100154

Moran, D., Cossar, F., Merkle, M. and Alexander, P. (2020). UK food system resilience tested by COVID-19. Nature Food 1(5), 242-242. https://doi.org/10.1038/s43016-020-0082-1

Motta, R. (2021). Social movements as agents of change: Fighting intersectional food inequalities, building food as webs of life. The Sociological Review 69(3), 603-625. https://doi.org/10.1177/00380261211009061

Mukherji, A., Arndt, C., Arango, J., Flintan, F., Derera, J., Francesconi, W., Jones, S, Loboguerrero, A.M., Merrey, D., Mockshell, J., Quintero, M., Mulat, D.G., Ringler, C., Ronchi, L., Sanchez, M, Sapkota, T. and Thilsted, S. (2023). Achieving agricultural breakthrough: A deep dive into seven technological areas. https://hdl.handle.net/10568/131852

Murphy, J.D. and Power, N.M. (2006). A Technical, Economic and Environmental Comparison of Composting and Anaerobic Digestion of Biodegradable Municipal Waste. Journal of Environmental Science and Health, Part A 41(5), 865-879. https://doi.org/10.1080/10934520600614488

Muscat, A., de Olde, E.M., de Boer, I.J.M. and Ripoll-Bosch, R. (2020). The battle for biomass: A systematic review of food-feed-fuel competition. Global Food Security 25, 100330. https://doi.org/10.1016/j.gfs.2019.100330

Mustafa, M.F.M.S., Navaranjan, N. and Demirovic, A. (2024). Food cold chain logistics and management: A review of current development and emerging trends. Journal of Agriculture and Food Research 18, 101343. https://doi.org/10.1016/j.jafr.2024.101343

Nakhimovsky, S.S., Feigl, A.B., Avila, C., O'Sullivan, G., Macgregor-Skinner, E. and Spranca, M. (2016). Taxes on Sugar-Sweetened Beverages to Reduce Overweight and Obesity in Middle-Income Countries: A Systematic Review. PLoS One 11(9), e0163358. 10.1371/journal.pone.0163358

Nicholson, C.F., Stephens, E.C., Kopainsky, B., Thornton, P.K., Jones, A.D., Parsons, D. et al. (2021). Food security outcomes in agricultural systems models: Case examples and priority information needs. Agricultural Systems 188, 103030. https://doi.org/10.1016/j.agsy.2020.103030

Nicolini, G., Bladon, A, Ducros, A, Swidersha, K, Torres Ledezma, C, Bortoletti, M (2023). Food systems governance and the environmental agenda. International Institute for Environment and Development (IIED), London. iied.org/21616IIED. https://www.iied.org/sites/default/files/pdfs/2023-09/21616IIED.pdf

Nielsen, T., Baumert, N., Kander, A., Jiborn, M. and Kulionis, V. (2021). The risk of carbon leakage in global climate agreements. International Environmental Agreements: Politics, Law and Economics 21(2), 147-163. https://doi.org/10.1007/s10784-020-09507-2

Niether, W., Jacobi, Johanna, Blaser, Wilma, Andres, Christian and Armengot, Laura (2020). Cocoa agroforestry systems versus monocultures: a multi-dimensional meta-analysis. Environmental Research Letter 15(10). https://iopscience.iop.org/article/10.1088/1748-9326/abb053

Nkuba, M., Chanda, R., Mmopelwa, G., Kato, E., Mangheni, M.N. and Lesolle, D. (2019). The effect of climate information in pastoralists' adaptation to climate change. International Journal of Climate Change Strategies and Management 11(4), 442-464. https://www.emerald.com/insight/content/doi/10.1108/ijccsm-10-2018-0073/full/html

Nordhaus, W.D. (2017). Revisiting the social cost of carbon. Proceedings of the National Academy of Sciences 114(7), 1518-1523. 10.1073/pnas.1609244114

Nyaplue-Daywhea, C., Ahiakpa, J. K, Mensah, O. A., Annor-Frempong, F. and Adjei-Nsiah (2021). Mobile phone-assisted agricultural extension services: User competency and usage frequency in Eastern Ghana. African Journal of Food, Agriculture, Nutrition and Development 21(10). https://doi.org/10.18697/ajfand.105.20335

Oh, S. and Lu, C. (2023). Vertical farming - smart urban agriculture for enhancing resilience and sustainability in food security. The Journal of Horticultural Science and Biotechnology 98(2), 133-140. https://doi.org/10.1080/14620316.2022.2141666

Ojha, S., Bußler, S. and Schlüter, O.K. (2020). Food waste valorisation and circular economy concepts in insect production and processing. Waste Management 118, 600-609. https://doi.org/10.1016/j.wasman.2020.09.010

Ortiz, A.M.D., Outhwaite, C.L., Dalin, C. and Newbold, T. (2021). A review of the interactions between biodiversity, agriculture, climate change, and international trade: research and policy priorities. One Earth 4(1), 88-101. https://doi.org/10.1016/j.oneear.2020.12.008

Pagiola, S., Honey-Rosés, J. and Freire-González, J. (2020). Assessing the Permanence of Land-Use Change Induced by Payments for Environmental Services: Evidence From Nicaragua. Tropical Conservation Science 13, 1940082920922676. https://doi.org/10.1177/1940082920922676

Paiva, C.L. and Ugaya, C.M.L. (2024). Environmental impacts assessment in packaging and its contribution to reducing food waste. Cleaner and Circular Bioeconomy 8, 100083. https://doi.org/10.1016/j.clcb.2024.100083

Pandey, A. and Caliskan, A. (2021). Disparate Impact of Artificial Intelligence Bias in Ridehailing Economy's Price Discrimination Algorithms. Proceedings of the 2021 AAAI/ACM Conference on AI, Ethics, and Society. Virtual Event, USA. Association for Computing Machinery 822–833 doi: 10.1145/3461702.3462561 https://doi.org/10.1145/3461702.3462561

Parikh, P., Semba, R., Manary, M., Swaminathan, S., Udomkesmalee, E., Bos, R. et al. (2022). Animal source foods, rich in essential amino acids, are important for linear growth and development of young children in low- and middle-income countries. Maternal & Child Nutrition 18(1), e13264. https://doi.org/10.1111/mcn.13264

Pe'er, G., Finn, J.A., Díaz, M., Birkenstock, M., Lakner, S., Röder, N. et al. (2022). How can the European Common Agricultural Policy help halt biodiversity loss? Recommendations by over 300 experts. Conservation Letters 15(6), e12901. https://doi.org/10.1111/conl.12901

Peeters, A., Lefebvre, O., Balogh, L., Barberi, P., Batello, C., Bellon, S., Gaifami, T., Gkisakis, V., Lana, M., Migliorini, P., Ostermann, O.P. and Wezel, A., (2020). A Green Deal for implementing agroecological systems – Reforming the Common Agricultural Policy of the European Union. Landbauforschung, 70(2), 83–93. https://doi.org/10.3220/LBF1610123299000

Perkins, O., Alexander, P., Arneth, A., Brown, C., Millington, J.D.A. and Rounsevell, M. (2023). Toward quantification of the feasible potential of land-based carbon dioxide removal. One Earth 6(12), 1638-1651. https://doi.org/10.1016/j.oneear.2023.11.011

Pettorelli, N., Graham, N.A.J., Seddon, N., Maria da Cunha Bustamante, M., Lowton, M.J., Sutherland, W.J. et al. (2021). Time to integrate global climate change and biodiversity science-policy agendas. Journal of Applied Ecology 58(11), 2384-2393. https://doi.org/10.1111/1365-2664.13985

Phelps, N.H., Singleton, R.K., Zhou, B., Heap, R.A., Mishra, A., Bennett, J.E. et al. (2024). Worldwide trends in underweight and obesity from 1990 to 2022: a pooled analysis of 3663 population-representative studies with 222 million children, adolescents, and adults. The Lancet 403(10431), 1027-1050. https://doi.org/10.1016/S0140-6736(23)02750-2

Piñeiro, V., Arias, J., Dürr, J., Elverdin, P., Ibáñez, A.M., Kinengyere, A. et al. (2020). A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. Nature Sustainability 3(10), 809-820. https://doi.org/10.1038/s41893-020-00617-y

Poore, J. and Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science 360(6392), 987-992. https://doi.org/10.1126/science.aaq0216

Popkova, E.G. and Sergi, B.S. (2023). Transition to Agriculture 4.0 Under the Influence of the Fourth Industrial Revolution (Introduction). In Food Security in the Economy of the Future: Transition from Digital Agriculture to Agriculture 4.0 Based on Deep Learning. Popkova, E.G. and Sergi, B.S. (eds.). Cham: Springer International Publishing. 1-5. https://doi.org/10.1007/978-3-031-23511-5_1

Pradhan, P., Fischer, G., Reusser, D. E., & Kropp, J. P. (2015). Closing Yield Gaps: How Sustainable Can We Be? PLoS One 10(6). https://doi.org/10.1371/journal.pone.0129487

Prasanna, S., Verma, P. and Bodh, S. (2024). The role of food industries in sustainability transition: a review. Environment, Development and Sustainability. http://dx.doi.org/10.1007/s10668-024-04642-1

Prestes Floriano, M.D. (2024). The role of emotions in reducing food waste. Revista de Administracao de Empresas |. http://dx.doi.org/10.1590/S0034-759020240501x

Rachel Sherrington, C.C.a.H.H. (9 December 2023). Big meat and dairy lobbyists turn out in record numbers at Cop28 https://www.theguardian.com/environment/2023/dec/09/big-meat-dairy-lobbyists-turn-out-record-numbers-cop28. Accessed 10 April 2025

Raj, S., Roodbar, S., Brinkley, C. and Wolfe, D.W. (2022). Food Security and Climate Change: Differences in Impacts and Adaptation Strategies for Rural Communities in the Global South and North. Frontiers in Sustainable Food Systems 5. https://doi.org/10.3389/fsufs.2021.691191

Ramos, A., Lowe, A., Herstein, J., Trinidad, N., Carvajal-Suarez, M., Quintero, S. et al. (2021). A rapid-response survey of essential workers in Midwestern meatpacking plants: Perspectives on COVID-19 response in the workplace. Journal of Environmental Health 84, 16-25. https://experts.nebraska.edu/en/publications/a-rapid-response-survey-of-essential-workers-in-midwestern-meatpa

Ramos, G.J., Borges, J.A.R., Domingues, C.H.d.F. and van Herpen, E. (2024). Reducing food waste by simply measuring it: insights from interventions to reduce household food waste. British Food Journal 126(2), 812-833. https://doi.org/10.1108/BFJ-02-2023-0092

Ranganathan, J.V., Daniel; Waite, Richard; Searchinger, Tim; Dumas, Patrice; and Lipinski, Brian (2016). Shifting diets: Toward a sustainable food future. In 2016 Global Food Policy Report. Chapter 8. Pp. 66-79. . International Food Policy Research Institute (IFPRI). https://doi.org/10.2499/9780896295827_08

Read, Q.D., Brown, S., Cuéllar, A.D., Finn, S.M., Gephart, J.A., Marston, L.T. et al. (2020). Assessing the environmental impacts of halving food loss and waste along the food supply chain. Science of The Total Environment 712, 136255. https://doi.org/10.1016/j.scitotenv.2019.136255

Regan Plekenpol, T.O., Joseph S. Beckmann, and Emily Broad Leib (2023). Promoting food donmation: Food waste deterrence policies

Reisch, L., Eberle, U. and Lorek, S. (2017). Sustainable food consumption: an overview of contemporary issues and policies. Sustainability: Science, Practice and Policy 9(2), 7-25. https://doi.org/10.1080/15487733.2013.11908111

Reisch, L.A. and Sunstein, C.R. (2021). Plant-Based By Default. One Earth 4(9), 1205-1208. https://doi.org/10.1016/j.oneear.2021.08.007

Ren, J., Stenton-Dozey, Jeanie, Plew, David, Fang, Jianguang, Gall, Mark (2010). An ecosystem model for optimising production in integrated multitrophic aquaculture systems. Ecological Modelling 246, 34-46. https://doi.org/10.1016/j.ecolmodel.2012.07.020

Ren, J.S., Stenton-Dozey, J., Plew, D.R., Fang, J. and Gall, M. (2012). An ecosystem model for optimising production in integrated multitrophic aquaculture systems. Ecological Modelling 246, 34-46. https://doi.org/10.1016/j.ecolmodel.2012.07.020

Renard, D. and Tilman, D. (2019). National food production stabilized by crop diversity. Nature 571(7764), 257-260. 10.1038/s41586-019-1316-y. https://www.nature.com/articles/s41586-019-1316-y#citeas

Reyes, V., Cahill, Emma, Solval, Mis Solval, Kevin (2024). The Potential for Reducing Food Waste through Shelf-Life Extension: Actionable Insights from Data Digitization. Sustainability 16(7), 1-15. https://ideas.repec.org/a/gam/jsusta/v16y2024i7p2986-d1369597.html

Reynolds, K. and Cohen, N. (2016). Beyond the Kale Urban Agriculture and Social Justice Activism in New York City. University of Georgia Press. http://www.jstor.org/stable/j.ctt189tsck

Rezvani Moghaddam, P., Huda, S., Parvez, Q. and Koocheki, A. (2017). Indigenous knowledge in agriculture with particular reference to medicinal crop production in Khorasan, Iran. Knowledge Management and Sustainable

Development in the 21st Century. https://www.taylorfrancis.com/chapters/edit/10.4324/9781351280242-6/indigenous-knowledge-agriculture-particular-reference-medicinal-crop-production-khorasan-iran-rezvani-moghaddam-huda-parvez-koocheki

Ricciardi, V., Ramankutty, N., Mehrabi, Z., Jarvis, L. and Chookolingo, B. (2018). How much of the world's food do smallholders produce? Global Food Security 17, 64-72. https://doi.org/10.1016/j.gfs.2018.05.002

Rico-Sapena, N., Galiana-Sanchez, M. E., Bernabeu-Mestre, J., Trescastro-López, E. M., & Vasallo, J. M. (2019). Efectos de un programa alternativo de promoción de la alimentación saludable en comedor escolar. Ciência & Saúde Coletiva 24, 4071-4082. https://doi.org/10.1590/1413-812320182411.02482018

Rini, L., Bayudan, S., Faber, I., Jietse Schouteten, J., Perez-Cueto, F.J.A., Bechtold, K.-B. et al. (2024). The role of social media in driving beliefs, attitudes, and intentions of meat reduction towards plant-based meat behavioral intentions. Food Quality and Preference 113, 105059. https://doi.org/10.1016/j.foodqual.2023.105059

Riseh, R.S., Vazvani, M.G., Hassanisaadi, M. and Thakur, V.K. (2024). Agricultural wastes: A practical and potential source for the isolation and preparation of cellulose and application in agriculture and different industries. Industrial Crops and Products 208, 117904. https://doi.org/10.1016/j.indcrop.2023.117904

Ritchie, H. (2024). How many animals are factory-farmed? Our World in Data. https://ourworldindata.org/how-many-animals-are-factory-farmed#article-citation

Robles-Piñeros, J., Ramírez-Olaya, L. C. J., & Baptista, G. C. S. (2019). Estrategias educativas e etnobiológicas: la huerta escolar como espacio para el rescate de saberes y el reencuentro com la natureza. Gaia Scientia XII, 4, 60 - 74. http://dx.doi.org/10.22478/ufpb.1981-1268.2018v12n4.42381

Rodriguez, L., Suárez, J.C., Pulleman, M., Guaca, L., Rico, A., Romero, M. et al. (2021). Agroforestry systems in the Colombian Amazon improve the provision of soil ecosystem services. Applied Soil Ecology 164, 103933. https://doi.org/10.1016/j.apsoil.2021.103933

Rojas-Downing, M.M., Nejadhashemi, A.P., Harrigan, T. and Woznicki, S.A. (2017). Climate change and livestock: Impacts, adaptation, and mitigation. Climate Risk Management 16, 145-163. https://doi.org/10.1016/j.crm.2017.02.001

Rombach, M., Dean, D., Vriesekoop, F., de Koning, W., Aguiar, L.K., Anderson, M. et al. (2022). Is cultured meat a promising consumer alternative? Exploring key factors determining consumer's willingness to try, buy and pay a premium for cultured meat. Appetite 179, 106307. https://doi.org/10.1016/j.appet.2022.106307

Romero-Natale, A., Acevedo-Sandoval, O.A. and Sanchez-Porras, A. (2024). Ecosystem Services in the Milpa System: A Systematic Review. One Ecosystem 9, e131969. https://doi.org/10.3897/oneeco.9.e131969

Rose, D.C., Wheeler, R., Winter, M., Lobley, M. and Chivers, C.-A. (2021). Agriculture 4.0: Making it work for people, production, and the planet. Land Use Policy 100, 104933. https://doi.org/10.1016/j.landusepol.2020.104933.

Rose, N., Reeve, B. and Charlton, K. (2022). Barriers and Enablers for Healthy Food Systems and Environments: The Role of Local Governments. Current Nutrition Reports 11(1), 82-93. https://doi.org/10.1007/s13668-022-00393-5

Rosegrant, M.W., Ringler, C. and Zhu, T. (2009). Water for Agriculture: Maintaining Food Security under Growing Scarcity. Annual Review of Environment and Resources 34(Volume 34, 2009), 205-222. https://doi.org/10.1146/annurev.environ.030308.090351

Rosenzweig, C., Mbow, C., Barioni, L.G., Benton, T.G., Herrero, M., Krishnapillai, M. et al. (2020). Climate change responses benefit from a global food system approach. Nature Food 1(2), 94-97. https://doi.org/10.1038/s43016-020-0031-z

Rubio, N.R., Xiang, N. and Kaplan, D.L. (2020). Plant-based and cell-based approaches to meat production. Nature Communications 11(1), 6276. https://doi.org/10.1038/s41467-020-20061-y

Ruel, M.T. and Alderman, H. (2013). Nutrition-sensitive interventions and programmes: how can they help to accelerate progress in improving maternal and child nutrition? The Lancet 382(9891), 536-551. https://doi.org/10.1016/S0140-6736(13)60843-0

Ruggeri Laderchi, C., Lotze-Campen, H., DeClerck, F., Bodirsky, B.L., Collignon, Q., Crawford, M.S., Dietz, S. et al. (2024). The Economics of the Food System Transformation. Food System Economics Commission (FSEC), Global Policy Report. https://foodsystemeconomics.org/wp-content/uploads/FSEC-GlobalPolicyReport-February2024.pdf

Russo, C., Sansone, M., Colamatteo, A. and Pagnanelli, M.A., (2023). Sustainability standards: Voluntary versus mandatory regulation. Publications Office of the European Union, Luxembourg. https://publications.jrc.ec.europa.eu/repository/handle/JRC130619

S., P.B.M.a.N.W. (2022). The nutrition taxation to a stage of high obesity and noncommunicable disease prevalence dominated by ultra processed food is not inevitable. Obesity Reviews 1(23). https://doi.org/10.1111/obr.13366

Sahoo, A., Dwivedi, A., Madheshiya, P., Kumar, U., Sharma, R.K. and Tiwari, S. (2024). Insights into the management of food waste in developing countries: with special reference to India. Environmental Science and Pollution Research 31(12), 17887-17913. https://doi.org/10.1007/s11356-023-27901-6

Santo, R.E., Kim, B.F., Goldman, S.E., Dutkiewicz, J., Biehl, E.M.B., Bloem, M.W. et al. (2020). Considering Plant-Based Meat Substitutes and Cell-Based Meats: A Public Health and Food Systems Perspective. Frontiers in Sustainable Food Systems 4. https://doi.org/10.3389/fsufs.2020.00134

Sapkota, T.B., Dittmer, K.M., Ortiz-Monasterio, I., Mathivanan, G.P., Sonder, K., Leyva, J.C. et al. (2022). Quantification of economically feasible mitigation potential from agriculture, forestry and other land uses in Mexico. Carbon Management 13(1), 594-607. https://doi.org/10.1080/17583004.2022.2151939

Sapkota, T.B., Jat, M.L., Rana, D.S., Khatri-Chhetri, A., Jat, H.S., Bijarniya, D. et al. (2021). Crop nutrient management using Nutrient Expert improves yield, increases farmers' income and reduces greenhouse gas emissions. Scientific Reports 11(1), 1564. https://doi.org/10.1038/s41598-020-79883-x

Sapkota, T.B., Singh, L.K., Yadav, A.K., Khatri-Chhetri, A., Jat, H.S., Sharma, P.C. et al. (2020). Identifying optimum rates of fertilizer nitrogen application to maximize economic return and minimize nitrous oxide emission from rice–wheat systems in the Indo-Gangetic Plains of India. Archives of Agronomy and Soil Science 66(14), 2039-2054. https://doi.org/10.1080/03650340.2019.1708332

Sapkota, T.B., Vetter, S.H., Jat, M.L., Sirohi, S., Shirsath, P.B., Singh, R. et al. (2019). Cost-effective opportunities for climate change mitigation in Indian agriculture. Sci Total Environ 655, 1342-1354. https://doi.org/10.1016/j.scitotenv.2018.11.225

Sarkar, J.G., Sarkar, A. and Sreejesh, S. (2023). Developing responsible consumption behaviours through social media platforms: sustainable brand practices as message cues. Information Technology & People 36(2), 532-563. https://doi.org/10.1108/ITP-01-2021-0044

Sathish Kumar, R.K., Sasikumar, R. and Dhilipkumar, T. (2024). Exploiting agro-waste for cleaner production: A review focusing on biofuel generation, bio-composite production, and environmental considerations. Journal of Cleaner Production 435, 140536. https://doi.org/10.1016/j.jclepro.2023.140536

Schubel, J.R. and Thompson, K. (2019). Farming the Sea: The Only Way to Meet Humanity's Future Food Needs. GeoHealth 3(9), 238-244. https://doi.org/10.1029/2019GH000204

Seherrington, R., Carlile, Clare, Healy, Hazel (2023). Big meat and dairy lobbyists turn out in record numbers at COP28. The Guardian https://www.theguardian.com/environment/2023/dec/09/big-meat-dairy-lobbyists-turn-out-record-numbers-cop28. Accessed 10 April 2025

Sekaran, U., Lai, L., Ussiri, D.A.N., Kumar, S. and Clay, S. (2021). Role of integrated crop-livestock systems in improving agriculture production and addressing food security – A review. Journal of Agriculture and Food Research 5, 100190. https://doi.org/10.1016/j.jafr.2021.100190

Semba, R.D., Neu, P., Berg, P., Harding, J., McKenzie, S. and Ramsing, R. (2024). The origins and growth of the Meatless Monday movement. Front Nutr 11, 1283239. https://doi.org/10.3389/fnut.2024.1283239

Sexton, A.E., Garnett, T. and Lorimer, J. (2019). Framing the future of food: The contested promises of alternative proteins. Environment and Planning E: Nature and Space 2(1), 47-72. https://doi.org/10.1177/2514848619827009

Shafqat, A.R., Hussain, M., Nawab, Y., Ashraf, M., Ahmad, S. and Batool, G. (2023). Circularity in Materials: A Review on Polymer Composites Made from Agriculture and Textile Waste. International Journal of Polymer Science 2023(1), 5872605. https://doi.org/10.1155/2023/5872605

Shangguan, S., Afshin, A., Shulkin, M., Ma, W., Marsden, D., Smith, J. et al. (2019). A Meta-Analysis of Food Labeling Effects on Consumer Diet Behaviors and Industry Practices. American Journal of Preventive Medicine 56(2), 300-314. https://doi.org/10.1016/j.amepre.2018.09.024

Shukla, P., Pullabhotla, H.K. and Baylis, K. (2023). The economics of reducing food losses: Experimental evidence from improved storage technology in India. Food Policy 117, 102442. https://doi.org/10.1016/j.foodpol.2023.102442

Sidaner, E., Balaban, D. and Burlandy, L. (2013). The Brazilian school feeding programme: an example of an integrated programme in support of food and nutrition security. Public Health Nutrition 16(6), 989-994. https://doi.org/10.1017/s1368980012005101

Sievert, K., Lawrence, M., Parker, C. and Baker, P. (2024). How power in corporate-industrial meat supply chains enables negative externalities: Three case studies from Brazil, the US, and Australia. One Earth 7(8), 1424-1441. https://doi.org/10.1016/j.oneear.2024.07.004

Sikka, A.K., Alam, M.F. and Mandave, V. (2022). Agricultural water management practices to improve the climate resilience of irrigated agriculture in India. Irrigation and Drainage 71(S1), 7-26. https://doi.org/10.1002/ird.2696

Sillman, J., Uusitalo, V., Ruuskanen, V., Ojala, L., Kahiluoto, H., Soukka, R. et al. (2020). A life cycle environmental sustainability analysis of microbial protein production via power-to-food approaches. The International Journal of Life Cycle Assessment 25(11), 2190-2203. https://doi.org/10.1007/s11367-020-01771-3

Sinclair, F., Wezel, Alexander, Mbow, Cheikh, Chokmba, Susan., Robiglio, Valentina, Harrison, Rhett (2019). The Contribution of Agroecological Approaches to Realizing Climate-Resilient Agriculture. Global Commission on Adaptation Background Paper. https://gca.org/reports/the-contributions-of-agroecological-approaches-to-realizing-climate-resilient-agriculture/

Sinke, P., Swartz, E., Sanctorum, H., van der Giesen, C. and Odegard, I. (2023). Ex-ante life cycle assessment of commercial-scale cultivated meat production in 2030. The International Journal of Life Cycle Assessment 28(3), 234-254. https://doi.org/10.1007/s11367-022-02128-8

Sitachew, M., Jeyabalasingh, Mansingh, Paul, Debela, Mulu (2018). Determinants of Rural Women's Participation in Agricultural Extension Services: Case of Irrigable Vegetable Production in Oromia Region, Ethiopia. Journal of Extension Education 30. http://dx.doi.org/10.26725/JEE.2018.3.30.6092-6099

Slater, S., Lawrence, M., Wood, B., Serodio, P., Van Den Akker, A. and Baker, P. (2024). The rise of multi-stakeholderism, the power of ultra-processed food corporations, and the implications for global food governance: a network analysis. Agriculture and Human Values. https://doi.org/10.1007/s10460-024-10593-0

Smith, M.D., Roheim, C.A., Crowder, L.B., Halpern, B.S., Turnipseed, M., Anderson, J.L. et al. (2010). Sustainability and Global Seafood. Science 327(5967), 784-786. https://doi.org/10.1126/science.1185345

Smith, O.M., Cohen, A.L., Rieser, C.J., Davis, A.G., Taylor, J.M., Adesanya, A.W. et al. (2019). Organic Farming Provides Reliable Environmental Benefits but Increases Variability in Crop Yields: A Global Meta-Analysis. Frontiers in Sustainable Food Systems 3. http://dx.doi.org/10.3389/fsufs.2019.00082

Smith, R., Kelly, B., Yeatman, H. and Boyland, E. (2019). Food Marketing Influences Children's Attitudes, Preferences and Consumption: A Systematic Critical Review. Nutrients 11(4), 875. https://doi.org/10.3390/nu11040875

Snapp, S., Sapkota, T.B., Chamberlin, J., Cox, C.M., Gameda, S., Jat, M.L. et al. (2023). Spatially differentiated nitrogen supply is key in a global food–fertilizer price crisis. Nature Sustainability 6(10), 1268-1278. https://doi.org/10.1038/s41893-023-01166-w

Sniatala, B., Kurniawan, T.A., Sobotka, D., Makinia, J. and Othman, M.H.D. (2023). Macro-nutrients recovery from liquid waste as a sustainable resource for production of recovered mineral fertilizer: Uncovering alternative options to sustain global food security cost-effectively. Science of The Total Environment 856, 159283. https://doi.org/10.1016/j.scitotenv.2022.159283

Soares, P., Martinelli, S.S., Atance, E.A., Fabri, R., Clemente-Gómez, V., Davó-Blanes, M.C. et al. (2024). Benefits and challenges of the public food procurement program: Perspectives of technicians and managers of family farmer organizations in Brazil. Heliyon 10(20), e39019. https://doi.org/10.1016/j.heliyon.2024.e39019

Soma, T., Shulman, T., Li, B., Bulkan, J. and Curtis, M. (2022). Food assets for whom? Community perspectives on food asset mapping in Canada. Journal of Urbanism: International Research on Placemaking and Urban Sustainability 15(3), 322-339. https://doi.org/10.1080/17549175.2021.1918750

Somlai, R. (2022). Integrating decision support tools into businesses for sustainable development: A paradoxical approach to address the food waste challenge. Business Strategy and the Environment 31(4), 1607-1622. https://doi.org/10.1002/bse.2972

Sousa, R.D., Bragança, L., da Silva, M.V. and Oliveira, R.S. (2024). Challenges and Solutions for Sustainable Food Systems: The Potential of Home Hydroponics. Sustainability, 2. https://doi.org/10.3390/su16020817

Springmann, M., Spajic, L., Clark, M.A., Poore, J., Herforth, A., Webb, P. et al. (2020). The healthiness and sustainability of national and global food based dietary guidelines: modelling study. BMJ 370, m2322. https://doi.org/10.1136/bmj.m2322

Sraku-Lartey, M. (2021). Connecting the world through local Indigenous Knowledge. Information Services & Use 41, 43-51. https://doi.org/10.3233/ISU-210115

Stahlbrand, L.M. (2016). A typology of 'infrastructure of the middle' in university food procurement in England and Canada: elaborating the 'to' in 'farm to cafeteria'. Raizes: Revista de Ciencias Sociais e Economicas, 36(2), pp. 32–44. http://www.ufcg.edu.br/~raizes/artigos/Artigo_392.pdf

Stephens, N., Di Silvio, L., Dunsford, I., Ellis, M., Glencross, A. and Sexton, A. (2018). Bringing cultured meat to market: Technical, socio-political, and regulatory challenges in cellular agriculture. Trends in Food Science & Technology 78, 155-166. https://doi.org/10.1016/j.tifs.2018.04.010

Surdulescui, A.M., et al. (2023). Study regarding solving food waste and food loss. Agricultural Management / Lucrari Stiintifice Seria I, Management Agricol. 25(3)

Swensson, L. and Tartanac, F. (2020). Public food procurement for sustainable diets and food systems: The role of the regulatory framework. Global Food Security 25, 100366. https://doi.org/10.1016/j.gfs.2020.100366

Swensson, L.F.J., Hunter, D., Schneider, S. and Tartanac, F. (2021). Public food procurement as a game changer for food system transformation. The Lancet Planetary Health 5(8), e495-e496. https://doi.org/10.1016/S2542-5196(21)00176-5

Tadele, Z. (2019). Orphan crops: their importance and the urgency of improvement. Planta 250(3), 677-694. https://doi.org/10.1007/s00425-019-03210-6

Taillie, L.S., Bercholz, M., Popkin, B., Reyes, M., Colchero, M.A. and Corvalán, C. (2021). Changes in food purchases after the Chilean policies on food labelling, marketing, and sales in schools: a before and after study. The Lancet Planetary Health 5(8), e526-e533. https://doi.org/10.1016/s2542-5196(21)00172-8

Talabi, A.O., Vikram, P., Thushar, S., Rahman, H., Ahmadzai, H., Nhamo, N. et al. (2022). Orphan Crops: A Best Fit for Dietary Enrichment and Diversification in Highly Deteriorated Marginal Environments. Frontiers in Plant Science 13. https://doi.org/10.3389/fpls.2022.839704

Tamagnone, P., Cea, L., Comino, E. and Rosso, M. (2020). Rainwater Harvesting Techniques to Face Water Scarcity in African Drylands: Hydrological Efficiency Assessment. Water, 9. https://doi.org/10.3390/w12092646

Taylor, B.C., Lejzerowicz, F., Poirel, M., Shaffer, J.P., Jiang, L., Aksenov, A. et al. (2020). Consumption of Fermented Foods Is Associated with Systematic Differences in the Gut Microbiome and Metabolome. mSystems 5(2). https://doi.org/10.1128/msystems.00901-19

Teng, A.M., Jones, A.C., Mizdrak, A., Signal, L., Genç, M. and Wilson, N. (2019). Impact of sugar-sweetened beverage taxes on purchases and dietary intake: Systematic review and meta-analysis. Obes Rev 20(9), 1187-1204. https://doi.org/10.1111/obr.12868

The Food and Land Coalition (2019). Growing Better: Ten Critical Transitions to Transform Food and Land Use. https://www.foodandlandusecoalition.org/wp-content/uploads/2019/09/FOLU-GrowingBetter-GlobalReport.pdf

The Good Food Institute (2022). 2022 State of the industry report: Plant-based meat, seafood, eggs, and diary. https://gfi.org/wp-content/uploads/2023/01/2022-Plant-Based-State-of-the-Industry-Report.pdf

Thivya, P., Bhanu Prakash Reddy, N., Bhosale Yuvraj, K. and Sinija, V.R. (2023). Recent advances and perspectives for effective utilization of onion solid waste in food packaging: a critical review. Reviews in Environmental

Science and Bio/Technology 22(1), 29-53. https://doi.org/10.1007/s11157-022-09642-z

Thow, A.M., Downs, S. and Jan, S. (2014). A systematic review of the effectiveness of food taxes and subsidies to improve diets: understanding the recent evidence. Nutr Rev 72(9), 551-565. https://doi.org/10.1111/nure.12123

Tittonell, P. and Giller, K.E. (2013). When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. Field Crops Research 143, 76-90. https://doi.org/10.1016/j.fcr.2012.10.007

United Nations Convention on Combatting Desertification and Convention on Biodiversity (2023). Land Restoration to Safeguard Nature and Livelihoods. https://www.unccd.int/sites/default/files/2023-05/Synergy%20Brief_UNCCD-CBD_March%202023.pdf

United Nations Department of Economic and Social Affairs (2023). The Sustainable Development Goals Report 2023: Special edition. Towards a Rescue Plan for People and Planet. https://sdgs.un.org/sites/default/files/2023-07/The-Sustainable-Development-Goals-Report-2023_0.pdf

United Nations Environment Programme (2016). Food Systems and Natural Resources. A Report of the Working Group on Food Systems of the International Resource Panel. https://www.resourcepanel.org/reports/food-systems-and-natural-resources

United Nations Environment Programme (2023) Frontiers 2023. What's Cooking? An assessment of the potential impacts of selected novel alternatives to conventional animal products. Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/44236/whats_cooking_frontiers.pdf?sequence=1&isAllowed=y

United nations environment Programme (2024). Food Waste Index Report 2024. Think Eat Save: Tracking Progress to Halve Global Food Waste. https://wedocs.unep.org/handle/20.500.11822/45230

United Nations Environment Programme and Food and Agriculture Organization of the United Nations (2024). Global Nitrous Oxide Assessment. https://wedocs.unep.org/20.500.11822/46562

United Nations Environment Programme and International Livestock Research Institute (2020). Preventing the Next Pandemic: Zoonotic diseases and how to break the chain of transmission. https://wedocs.unep.org/bitstream/handle/20.500.11822/32316/ZP.pdf?sequence=1&isAllowed=y

United Nations Environment Programme, Food and Agriculture Organization of the United Nations and United Nations Development Programme. (2023). Rethinking our food systems: A guide for multi-stakeholder collaboration. https://www.undp.org/publications/rethinking-our-food-systems-guide-multi-stakeholder-collaboration

United Nations Environment Programme, WRAP, World Resources Institute and Food Law and Policy Clinic (2022). Changing behaviour to help more people waste less food. https://champions123.org/sites/default/files/2022-09/Champions_12.3_Playbook_HIGH-RESOLUTION.pdf

United Nations Water (2017). Water quality and wastewater. https://www.unwater.org/water-facts/water-quality-and-wastewater

Vafadarnikjoo, A., Moktadir, M.A., Paul, S.K. and Ali, S.M. (2023). A novel grey multi-objective binary linear programming model for risk assessment in supply chain management. Supply Chain Analytics 2, 100012. https://doi.org/10.1016/j.sca.2023.100012

Vågen, T.-G. and Winowiecki, L.A. (2019). Predicting the Spatial Distribution and Severity of Soil Erosion in the Global Tropics using Satellite Remote Sensing. Remote Sensing, 15. https://doi.org/10.3390/rs11151800

Valicente, V.M., Peng, C.-H., Pacheco, K.N., Lin, L., Kielb, E.I., Dawoodani, E. et al. (2023). Ultraprocessed Foods and Obesity Risk: A Critical Review of Reported Mechanisms. Advances in Nutrition 14(4), 718-738. https://doi.org/10.1016/j.advnut.2023.04.006

van Delden, S.H., SharathKumar, M., Butturini, M., Graamans, L.J.A., Heuvelink, E., Kacira, M. et al. (2021). Current status and future challenges in implementing and upscaling vertical farming systems. Nature Food 2(12), 944-956. https://doi.org/10.1038/s43016-021-00402-w

van den Broek, S., Nybom, I., Hartmann, M., Doetterl, S. and Garland, G. (2024). Opportunities and challenges of using human excreta-derived fertilizers in agriculture: A review of suitability, environmental impact and societal acceptance. Science of The Total Environment 957, 177306. https://doi.org/10.1016/j.scitotenv.2024.177306

van der Weele, C. and Driessen, C. (2019). How Normal Meat Becomes Stranger as Cultured Meat Becomes More Normal; Ambivalence and Ambiguity Below the Surface of Behavior. Frontiers in Sustainable Food Systems 3. https://doi.org/10.3389/fsufs.2019.00069

van Groenigen, J.W., van Kessel, C., Hungate, B.A., Oenema, O., Powlson, D.S. and van Groenigen, K.J. (2017). Sequestering Soil Organic Carbon: A Nitrogen Dilemma. Environmental Science & Technology 51(9), 4738-4739. https://doi.org/10.1021/acs.est.7b01427

Vanlauwe, B., Coyne, D., Gockowski, J., Hauser, S., Huising, J., Masso, C. et al. (2014). Sustainable intensification and the African smallholder farmer. Current Opinion in Environmental Sustainability 8, 15-22. https://doi.org/10.1016/j.cosust.2014.06.001

Vecchio, R. and Cavallo, C. (2019). Increasing healthy food choices through nudges: A systematic review. Food Quality and Preference 78, 103714. https://doi.org/10.1016/j.foodqual.2019.05.014

Verdegem, M., Buschmann, A.H., Latt, U.W., Dalsgaard, A.J.T. and Lovatelli, A. (2023). The contribution of aquaculture systems to global aquaculture production. Journal of the World Aquaculture Society 54(2), 206-250. https://doi.org/10.1111/jwas.12963

Vergeer, R., Odegard, I. and Sinke, P. (2021). TEA of cultivated meat. Future projections for different scenarios. Delft: CE Delft. https://cedelft.eu/publications/tea-of-cultivated-meat/

Vermeulen, S.J., Park, T., Khoury, C.K. and Béné, C. (2020). Changing diets and the transformation of the global food system. Annals of the New York Academy of Sciences 1478(1), 3-17. https://doi.org/10.1111/nyas.14446

Veselá, L., Králiková, A. and Kubíčková, L. (2023). From the shopping basket to the landfill: Drivers of consumer food waste behaviour. Waste Management 169, 157-166. https://doi.org/10.1016/j.wasman.2023.07.002

Vieira, J., Castro, S.L. and Souza, A.S. (2023). Psychological barriers moderate the attitude-behavior gap for climate change. PLoS One 18(7), e0287404. https://doi.org/10.1371/journal.pone.0287404

Voge, J., Newiger-Dous, T., Ehrlich, E., Ermann, U., Ernst, D., Haase, D. et al. (2023). Food loss and waste in community-supported agriculture in the region of Leipzig, Germany. International Journal of Agricultural Sustainability 21(1), 2242181. https://doi.org/10.1080/14735903.2023.2242181

Wan Azman, W.N.F.S., Ku Azir, K.N.F. and Mohd Khairuddin, A. (2024). An Embedded Machine Learning-Based Spoiled Leftover Food Detection Device for Multiclass Classification. Journal of Information and Communication Technology 23(2), 253-292. https://doi.org/10.32890/jict2024.23.2.4

Wang, Y., Weng, F. and Huo, X. (2023). Can Digital Finance Promote Professional Farmers' Income Growth in China?—An Examination Based on the Perspective of Income Structure. Agriculture, 5. https://doi.org/10.3390/agriculture13051103

Wattel, C., Negede, B., Desczka, S., Pamuk, H., Van Asseldonk, M., Castro Nunez et al. (2024). Finance for low-emission food systems: Six financial instruments with country examples. Technical Report, CGIAR Research Initiative for Low-Emission Food Systems. https://edepot.wur.nl/646851

Webb, D. and Byrd-Bredbenner, C. (2015). Overcoming consumer inertia to dietary guidance. Adv Nutr 6(4), 391-396. https://doi.org/10.3945/an.115.008441

Webb, P., Stordalen, G.A., Singh, S., Wijesinha-Bettoni, R., Shetty, P. and Lartey, A. (2018). Hunger and malnutrition in the 21st century. BMJ 361, k2238. https://doi.org/10.1136/bmj.k2238

Wilks, M., Phillips, C.J.C., Fielding, K. and Hornsey, M.J. (2019). Testing potential psychological predictors of attitudes towards cultured meat. Appetite 136, 137-145. https://doi.org/10.1016/j.appet.2019.01.027

Wolfson, J.A., Musicus, A.A., Leung, C.W., Gearhardt, A.N. and Falbe, J. (2022). Effect of Climate Change Impact Menu Labels on Fast Food Ordering Choices Among US Adults: A Randomized Clinical Trial. JAMA Netw Open 5(12), e2248320. https://doi.org/10.1001/jamanetworkopen.2022.48320

Wolfson, J.A., Ramsing, R., Richardson, C.R. and Palmer, A. (2019). Barriers to healthy food access: Associations with household income and cooking behavior. Prev Med Rep 13, 298-305. https://doi.org/10.1016/j.pmedr.2019.01.023

Wongpiyabovorn, O., Plastina, A. and Crespi, J.M. (2023). Challenges to voluntary Ag carbon markets. Applied Economic Perspectives and Policy 45(2), 1154-1167. https://doi.org/10.1002/aepp.13254

Wood, A., Moberg, E., Curi-Quinto, K., Van Rysselberge, P. and Röös, E. (2023). From "good for people" to "good for people and planet" – Placing health and environment on equal footing when developing food-based dietary guidelines. Food Policy 117, 102444. https://doi.org/10.1016/j.foodpol.2023.102444

Wood, B., Williams, O., Baker, P., Nagarajan, V. and Sacks, G. (2021). The influence of corporate market power on health: exploring the structure-conduct-performance model from a public health perspective. Globalization and Health 17(1), 41. https://doi.org/10.1186/s12992-021-00688-2

Wood, B., Williams, O., Baker, P. and Sacks, G. (2023). Behind the 'creative destruction' of human diets: An analysis of the structure and market dynamics of the ultra-processed food manufacturing industry and implications for public health. Journal of Agrarian Change 23(4), 811-843. https://doi.org/10.1111/joac.12545

World Bank (2022). The World Bank Annual Report 2022. https://documents1.worldbank.org/curated/fr/630671538158537244/pdf/The-World-Bank-Annual-Report-2018.pdf

World Health Organization (2016). Taxes on sugary drinks: why do it? https://iris.who.int/bitstream/handle/10665/260253/WHO-NMH-PND-16.5Rev.1-eng.pdf

World Health Organization (2022). Policy Brief: Taxing sugar-sweetened beverages. https://iris.who.int/bitstream/handle/10665/357078/WHO-EURO-2022-5721-45486-65112-eng.pdf?sequence=1

World Health Organization (2024). Commercial Determinants of Noncommunicable Diseases in the WHO European Region. World Health Organization. Regional Office for Europe. https://iris.who.int/bitstream/handle/10665/376957/9789289061162-eng.pdf?sequence=2

Wunder, S.a.B., Jan and Ezzine-de-Blas, Driss and Feder, Sarah and Pagiola, Stefano (2020). Payments for Environmental Services: Past Performance and Pending Potentials. Annual Review of Resource Economics 12(1). http://dx.doi.org/10.1146/annurev-resource-100518-094206

Xu, Y., Li, P., Zou, C., Lu, Y., Xie, C., Zhang, X. et al. (2017). Enhancing genetic gain in the era of molecular breeding. J Exp Bot 68(11), 2641-2666. https://doi.org/10.1093/jxb/erx135

Xu, Y., Liu, X., Fu, J., Wang, H., Wang, J., Huang, C. et al. (2020). Enhancing Genetic Gain through Genomic Selection: From Livestock to Plants. Plant Commun 1(1), 100005. https://doi.org/10.1016/j.xplc.2019.100005

Xu, X., Sharma, P., Shu, S., Lin, T.-S., Ciais, P., Tubiello, F.N. et al. (2021). Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. Nature Food 2(9), 724-732. https://doi.org/10.1038/s43016-021-00358-x.

Yaser, A.Z., Lamaming, J., Suali, E., Rajin, M., Saalah, S., Kamin, Z. et al. (2022). Composting and Anaerobic Digestion of Food Waste and Sewage Sludge for Campus Sustainability: A Review. International Journal of Chemical Engineering 2022(1), 6455889. https://doi.org/10.1155/2022/6455889

Yi, J., Meemken, E.-M., Mazariegos-Anastassiou, V., Liu, J., Kim, E., Gómez, M.I. et al. (2021). Post-farmgate food value chains make up most of consumer food expenditures globally. Nature Food 2(6), 417-425. https://doi.org/10.1038/s43016-021-00279-9

Yıldırım, S. (2021). Do green women influencers spur sustainable consumption patterns? Descriptive evidences from social media influencers. Ecofeminism and Climate Change 2(4), 198-210. https://www.emerald.com/insight/content/doi/10.1108/efcc-02-2021-0003/full/pdf

Zhang, T., Nickerson, R., Zhang, W., Peng, X., Shang, Y., Zhou, Y. et al. (2024). The impacts of animal agriculture on One Health—Bacterial zoonosis, antimicrobial resistance, and beyond. One Health 18, 100748. https://doi.org/10.1016/j.onehlt.2024.100748

Zhong, S. (2023) Relational proximity: The search for local food in China. Food, Culture & Society, 1-19. https://doi.org/10.1080/15528014.2023.2239105

Zurek, M., Hebinck, A. and Selomane, O. (2022). Climate change and the urgency to transform food systems. Science 376(6600), 1416-1421. https://doi.org/10.1126/science.abo2364

Zuza, E.J., Lambert K., Macmillan, T., Chiyemura F., Araya, Y., Bowskill. V., et al. (2024). Crop species diversity: A key strategy for sustainable food system transformation and climate resilience. Food and Energy Security 13. https://doi.org/10.1002/fes3.558

18 Solution Pathways Enabling a Sustainable and Resilient Environment for Systems Transformation

Coordinating Lead Authors: Binaya Raj Shivakoti (Institute for Global Environmental Strategies), Gail Taylor (University College London)

Lead authors: Adolf Acquaye (Khalifa University of Science and Technology), Alex Godoy-Faúndez (Universidad del Desarrollo), Kalim Shah (University of Delaware), Svetlana Radionova (Natural Resources of the Russian Federation)
Contributing author: Olga Illarionova (Lomonosov Moscow State University)

Fellow: Soham Vaidya (Global Shield Secretariat)

Credit: Lazy_Bear/Envato

Chapter summary

Credit: Shaiith/Envato

The global crises of climate change, biodiversity loss and pollution, together with land degradation, are putting both people and nature at risk by pushing the environment system beyond six out of nine planetary boundaries, which are critical for maintaining a safe operating space for human existence *(very well established)*. Sustainable development requires that society works together through action across social, technological, political and economic levers to build a resilient, culturally meaningful, and sustainable environment system. This also means transforming how production and consumption of energy, food, and resources in circularity and management economic and financial systems are carried out *(established but incomplete)*.

Three overarching goals with significant transformative potential to support nature, alongside circularity, energy and food systems are identified:

- strengthen the nature-society-economics nexus enabling integrated ecological health with an inclusive social and economic well-being

- adopt transformative adaptation of socioecological systems for climate resilience and delivering enhanced benefits to nature and people

- restore natural capital through a sociotechnological approach to enable sustainable bioeconomy to substantially reduce pressures on ecosystems and biodiversity.

A sustainable and resilient environment, delivering for both humans and nature, can be achieved, but only if management of natural resources changes. This means using less, wasting less, and protecting valuable ecosystem services, such as clean water and air and healthy soils. To do this, the solutions need to be fair and inclusive, and shaped by the knowledge of Indigenous Peoples and local communities *(established but incomplete)*. Internationally agreed goals for addressing climate change, reducing biodiversity loss and stopping pollution, cannot be achieved without a transformative approach to environmental protection and management *(very well established)*. In GEO-7, earlier chapters present methods and solutions for transforming four key human-controlled systems: economic and financial, circularity, energy, and food. Building on these insights, this chapter develops a narrative to create a sustainable and resilient environment system, outlining clear goals and the solutions needed to address the challenges of global crises. These goals are reached through a series of solution pathways, which involve specific actions carried out across different time frames and scales and by various actors.

The first goal is to strengthen the alignments among nature, society and the economy through sustainable land use, green infrastructure, climate change adaptation, and sustainable consumption. {18.1} This integrated systems approach supports ecological health, social inclusion, and economic well-being, enabling a balance across all systems *(established but incomplete)*. Implementing these actions can enhance biodiversity across urban, rural, and marine areas, while supporting vital ecosystem services that benefit both people and nature. They also align with key global frameworks, including the One Health approach, the 2030 Sustainable Development Agenda, the Paris Agreement, and the 2022 Kunming-Montreal Global Biodiversity Framework (GBF) *(well established)*.

The second goal – transformative adaptation – will alleviate the worsening effects of climate change and build future resilience of socioecological systems across land and sea. {18.1} Without effective climate change adaptation (CCA), progress on biodiversity conservation and restoration, food security, and community resilience is at risk *(well established)*. There is an overwhelming scientific consensus that transformative adaptation is needed, rather than incremental steps (UNDRR 2015; IPCC 2022). Rapid scaling up of locally led adaptation (LLA) actions and disaster risk management (DRM) is crucial for driving transformative adaptation, while minimizing loss and damage from extreme climate events and complex multi-hazard emergencies.

The third goal is to restore natural capital by substantially reducing pressures on ecosystems and biodiversity. This will help to halt ecosystem degradation and support conservation goals and targets, including the targets of the GBF, such as the 30 x 30 target to conserve 30 per cent of the world's land and oceans by 2030, in line with the human rights-based approach. {18.1} *(established but incomplete)*. The circular economy plays a key role in restoring natural capital by moving away from the traditional linear model of "take, make, dispose". It promotes recycling, reusing, refurbishing and sharing products to minimize waste and reduce the extraction of new resources. Innovative biobased materials, such as biodegradable products derived from agricultural waste and perennial feedstocks, offer sustainable alternatives to fossil-based products. Scaling up bioeconomy infrastructure, including biorefineries and supply chains for biobased products, is essential for using renewable biological resources at a larger scale. Efficiently managed protected areas is another vital component of the GBF 30 x 30 target, though it remains a challenge for many regions. When successfully implemented, it can significantly improve ecosystems' resilience and health. Regional policies, legislations and initiatives are needed to promote nature restoration and sustainable land use.

We identify five solution pathways to enable a sustainable and resilient environment system. {18.2} The first is conserving ecosystems and biodiversity, including sustainable land management practices. {18.2.1} The second is widescale implementation of nature-based solutions (NbS). {18.2.2} The third is upscaling LLA. {18.2.3} The fourth is accelerating a biobased circular economy. {18.2.4} The fifth is expanding integrated solutions through strong governance, local community

engagement and inclusion of Indigenous Knowledge and Local Knowledge {18.2.5}.

These solution pathways are complex and involve trade-offs, but they also offer co-benefits that help nature, energy and food systems to be more resilient, while enabling circular economies in the future *(established but incomplete)*. They are aligned with the ambitions of the GEO-7 target seeking scenarios, that in different ways, particularly with respect to land use, enable ambitious global targets for the environment to be met.

The first solution pathway – protection and conservation of ecosystems and biodiversity – is critical for the planet's overall sustainability and the implementation of the ambitious 30 x 30 target of the Global Biodiversity Framework *(very well established)*. The target seeking scenarios of GEO-7, show that ecosystem protection, conservation and restoration require faster, more coordinated efforts that combine a wide mix of proven and innovative approaches to manage environmental drivers and pressures. These efforts are aimed at improving both the quantity and quality of natural capital and ecosystem services. Successful actions could include NbS, regenerative production systems, expanding and connecting protected areas to form biodiversity corridors, and strengthening pollution control, including plastic waste {18.2.1}.

Analysis of the two GEO-7 target seeking scenarios illustrates that protection of existing ecosystems, restoration of degraded lands and improved land management are crucial to preserving biodiversity, halting land degradation, and increasing carbon storage *(well established)*. Both target seeking scenarios envision an increase in protected areas, ranging from 30 per cent with strict protection to 50 per cent with more symbiotic relations between humans and nature. This strongly contributes to preventing the conversion of natural land and increases the possibilities of tackling biodiversity loss. Furthermore, conservation and expansion of natural lands enables them to act as important carbon sinks and thus contribute to climate change mitigation, while improving natural capital {18.2.1; 18.2.1.2; 18.2.1.3}.

The second solution pathway involves broad adoption of NbS, which offers a holistic strategy to foster a resilient and sustainable environment. This facilitates systems transformation, with many practices already recognized and implemented worldwide *(well established)*. However, NbS need to be scaled up significantly to unlock greater systems transformation. {18.2.2} This includes expanding ecosystem restoration, strengthening climate resilience, and maximizing co-benefits across socioecological systems. As a broad approach, NbS works across sectors and actions – including enhancing ecosystem services, regenerating food and energy systems, implementing green infrastructure, promoting sustainable agriculture, applying ecosystem-based adaptation (EbA) and disaster risk reduction, expanding and interconnecting protected areas to create biodiversity corridors, and using NbS for greenhouse gas mitigation through biogeochemical carbon capture {18.2.2}.

By definition, NbS are balanced and cost-effective approaches that can build on Indigenous Knowledge and Local Knowledge *(incomplete)*. They aim to enhance ecosystem services by supporting and improving both natural and human-made systems. However, the choice and implementation scope of NbS must be tailored to the local conditions to ensure the interests and the well-being of local communities are protected, while preserving the integrity of natural ecosystems {18.2.2.3}.

The third solution pathway integrates approaches for socioecological resilience through scaling up LLA and DRM with a multi-hazard perspective. This solution narrative is crucial for driving transformative adaptation and minimizing loss and damage to both humans and nature across land, island, and marine environments *(well established)*. LLA draws on the wealth of knowledge and experience of the Indigenous Peoples as well as local communities, while incorporating robust DRM to address the increasing challenges of unprecedented multi-hazards.

A combination of bottom-up and top-down adaptation strategies can leverage Indigenous Knowledge and Local Knowledge to promote innovation. This approach ensures that solutions are culturally suitable and have community support, which is essential for their long-term effectiveness {18.2.3}.

The fourth solution pathway enables the acceleration of circularity by developing innovative sustainable biomass feedstocks and building a sustainable bioeconomy infrastructure. This shift aims to replace fossil fuel-based supply chains and support a resilient and sustainable environment in the future *(well established)*.

Transitioning to circularity and a sustainable bioeconomy is a significant step towards reducing reliance on

fossil-based energy, food production, materials, pharmaceuticals, and chemicals, with 23 countries with bioeconomy strategies and 15 others in development. In the EU, 130 woody biomass-based biorefineries are in operation, with more planned. Both of the GEO-7 target seeking scenarios identify sustainable biomass as a key part of achieving a transition to a low-carbon energy system, consistent with the Paris Agreement, with the behaviour-focused enabling a sustainable environment system for people and planet. This transformation requires a significant increase in biobased and microbial resources, while managing land, oceans and waste streams more responsibly and in harmony with nature (well established). Emerging technologies, such as bioengineering of new plant, animal and microbial resources, can enable the production of high-value chemicals, pharmaceuticals, energy, fuels, climate change mitigation and materials, as well as new types of engineered foods and medicines *(incomplete)* {18.2.4}.

The fifth solution pathway is establishing a strong adaptive governance to integrate the four other solution pathways across economic and financial, food, energy, and circularity systems. This approach enables adaptive decision-making and the balancing of multiple priorities, laying the foundation for scaling up and expanding the sustainability transformation *(established but incomplete)*. While these solutions are already known, they are poorly connected, inconsistently implemented, and ineffective without strong governance. Adaptive governance can play a crucial role by connecting local communities and integrating Indigenous Knowledge and Local Knowledge with national policies for biodiversity conservation, CCA, and the bioeconomy transition. This integrated approach could be instrumental for addressing the key drivers and pressures of environmental systems {18.2.5}.

The success of these transformative solution pathways relies on how quickly tools and actors, both government and non-government, are put into coordinated action across different levels and scales of socioecological and sociotechnological systems. Action is needed to activate key enabling levers using the new framework of GEO-7, aligned to approaches outlined in the target seeking scenarios. If actions are not coordinated soon, society risks irreversible setbacks, so renewed efforts are required to overcome the challenges and put key levers into motion, (inconclusive). In the short term, knowledge and innovation levers can improve the monitoring of the environment and biodiversity, enhance pollution and waste control, and make a better use of technologies *(unresolved)*. These can be combined with individual actions and group decision-making levers, as well as financial and economic levers, to create new financial and governance mechanisms that recognize the value of ecosystem services, all supported by institutional and policy levers. For ecosystem and biodiversity protection and conservation, both target seeking scenarios of GEO-7 envision pathways to increase protected areas, ranging from 30 per cent to 50 per cent. New knowledge and technologies required in the short term should be combined with the individual actions and group decisions and the financial and economic levers for new mechanisms to value ecosystems services, underpinned by governance levers. {18.2.1}.

Evidence from science, policy, and practice demonstrates that NbS can be a powerful way to restore ecosystems when they are designed around people's needs. Effective NbS efforts must involve key stakeholders, representing social and cultural diversity, as well as institutions and governance structures that hold knowledge assets and help guide decisions. For NbS to succeed, they must be tailored to the local context, based on solid evidence, well integrated into wider plans, be fair and inclusive, and shaped by transdisciplinary inputs. To make this happen, increased engagement through individual and collective action is necessary. In the short term, the focus should be on increasing knowledge, encouraging innovation, and strengthening institutions and governance. Building skills and capabilities will also be important to support a successful transition in the medium to long term. Once this foundation is in place, the next step would be to update financial, economic, institutional, and governance systems to make the most out of these innovations, especially those based on computational and data-driven approaches, biobased discoveries and novel engineering solutions. Valuing environmental goods and ecosystem services while advancing the circular economy will be central to this phase {18.2.2}.

The success of transformation will depend on how effectively and quickly levers and actors can be mobilized across scales and diverse socioecological systems *(established but incomplete)*. Local communities, including vulnerable groups, youth, women, older people, and Indigenous Peoples, play a central role as custodians of socioecological

systems (SES) and as those directly reliant on ecosystem services. Their leadership is crucial in planning and executing enabling solutions, which can be strengthened by new technological innovations in monitoring and data. Other actors, including the public and private sector at local, national and international levels have key supporting and networking roles. They help provide access to technology, finance, and capacity needed to ensure the success of the adaptation efforts {18.2.3}. In the short term, the use of enabling technologies, like sensors and AI-based computations, will support sustainable land and ocean management to sustainably increase bioresource production and supply to facilitate a circular bioeconomy. This will require science and technology, in partnership with strong institutional and policy actions to ensure governance of trade-offs with land for food, energy and nature. In the medium to long term, developing a newly skilled workforce with new knowledge and capabilities in biology, chemistry, engineering and infrastructure, as well as new finance, economics, and strong institutions, will be crucial for scaling up infrastructure and achieving as future sustainable bioeconomy {18.2.4}.

Across all timescales, from short to long term, building capabilities and encouraging both individual and collective action will be essential, especially as new stakeholder groups and social systems emerge around the transformed environment system.

A resilient and sustainable environment is the foundation of transformative change across nature, food, energy, finance and the delivery of a circular economy – key to addressing the global environmental crises *(well established)*. This chapter outlines a road map with clear signposts through a set of goals, solution pathways and key actors to enable future success. A common theme across all solution pathways is that early actions require new technologies to be harnessed in monitoring, assessment and data-driven approaches, linked to locally-engaged individuals and communities. These actions should be underpinned by innovative financial and policy instruments. and in the long term, capacities and skills development.

Credit: bilanol/Envato

18.1 Introduction

The global environmental crises reflect a complex interaction of unsustainable relationships between humans and nature, where several planetary boundaries are now surpassed beyond the safe operating space for humanity (Steffen et al. 2015; Richardson et al. 2023) (**Figure 18.1**). Representing a "global tragedy of the commons" that demands global collective action at all levels, these crises undermine humanity's ability to live in harmony with nature to achieve long-lasting sustainability (Ostrom 2010). However, individuals, communities, and governments lack adequate tools, approaches, incentives and motivation to act within current social, political and economic systems and priorities.

Global efforts through agreements, assessments, and initiatives reflect a broad consensus on the need for transformative changes in key human systems to tackle global environmental crises and GEO-7, Chapter 11 provides evidence that these transformations can achieve targets and goals, despite these being missed over the last two decades. Concerns from current trends and business as usual scenarios (Chapter 10) suggest that policy implementations to reduce GHG emissions will impede the achievement of the Paris Agreement's goals by 2030 (Stechemesser et al. 2024).

All major global initiatives – including the Sustainable Development Agenda 2030 and Sustainable Development Goals (SDGs), the 2022 Kunming-Montreal Global Biodiversity Framework (KMGBF), the Paris Agreement, the Land Degradation Neutrality goal under the United Nations Conventions to Combat Desertification, the United Nations Decade of Ecosystem Restoration, and the Early Warnings for All – clearly outline what actions are necessary. They emphasize the importance of transformative change across key human systems like energy, food, material resource circulation, and the economy. However, their implementation encounters obstacles and legacy challenges, such as resource shortages, policy inconsistencies, limited political commitment, weak enforcement, and gaps in local capacity, particularly in lower-income regions, where mainstreaming at the local level is often lacking.

These failures stem from multiple factors, including weak leverage points (Abson et al. 2017), insufficient monitoring of their application, limited collaboration between researchers and other stakeholders (Norström et al. 2020), neglect of social-ecological systems (Fischer et al. 2021), and inadequate transnational coordination and engagement (Folke et al. 2019). Driving transformational change across critical human systems while safeguarding the environment is both the most significant challenge and the greatest opportunity of these times.

There is strong evidence from legal, social, governance, and ecological viewpoints that a system-wide transformation is urgently needed (Atmadja et al. 2021; IPBES 2019; UN 2019; FAO 2021; UN 2023; IPCC 2023; Gupta et al. 2023). However, as emphasized in Chapters 11 and 12, many existing conceptual models primarily explore why transformation is essential, what it might look like and what could happen as a result.

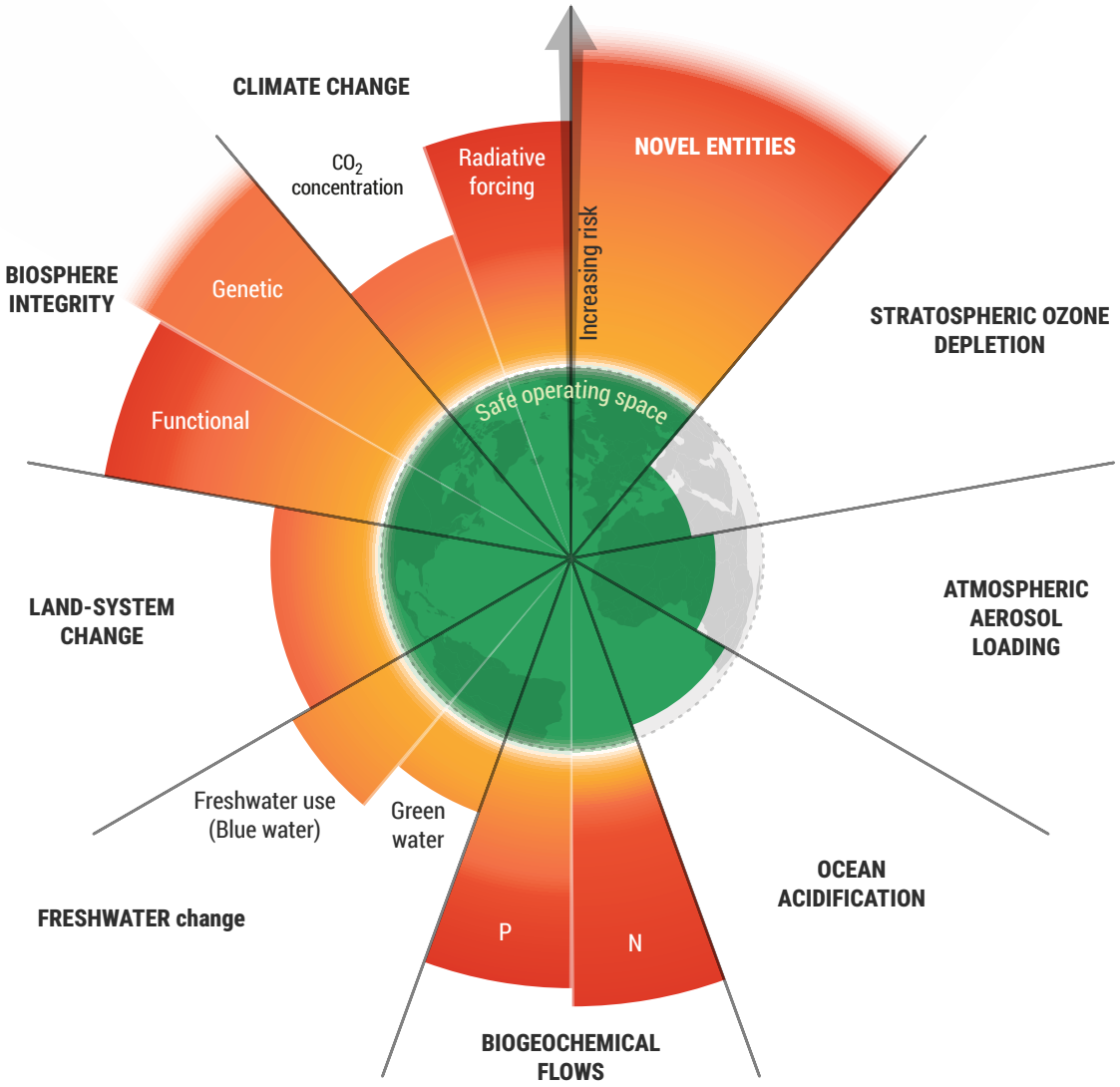
However, there is limited understanding of how to make this transformation happen or how to distinguish between incremental changes and deep, systemic transformation.

To help fill this knowledge gap, this chapter, and the GEO-7 report as a whole, aims to illustrate solution pathways and their implementation using two target seeking scenarios that enable a more resilient and sustainable environment. This objective requires fostering transformation across the human-controlled energy, food, financial, and circularity systems for a future in which global targets for climate and biodiversity are met. Real-life examples and case studies are presented in this Chapter offering lessons that can serve as seeds for broader systems change.

One specific planetary boundary, the stratospheric ozone hole, was once an environmental issue but has been largely addressed – except for some recent anomalies in the southern hemisphere (European Environment Agency 2024).

This success is mainly due to the effective implementation of the Montreal Protocol (United Nations Environment Programme 1987), which is the only United Nations treaty ratified by every country and is known as a landmark achievement in scientific cooperation (Whitesides 2020). The treaty's effectiveness was supported by several factors. These include a relatively short period – a decade – during which scientific consensus was accepted, the availability of technological solutions, the straightforward nature of the problem since the

Figure 18.1: Current status of control variables for all nine planetary boundaries



Source: Azote for Stockholm Resilience Center, based on analysis in Richardson et al. (2023). Licensed under CC-BY-NC-ND 3.0

ozone hole was observed and measured, and strong collaboration between industry and policy.

This positive example does not represent the current complexities of global environmental crises but instead emphasizes the need for coordinated, multi-actor strategies, where strong levers are effectively integrated and applied. In GEO-7, earlier chapters present methods and solutions for transforming four key human-controlled systems: economy, circularity, energy, and food. Building on these insights, this chapter develops a narrative to create a sustainable and resilient environment system, outlining clear goals and the solutions needed to address the challenges of global crises. These goals are reached through a series of solutions narratives, which involve specific actions carried out across different time frames, scales, and by various actors. The chapter discusses various combinations of levers to overcome identified barriers and challenges in the transformation process. It aims to motivate key actors to implement solutions sustainably. The focus is on achieving the necessary scale and speed of transformation (Chapter 21), since there are numerous feasible solutions with strong scientific, technical, financial, and social potential already exist.

The chapter uses the concepts of socioecological systems (SES), which are self-sustaining and adaptable, including both nature and humans, and sociotechnical

Table 18.1: Goals to enable sustainable and resilient environment system for nature, circularity, energy and food

Goal
Ensure and Strengthening the Nature-Society-Economics Nexus
Enable Transformative Adaptation of Socioecological Systems for Climate Resilience and Deliver Enhanced Benefits to Nature and People
Restore Natural Capital through Circular Economy Strategies and an emerging Sustainable Bioeconomy

systems (STS), as fundamental units for change. SES and STS here are not limited to natural ecosystems but also encompass human-made systems such as urban and agricultural environments. SES refers to a coupled natural-human system that is interconnected and interdependent in complex ways. SES highlights that human-designed systems, like economies, societies, and cultures, are embedded within, influenced by, and evolving alongside the biosphere across local to global levels (Folke et al. 2016). The goal of transformative SES is to establish a safe operating space capable of adapting and transforming amid adverse drivers and pressures. This requires transformative changes in SES governance and resource use patterns to foster climate-resilient and biodiversity-caring development pathways (IPCC 2022). Such transformations should be safe, just for all, and aligned with the no-one-left-behind principle of the 2030 Sustainable Development Agenda. Simultaneously, science, technology, and service are essential for rapid shifts away from a fossil fuel-based economy and for modifying how society interacts with technology (Muscat et al. 2021).

To achieve a sustainable and resilient environment system for nature and facilitate transformation across four other systems, it is vital to adopt an integrated approach that aligns human activities with natural processes. This requires implementing transformative changes in economic, social, technological, and governance structures to address the global environmental crises (Rockström et al. 2009; Steffen et al. 2015). A sustainable circular economy, supported by suitable bioeconomy infrastructure, must be developed to reduce waste and optimize resource uses (Geissdoerfer et al. 2017; International Renewable Energy Agency [IRENA] 2020).

Similarly, food systems must adopt sustainable and regenerative practices that enhance biodiversity while securing food security, use new agri-technologies alongside preserving Indigenous and local farming methods, cut GHG emissions, and improve soil health (FAO 2018; IPCC 2019). Tackling the trade-offs between food and nature, while ensuring economic benefits for farmers, is recognized as significant and calls for systemic change as discussed in Chapter 17 on Food Systems. The use of SES and STS frameworks is important, recognizing the interconnectedness of human and natural systems, along with the potential of new technology and building resilience through adaptive governance, fair policies, innovation, and collaborative efforts (Ostrom 2009; Folke et al. 2016). Transformational strategies will also differ across regions and over time – as regional differences must be considered based on social, economic, technical, and natural features and limitations.

Three goals are proposed to enable a sustainable and resilient environment system that address how to support transformations across Circularity (Chapter 15), Energy (Chapter 16), and Food Systems (Chapter 17). These goals, presented in Table 18.1, are closely connected to the economic system and financial mechanisms outlined in Chapter 14.

18.1.1 Ensure and strengthening the nature-society-economics nexus

This goal emphasizes One Health approach that links ecological health with social and economic well-being to enhance the health of people, animals, plants, and ecosystems. It acknowledges that sustainable development depends on the harmonious coexistence of natural ecosystems, human societies, and economic activities (Rockström et al. 2009; Folke et al. 2016). By highlighting their interdependence, the goal seeks to encourage policies and practices that advance environmental sustainability, social equity, and economic resilience. (Ostrom 2009; Steffen et al. 2015). Implementing sustainable land use involves conserving natural habitats, promoting regenerative agriculture (Chapter 17), and preventing deforestation. These actions protect biodiversity and boost ecosystem services like water purification and carbon sequestration (Altieri, Nicholls, and Montalba 2017; Pretty et al. 2018). Using green infrastructure in urban areas, such as green roofs, permeable pavements, and urban forests, can lower urban heat islands, reduce flood risks, and improve air

quality, benefiting public health (Gill et al. 2007; Tzoulas et al. 2007). Supporting sustainable consumption and production patterns includes adopting renewable energy, minimizing waste through prevention, recycling, and composting, and supporting local, sustainable products. (Geissdoerfer et al. 2017; Kirchherr, Reike, and Hekkert 2017). These efforts help protect biodiversity, mitigate climate change, and ensure that economic growth does not compromise the well-being of people, animals, and the environment, while also promoting social equity and justice (Díaz et al. 2019). For instance, urban planning that integrates green spaces and promotes biodiversity can improve air quality, boost residents' well-being, and create economic opportunities through ecotourism and sustainable businesses (Elmqvist et al. 2013; Wu 2014). Strengthening these positive connections enables societies to develop more resilient and fair communities that operate within the planet's ecological boundaries (Steffen et al. 2015; Folke et al. 2016).

18.1.2 Enable transformative adaptation of socioecological systems for climate resilience and delivering enhanced benefits to nature and people

The goal is to develop the adaptive capacity and resilience of various types of SES across regions, while also providing greater benefits to nature and people over time. Moving beyond incremental adaptation, it emphasizes transformative adaptation achieved through strategic, spatially targeted planning, along with effective monitoring, reporting, and evaluation to tackle severe climate impacts. It also highlights the importance of avoiding unintended consequences, when necessary, by fundamentally alteration of certain attributes of SES. When systematically designed and implemented, planned transformative adaptation can be accelerated by solutions that are locally appropriate, based on Indigenous Knowledge and Local Knowledge. This approach integrates disaster risk reduction (DRR) so communities can better anticipate and prepare for, and respond to climate impacts, such as from forest fires or to the energy systems, thereby minimizing damages to ecosystem, human health, and property, and loss of life (Berkes 2007; Lavell et al. 2012). Utilizing Indigenous Knowledge and Local Knowledge enhances climate change adaptation (CCA) effectiveness by incorporating proven practices rooted in local ecosystems (Berkes, Colding, and Folke 2000; Hill et al. 2020), while also avoiding maladaptation. Since CCA often requires responses tailored to specific contexts, the focus is on initiatives that strengthen local resilience, such as establishing community-based adaptation (CBA) or community-based DRR groups. These efforts can promote collective action and empower communities to manage their CCA processes (Ostrom 1990; Agrawal 2001). Transformative adaptation goes beyond merely enhancing livelihood resilience or helping vulnerable groups cope with and recover from climate shocks. It also involves protecting ecosystems and biodiversity, preventing land degradation, and supporting climate mitigation, such as through deployment of agrivoltaics or solar panels (Chapter 16) (Adger 2006; Cutter et al. 2008). It offers co-benefits like better water quality, higher biodiversity, and improved livelihoods for local communities, aligned to the target seeking scenarios of GEO-7 (The Economics of Ecosystems and Biodiversity [TEEB] 2010; Barbier et al. 2011). Moreover, incorporating CCA into urban planning, energy systems, forest management, agriculture, and water management can foster more resilient and sustainable systems that enhance human well-being and ecological health (IPCC 2014; UNEP 2019).

18.1.3 Restore natural capital through circular economy strategies and a sustainable bioeconomy

The goal aims to decrease resource depletion and environmental harm by shifting to sustainable consumption and production systems (Chapter 15). By tilizing biological resources for various applications (IEA 2022), a sustainable bioeconomy employs renewable biological materials to generate energy, food, chemicals, and other products in a sustainable way. This approach helps cut fossil fuel dependence, lowers greenhouse gas emissions, stores carbon, and reduces economic stress on ecosystems and biodiversity (Bugge, Hansen, and Klitkou 2016; Kirchherr, Reike, and Hekkert 2017). Numerous examples and case studies demonstrate the advantages of utilizing biological resources for multiple purposes and is aligned to the GEO-7 target seeking scenarios, where biomass, including from waste streams, is critical in both Behaviour- and Technology-focused Scenarios to meet climate targets for 2050. A comprehensive life cycle assessment of biorefineries is essential to confirm that these methods have lower environmental impact than fossil fuels, despite considerable variations. Overall, studies show that biorefineries show clear environmental benefits (Munagala et al. 2021; Lindorfer, Zeilerbauer, and Hrbek

2022). These facilities convert biomass into valuable products, such as biofuels and bioplastics, reducing the environmental impact of production processes (Cherubini 2010). Promoting sustainable agricultural practices, that enhance soil health and biodiversity (Chapter 17) such as agroforestry, crop rotation, and organic farming, can boost yields, strengthen resilience to climate change, and decrease reliance on synthetic fertilizers and pesticides (Altieri, Nicholls, and Montalba 2017; Pretty et al. 2018). Developing markets for biobased products involves researching, developing, and commercializing innovations such as biodegradable packaging, biobased textiles, and biofuels (Carus and Dammer 2018). Combining these strategies aims to regenerate natural capital, improve ecosystem services, and foster economic growth that is environmentally sustainable and socially inclusive (El-Chichakli et al. 2016). For instance, utilizing agricultural waste to produce bioenergy or sustainable aviation fuels offers a renewable energy source, reduces pollution, and boosts economic opportunities in rural areas (Scarlat et al. 2015). Additionally, shifting to a circular economy can foster new technologies and innovations, open up new business prospects, and promote economic growth while conserving natural resources and restoring ecosystems (Chapter 15) (Geissdoerfer et al. 2017).

18.2 Solution pathways for a resilient and sustainable environment system

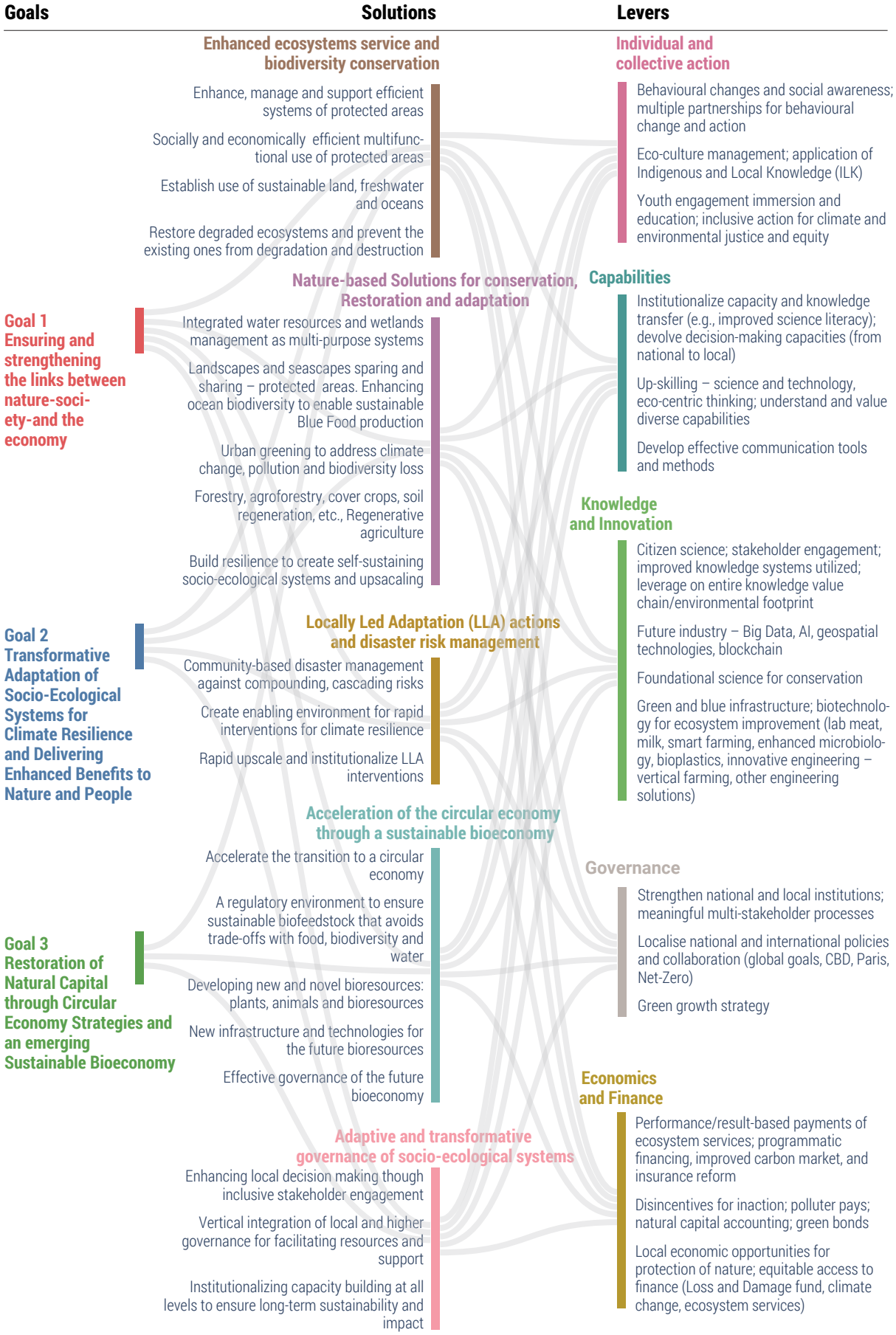
Five integrated solution pathways have been identified to achieve the three overarching goals (**Figure 18.2**).

First, biodiversity protection, conservation and restoration can be advanced by enhancing ecosystem services (**Box 18.1**) through multiple approaches. Expanding and connecting protected areas, along with establishing biodiversity buffers and corridors, allows species to migrate, adapt, and thrive in changing environments. This helps to maintain ecosystem integrity, safeguarding natural ecosystems while providing co-benefits such as improved water quality, increased biodiversity, improved soil and air quality, and enhanced livelihoods.

Second, wide scale implementation of NbS can simultaneously achieve conservation, restoration, GHG mitigation, DRR, and CCA. NbS, such as reforestation, wetland restoration, urban greening, and sustainable agriculture, offer multiple benefits including habitat protection, climate mitigation, carbon sequestration, energy savings and improved water quality. Regenerative production systems like agroecology and permaculture

Credit: High-Fliers/Envator

Figure 18.2: The Goals and Solution Pathways, with key levers identified to enable a sustainable and resilient environment system for nature, finance, waste/circularity, energy and food



Box 18.1: Biodiversity conservation and enhanced ecosystem services

Biodiversity, encompassing ecosystem, species, and genetic diversity (International Fund for Agricultural Development 2024), is essential for the provision of ecosystem services (Reid et al. 2005). According to the Millenium Ecosystem Assessment, ecosystem services are the benefits people obtain from ecosystems. These include provisioning, regulating, cultural and supporting service. The type and magnitude of the ecosystem services is directly influenced by the level of biodiversity. Certain ecosystems, like tropical rainforests, mangroves, wetlands, and coral reefs, are particularly effective in providing regulating and supporting services such as carbon sequestration and water purification, although they may offer less provisioning or cultural services. Therefore, biodiversity of an ecosystem largely determines the range and quality of services it can provide to people.

Specifically, species diversity plays a critical role in ecosystem functioning and service delivery capacity, shaped by species interactions and environmental conditions. It supports natural pest control and pollination, and agricultural productivity, and ensures the availability of essential materials (FAO 2022). Genetic diversity is equally important. It enhances ecosystem resilience, supports self- regulation, and improves the ability of ecosystems to adapt to environmental changes. In turn, this is what determines the long-term provision of ecosystem services for human well-being (Hoban et al. 2021).

restore soil health, boost biodiversity, and strengthen ecosystem resilience.

Third, CCA strategies can be improved by implementing integrative methods to strengthen SES resilience through scaling up LLA, combined with effective DRR. LLA efforts draw on Indigenous Knowledge and Local Knowledge to develop context-specific solutions that enhance community resilience.

Fourth, accelerating the development of a biobased circular economy shifts from the traditional linear model of "take, make, dispose" to one that minimizes waste and limits the extraction of new resources. Sustainable bioresources provide environmentally friendly alternatives to fossil fuel-based products. Building the bioeconomy infrastructure, such as biorefineries and supply chains for biobased products, enhances resource management, cuts waste, and encourages the use of renewable biological materials. These efforts support the creation of a resilient and sustainable economy.

Fifth, the solution is adaptive and transformative governance that connects local communities, enhances society's environmental awareness, and fosters a better attitude towards nature. It aims to transform people's consumption behaviours and habits while integrating Indigenous Knowledge and Local Knowledge. This solution involves moving governance towards collaborative networked structures, where decision-making takes place at various scales and a higher degree of power is given to communities. This approach ensures their knowledge and needs are incorporated into broader policy frameworks (Folke et al. 2005; Armitage, Berkes, and Doubleday 2007).

18.2.1 Enhancing ecosystem services through regenerative systems and biodiversity conservation

We define four consecutive actions to strengthen ecosystem services through regenerative systems and biodiversity conservation, aiming to achieve Environmental Goals.

18.2.1.1 Action One: Enhance, manage and support an effective networks of protected areas

Creating protected areas, as identified in the GBF 30 x 30 target 3, doesn't automatically result in better ecosystem health or increased biodiversity conservation. Protected areas, regardless of size, must be interconnected, preserved, and effectively managed (Geldmann et al. 2018). Both target seeking scenarios of GEO-7 envision pathways to increase protected areas, ranging from 30 per cent to 50 per cent. Several nations demonstrate strong potential for successful management of protected areas (Watson et al. 2014). Australia has met its international goals by achieving 17 per cent of its land designated

as protected, fulfilling Aichi Target 11. Meanwhile, South Africa and Canada have significantly expanded their protected area networks since 2010. At both national and regional levels, there is a need for in situ conservation approaches – protecting species in their natural habitat – is needed at both regional and national levels. This includes establishing and maintaining natural parks, wildlife sanctuaries, marine protected areas, and biosphere reserves, ideally through regional collaboration with neighbouring countries.

Protection status should be extended not only to threatened, representative, or rare ecosystems but to all ecosystem types that provide essential services (Coad et al. 2019). Some habitats, like coastal areas, are more vulnerable than others (Mammides et al. 2024). The size of protected areas may vary based on economic, social, and natural factors, but they should form a continuous network. This includes incorporating corridors and service-rich areas to allow the flow of species, nutrients and energy between different ecosystems or their parts. While creating a single global network of protected ecosystems may be unrealistic, a regional level is feasible. Examples of success include the international Emerald Network and Natura 2000 projects in Europe, the Ecological Conservation Redline national programme in China, the Yellowstone to Yukon Conservation Initiative that aims to create a continuous wildlife corridor spanning over 3,200 km and connects Yellowstone National Park in the US to the Yukon in Canada, and on a local level in cities by organizing a multifunctional and interconnected green infrastructure, such as in Canberra and Minsk (Hilty and Laur 2021).

Depending on an area's fragility or exposure, different kinds of economic activities may be permitted, like IUCN categories imply, to make conservation areas economically viable for local populations and governments. Legal instruments, such as Chile's Real Right of Conservation, which allows landowners to protect their land indefinitely while pursuing economic activities. These frameworks serve as the cornerstone for conservation initiatives, encouraging the preservation and flourishing of ecosystems (Government of Chile 2016). Spatial tools and technologies, such as GIS, sensors, drones and satellites provide real-time information about ecosystems health and patterns of biodiversity. This is particularly valuable for managing biodiversity corridors, by tracking species movement and monitoring habitat conditions (Soubry et al. 2021).

Developing locally appropriate infrastructure is crucial for making protected areas economically viable. Low-impact roads, visitor centres, and energy-efficient lodges can foster ecotourism and other economic activities. For example, Norway's Jotunheimen National Park introduced eco-friendly infrastructure without causing harm to the delicate alpine ecosystem (Visit Norway 2024). In Costa Rica, the Ministry of Environment and Energy implements a National Policy for Production and Sustainable Consumption (2018–2030), which integrates sustainability into tourism. This policy helps to reduce habitat destruction, resource overuse, and pollution caused by the industry, while promoting economic resilience by fostering local entrepreneurship and creating green jobs.

Conflicts of interest, such as mining, urbanization, forestry or fishing, can generate larger short-term profits than conservation should be addressed through conflict resolution and co-management strategies. Participatory land-use planning, like practiced in Madidi National Park (Bolivia), involves stakeholders in mapping resource use and designating areas for conservation and development. Benefit-sharing models, such as revenue-sharing with Maasai communities around Amboseli National Park (Kenya), encourage conservation by linking park income to local education and health care. Employing residents as rangers or guides in these areas also offers economic opportunities linked to conservation (Bauer et al. 2022).

Biodiversity hotspots in Bolivia, Brazil, Colombia, and Congo are increasingly impacted by urban sprawl, making conservation near large cities challenging and often leading to human-wildlife conflicts (Molotoks et al. 2017). In Brazil, Brasília National Park, which surrounds the city of Brasília, has been affected by rapid urban expansion (Diniz and Vieira 2016). Similarly, urban sprawl in Nairobi has degraded Nairobi National Park by shrinking wildlife corridors, increasing human-wildlife conflicts, and raising the levels of pollution from point sources (Onkangi et al. 2023).

In some areas, conservation has been shown to economically benefit only a few elite leaders and investors, rather than most community members who forgo advantages from non-conservation land uses when protected areas are established (Sene 2024).

To overcome such barriers, conservation laws or rights established in some countries have proven to be effective tools, such as in the case of Chile, the Real Right of

Conservation involves a binding agreement between the property owner and a third party, whereby the landowner permanently restricts the development and future use of their land to ensure its protection and conservation. In turn, the third party, which may be a university, research centre, non-governmental organization (NGO) or individual, commits to protecting and conserving the natural resources of the property.

18.2.1.2 Action Two: Offer a socially and economically efficient multifunctional use of protected area by leveraging the resources approach

It is essential to account for the cultural and provisional services of protected areas to enhance their appeal and utility for local governments and communities, including women and marginalized groups, who often perceive protected areas as mere lands that are unprofitably withdrawn from development (United Nations Educational Scientific and Cultural Organization 1971). The following examples offer opportunities to ensure success:

- Acknowledging that expanding protected areas involves many of the poorest rural regions in the world, Green Colonialism and land grabs for conservation should be avoided. Global justice, such as fair sharing of costs, benefits, and responsibilities should be a future high priority (Ma et al. 2020).

- Fostering sustainable ecotourism, which connects visitors to the protected areas while contributing to the income of local communities and ecosystem conservation should be prioritized. Eco-lodges, guided wildlife excursions, and educational programmes provide a means to attract visitors without causing harm to the ecosystem, such as in Costa Rica's Monteverde Cloud Forest, where eco-tourism is providing local employment opportunities, with revenue reinvested in preserving the forest, making eco-tourism a powerful instrument for both economic development and conservation (Miller, Cox, and Morse 2023).

- Collaborative management approaches, where communities actively engage in the administration of protected areas, cultivate a sense of ownership and responsibility for conservation efforts and create jobs. In Kenya, community-based conservation initiatives engage residents in management of protected lands and offer economic opportunities through ecotourism and sustainable farming. Similarly, in Türkiye's Gökova marine protected area local fishers are trained and employed as marine rangers to stop illegal fishers from other regions (Ünal and Kizilkaya 2019). This approach has led to a significant recovery of fish stocks and increases in the apex predator biomass with higher incomes for local communities (Vasconcellos and Unal 2022).

- Agroforestry practices can help communities near protected areas to earn income while conserving biodiversity through sustainable harvesting of non-timber forest products and food. In Kenya, many protected areas allow local people to manage livestock grazing in a way that balances conservation and livelihood needs (Bedelian and Ogutu 2017).

- Using protected areas as platforms for scientific exploration and education, such as in Ecuador's Yasuni National Park (Bass et al. 2010).

18.2.1.3 Action Three: Establish a sustainable use of land, fresh water and oceans

Biodiversity conservation can be established not only in protected areas, which currently cover about 16.44 per cent of land and fresh water and 8 per cent of oceans (OECM 2022), but also in areas used for other economic activities. These areas can directly support Target 10 of the GBF on sustainable management of these sectors. Such practices also contribute to achieving other KM-GBF goals, including Target 1 on sustainable management and Target 7 on pollution reduction and is relevant to sustainable practices for agriculture, fishing and forestry, sustainable urban development and fossil fuels and actions one and two greatly contribute towards this third action.

Sustainable agriculture can help prevent biodiversity loss by reducing the use of pesticides and fertilizers, and more efficient use of arable lands and water through regenerative practices (Chapter 17). In Sub-Saharan countries, regenerative agroecological practices, such as minimizing soil disturbance, using legume crops to boost nitrogen levels and suppress weeds, and diversifying crops, have improved soil health and stabilized yields even in stressful climates (Nyirenda and Balaka 2021).

Sustainable forestry is currently the sector which has the most well-studied practices to conserve forest ecosystems and their biodiversity. It includes delivering collateral-free microfinance to small forest-based businesses through the power of collective organizations, applying new diagnostic tools and methodologies to catalyse legal-reform processes for sustainable wildlife management, harnessing digital technologies to improve the efficiency of timber-tracking and promote sustainable supply chains, all aimed at increasing sustainable forest management. Programs like Sembrando Vida in Mexico promote agroforestry and silvopasture systems to restore ecosystems. These systems use such practices as no-till farming, cover crops, and crop rotations to regenerate depleted pastures (Altieri and Nicholls 2012).

Managing pollution requires reducing the duration, amount, and pattern of pollutant exposure to protect vulnerable ecosystems from pollutants like plastics and microplastics in freshwater and marine environments (UNEP 2023). Establishing marine conservation zones and promoting responsible fishing are essential for maintaining marine biodiversity and avoiding overfishing. In New Zealand, a network of marine protected areas conserves key habitats, while the Quota Management System enforces strict fishing limits to keep fish populations sustainable (Mossop 2020).

Urban biodiversity presents another challenge because habitats in cities are often limited and unsuitable for many species. The sponge-city models in China, which incorporate urban wetlands, public gardens, and renaturalized river valleys, help boost urban biodiversity by creating additional habitats (Ronchi and Salata 2022).

Since all natural resources are interconnected, management plans need to reflect these relationships. For instance, Integrated Coastal Zone Management programmes, like those in the Mediterranean, adopt a comprehensive approach by coordinating policies across various sectors such as agriculture, fisheries, tourism, and urban development. This helps ensure that land-based activities do not harm freshwater and marine ecosystems, promoting a sustainable balance between development and environmental protection (Ramieri, Bocci and Markovic 2019).

Marine Spatial Planning is another example of a decision-making approach that integrates managed and protected zones to enhance resilience in natural resource management. Establishing legal frameworks and policies for resource use is vital for regulating land, water, and ocean activities. For example, the European Union's Common Fisheries Policy sets fishing quotas to prevent overfishing and allow marine ecosystems to recover. Similarly, Brazil's Forest Code ensures land-use practices do not lead to deforestation or harm freshwater systems. These legal structures help prevent overexploitation and promote sustainable practices across agriculture, forestry, and fisheries (Frost and Andersen 2006).

To ensure sustainability initiatives are truly rooted in local contexts, promoting community-led resource management is essential. In the Pacific Islands, community-based fisheries management merges traditional knowledge with modern conservation methods, helping to preserve fish stocks for future generations while supporting local economies (Lalavanua, Govan, and Steenbergen 2021).

Market-based tools and financial mechanisms, such as payments for ecosystem services (PES), carbon credits, and certification schemes, serve as effective incentives for sustainable practices, as detailed in Chapter 14. For example, in Costa Rica, the PES programme rewards landowners for conserving forests that benefit fresh water and biodiversity. To improve PES outcomes, it is crucial to broaden its scope beyond just compensation by incorporating capacity-building initiatives and educational programmes. This approach equips landowners with the technical skills and resources needed for sustained, active participation in sustainable practices. Certifications like the Forest Stewardship Council and the Marine Stewardship Council for fisheries recognize companies that demonstrate responsible ecosystem management and have been effective.

To ensure the success of sustainability efforts, building solid partnerships among governments, NGOs, private companies, and local communities is crucial. An example is The Amazon Cooperation Treaty Organization serves as a prime illustration of cross-border collaboration in managing the Amazon rainforest's vast biodiversity. In Norway, public education initiatives around sustainable seafood have increased consumer demand for sustainably certified fish, strengthening market-driven conservation.

18.2.1.4 Action Four: Restore degraded ecosystems and prevent the existing ones from degradation and destruction

Restoring degraded ecosystems is challenging, long-term, and expensive. Ecosystem restoration encompasses

a wide range of actions designed to repair damaged, degraded, or destroyed ecological systems, thereby restoring their biological and physical integrity (Aronson et al., 2020). It also includes conserving ecosystems that remain undamaged (UNEP and FAO 2020). The primary goal of ecosystem restoration is to accelerate recovery after damage or degradation, guiding ecosystems back towards their natural development path rather than their exact historical state (Balaguer et al. 2014). The GBF and UN Decade on Ecosystem Restoration (2021-2030) calls for global efforts to protect and revive ecosystems for the benefit of both people and nature. Initiatives like the Bonn Challenge and Latin America's 20x20 have already restored millions of hectares of degraded land, supporting food security and climate change mitigation.

Wetland restoration remains vital for enhancing biodiversity, maintaining freshwater supplies, and preventing floods. The Florida Everglades restoration (US Army Corps of Engineers 2020) demonstrates efforts to counteract the effects of urban development and intensive farming. Coastal ecosystems, including mangroves, coral reefs, and seagrass beds, function as natural shoreline protectors, support marine fisheries, and help absorb carbon. In Bangladesh, coastal mangrove restoration initiatives have protected communities from flooding and storm surges, while offering habitats for fisheries (United Nations Development Programme 2021). Similarly, restoring coral reefs and seagrass meadows has been vital for conserving marine biodiversity. In Australia, the Great Barrier Reef is safeguarded through coral restoration efforts that employ advanced methods, including robotic technology to plant coral fragments (Great Barrier Reef Foundation 2023).

To avoid further deterioration and destruction of ecosystems, it is crucial to adopt measures for pollution control and cleaner industrial practices aligned with circular economy principles, along with effective waste management systems to reduce industrial effluent and chemical waste. Germany's Circular Economy Act encourages businesses to focus on waste prevention, reuse, and recycling, leading to a significant decrease in landfill waste and enhanced resource efficiency (Federal Ministry for the Environment Climate Action, Nature Conservation and Nuclear Safety 2012). Likewise, implementing cleaner production techniques in Bangladesh's textile industry, supported by initiatives such as the Partnership for Cleaner Textiles, has resulted in notable reductions in water and chemical consumption, improved worker safety, and decreased environmental pollution in rivers (International Finance Corporation, 2017). In China's Yangtze River Basin, pollution control efforts have effectively decreased factory-related water pollution, safeguarding aquatic life and improving water quality for millions. Involving local communities in ecosystem restoration and conservation is essential. Empowering these communities encourages sustainable stewardship and reinforces social and cultural connections to the environment. Namibia's Community-Based Natural Resource Management programmes, which grant local communities rights over natural resources, have led to reductions in poaching, growth of wildlife populations, and improved livelihoods (Ministry of Environment Forestry and Tourism and Namibian Association of CBNRM Support Organizations 2021). Similarly, in Nepal's Annapurna Conservation Area, community forestry has enhanced forest cover, biodiversity, and water resources while providing communities with forest products (Baral and Heinen 2020).

Revitalizing soil health is essential for ecosystem restoration. Methods for soil restoration, such as planting cover crops, rotating crops, using crop waste for compost improve soil fertility, decrease erosion, boost carbon storage, and remediate polluted soils.

A key part of any nature restoration strategy is developing regulatory and legal frameworks that enforce ecosystem restoration and penalize degradation. Governments need to establish strong regulations that require companies in sectors like agriculture, resource extraction, construction, and industry to adopt sustainable practices. For instance, Brazil's Forest Code requires landowners to restore forests in designated areas like riverbanks and enforces penalties for non-compliance. Applying similar regulations to other sectors would make environmental restoration a legal requirement rather than a voluntary effort, compelling companies to incorporate restoration into their operations. Additionally, the EU's Nature Restoration Law aims to restore at least 20 per cent of the EU's land and sea areas by 2030 and all ecosystems needing restoration by 2050.

Environmental permits and conditional licences should be connected to commitments for restoring ecosystems. By mandating companies to provide financial guarantees like environmental bonds, it can be ensured that funds are available for future restoration efforts, holding companies accountable for their environmental responsibilities. For instance, in Australia, mining companies are legally obliged to supply financial bonds to cover the costs of rehabilitating mine sites after operations end

(Government of Western Australia 2012). These bonds are only refunded once the rehabilitation satisfies specific environmental standards.

Public-private partnerships play a vital role in large-scale ecosystem restoration, where businesses, governments, and NGOs collaborate to rehabilitate degraded lands. Initiatives like the Bonn Challenge, a global effort to restore such lands, highlight the potential of collaboration. Governments can motivate companies to get involved through financial or tax benefits, fostering a positive cycle that encourages voluntary corporate engagement in restoration efforts.

18.2.2 Nature-based solutions for conservation, restoration and adaptation

Strategies for the widespread implementation of NbS to promote conservation, restoration, and CCA are key to increase environmental sustainability and resilience (**Figure 18.3, Box 18.2**).

18.2.2.1 Action One: Rapidly develop and implement nature-based solutions

The development of NbS is an adaptive and iterative process that can be achieved by following a series

Figure 18.3: Examples of nature based solutions for climate change adaptation

Air and water pollution

- Riparian buffer strips: Vegetated areas along waterways trap sediments and filter pollutants.
- Urban green belts: Trees absorb air pollutants and fine particulates.
- Wetland conservation: Filters industrial and agricultural runoff naturally.
- Algal ponds & constructed wetlands: Clean wastewater while supporting biodiversity
- Crop plants engineered to be more resource use efficient: plants that use phosphorous and nitrogen more efficiently, with less run-off into aquatic systems.

Flooding

- Riverbank reforestation: Roots stabilize banks and reduce erosion.
- Floodplain restoration: Allows rivers to safely overflow and recharge groundwater.
- Urban permeable surfaces: Green infrastructure such as permeable paving, rain gardens, and green roofs.
- Mangrove belts: Break storm surges and slow tidal flooding.

Vulnerable small-scale farmers

- Diversified cropping systems: Reduces risk from single crop failure.
- Community seed banks: Preserve climate-resilient local varieties.
- Agroecology training: Builds capacity to farm with fewer external inputs.
- Payments for ecosystem services: Farmers get income for conserving biodiversity or sequestering carbon.

Soil drought

- Agroforestry: Shade trees reduce evaporation and improve soil moisture.
- Mulching and cover crops: Maintain soil humidity and reduce temperature extremes.
- Terracing and contour farming: Slow runoff and allow more water to infiltrate soil.
- Wetland restoration: Retains groundwater and stabilizes the local water table.
- Resilient germplasm: germplasm able to tolerate lowered ground water and still producing yieldable crops.

Soil pollution by chemical fertilizer

- Organic soil amendments: Compost, manure, and biochar bind toxins and restore soil structure.
- Phytoremediation: Plants such as Viola baoshanensis can absorb and break down pollutants.
- Crop rotation with legumes: Fix nitrogen naturally, reducing need for synthetic fertilizers.
- Mycoremediation: Fungi break down harmful chemicals in soil.

Drought

- Watershed restoration: Reforestation to improve water infiltration and storage.
- Rainwater harvesting with vegetative catchments: Plants slow and store runoff for later use.
- Soil organic matter enrichment: Improves water retention capacity.
- Mangrove and wetland protection: Maintain regional humidity and rainfall cycles.

Fossil fuel-based energy system

- Bioenergy from waste and sustainable cropping: Agricultural residues, manure, forest and grass non-food cropping and by-products for renewable energy.
- Agroforestry for biomass: Sustainable wood and bamboo production.
- Passive cooling and heating: Green roofs, living walls, and urban tree cover to reduce energy demand.

Sources: Comin et al. (1997); Shrawat et al.(2008); Hubble et al. (2010); Cigolotti (2012); Townsend et al (2012); Zinzi and Agnoli (2012); Bovill et al.(2013); Rhodes (2014); Vernooy et al. (2017); Zhu et al. (2017); Jayachandran et al. (2017); UNEP-DHI (2017); Islam and Ashilenje (2018); Koh et al.(2018); Kumar et al (2020); Webber et al.(2020); Ochieng et al.(2021); Li et al. (2022); Mganga et al (2022); Serra-Llobet et al. (2022); Wu et al. (2023); Aryal (2024); Romero Antonio et al.(2025).

Box 18.2: Features of nature-based solutions

Nature-based solution (NbS) are actions that protect, conserve, restore, sustainably manage natural or modified terrestrial, freshwater, coastal, and marine ecosystems. They aim to address social, economic, and environmental challenges in an effective and adaptive way, while also providing benefits for human well-being, ecosystem services, resilience and biodiversity (UNEP 2022).

- **Societal focus:** Unlike traditional conservation, restoration and adaptation that primarily focus on nature, NbS begin with societal needs and use nature to deliver sustainable outcomes.

- **Guiding principles**: The design and implementation of NbS should follow eight principles of the IUCN Global Standard (International Union for Conservation of Nature 2020), ensuring that solutions are scalable, contribute to biodiversity and ecosystem integrity, economically viable, equitably balance trade-offs, based on inclusive governance, and adaptively managed using evidence for long-term sustainability.

- **Applications**: NbS are applied in conservation, restoration and adaptation of ecosystems to deliver enhanced benefits for nature and people.

- **Benefits**: NbS support the development of sustainable and resilient environment system and can drive broader systems transformation (Kinol, Arango-Quiroga, and Kuhl 2023). NbS are cost-effective (Lafortezza et al. 2018), multifunctional and adaptable across different sectors (Engström et al. 2018). NbS also offer co-benefits, such as nature conservation as well as improved human livelihoods and well-being (Dhyani et al. 2020). Additionally, many Indigenous Knowledge and Local Knowledge systems are inherently nature based.

- **Justification for NbS**: According to Palomo et al. (2021), ten elements underpin successful NbS. These are: Nature's values, Knowledge types, Community engagement instruments, Economic and financial tools, Rights-based and customary norms, Legal and regulatory frameworks, Management practice, Strategic planning, Behavioural change, and Technology.

- **Types of NbS**: The Technical Handbook of NbS describes three main types of NbS categorized by function and the level of ecosystem intervention (Eisenberg et al. 2022).

    - Type 1: Minimal intervention
    - Type 2: Moderate intervention
    - Type 3: High intervention

NbS case examples: An example of Type 1 is the protection of mangroves in coastal areas, such as the Mangrove National Park in the desert landscape of Abu Dhabi in UAE, that help to limit climate risks and provide socioeconomic benefits and non-material ecosystem services. Agroecology and natural systems agriculture as demonstrated by the 5,500-member eco-village located in the semi-arid drylands of Chololo, the United Republic of Tanzania (Ramesh et al. 2015; IPBES 2019) is an example of a Type 2 NbS. An example of Type 3 NbS is engineered green and blue infrastructures in Bishan-Ang Mo Kio Park, Singapore.

of four subactions: defining the problem, planning, implementation, and monitoring and governance.

NbS begins by clearly defining the problem from a societal perspective. For instance, the success of the West Africa Coastal Areas Management Program can be attributed to its problem-solving approach, which uses NbS to address community needs and protect against natural and man-made risks such as coastal erosion and flooding (Ramesh et al. 2015). This influences the socioecological interactions of coastal communities. This people-centric approach to NbS aims to transform these communities by providing enhanced benefits to both nature and people.

In this context, knowledge assets held by various actors can clarify expectations and limitations of stakeholder involvement, helping to address barriers like mutual misunderstanding (Gardner 2021) and avoid deployment a one-size-fits-all solutions approach (Kabisch et al. 2016).

The second step in planning for NbS involves co-creation and development that includes several detailed steps: defining settings together, understanding challenges, creating visions and scenarios, assessing potential impacts, developing solution strategies, and implementing and monitoring initial actions (Albert et al. 2021; Brierley and Fryirs 2022). The Intercontinental Biosphere Reserve of the Mediterranean, spanning Andalusia (Spain) and Morocco (Barbosa et al. 2019), demonstrates that involving key stakeholders—including regional and local governments of Andalusia and the Kingdom of Morocco—in NbS planning helps identify the most effective network of multipurpose protected areas. The success of NbS is further supported when project mandates are approved by relevant and major stakeholders.

Research and practice show that successful implementation, the third subaction of NbS, is required to follow certain principles to ensure success —such as Place-specificity, Evidence base, Integration, Equity, and Trans-disciplinarity—and collaboration among key stakeholders from both public and private sectors (Kabisch, Frantzeskaki, and Hansen 2022). A community-managed NbS was used to address climate-related risks in the Duwa and Sutebwo forests of the Segou Region in Mali by restoring the dryland through regrowth (Hou-Jones, Roe, and Holland 2021). Since NbS tend to be linked to specific locations (Schröter et al. 2023), the principle of place-specificity was demonstrated in this farmer-managed natural regeneration approach. It was reported that 8,300 hectares of degraded forest land saw improvements in water retention and soil fertility (Hou-Jones, Roe, and Holland 2021). Additionally, 75 per cent of intervention beneficiaries reported having fairer and more equitable access to forest resources.

Implementing NbS faces several barriers, including lack of accessible funding and financial tools, that required innovations in financial systems as described in Chapter 14, resistance rooted in knowledge gaps, limited participation of local stakeholders, and poor coordination among sectors and actors (Sarabi et al. 2019, Dubo et al. 2023). Funding options for NbS range from purely public sources to public-private partnerships and blended finance, but research indicates the private sector could contribute more significantly to achieving transformative goals at scale. A 2022 report on NbS financing revealed that to meet climate, biodiversity, and land degradation targets through NbS, investments need to rise sharply to $384 billion annually by 2025, more than doubling the current $154 billion annual investment (UNEP 2022). The private sector has a crucial role in effectively implementing NbS, especially in developing and emerging economies by overcoming major financial, technical, and governance challenges. With a notable funding shortfall in NbS projects, private investments via blended finance, public-private partnerships, and impact-investment models can provide vital resources to expand NbS initiatives (UNEP, 2022). Furthermore, businesses can incorporate NbS into their sustainability plans, using ecosystem services to support climate adaptation, protect biodiversity, and strengthen supply chain resilience. Additionally, capabilities are crucial, as stakeholder participation plays a key role — issues like limited local stakeholder engagement, poor coordination among actors, and low stakeholder capacity can impact project success (Dubo et al. 2023).

The fourth subaction of NbS involves monitoring and governance, which should concentrate on meeting the goals established during problem analysis and planning. The governance framework presented by Matson, Clark, and Andersson (2016) for managing SES illustrates how a broad analysis of the system being transformed can be conducted through this framework. Governance quality acts as a tool to track progress in implementing and achieving NbS objectives. Effective governance played a key role in restoring drylands in

the Duwa and Sutebwo forests of Mali's Segou Region. The project employed a decentralized, participatory, and inclusive forest governance model and established two inter-communal cooperatives (Hou-Jones, Roe, and Holland 2021).

Governance levers are crucial for supporting the monitoring and governance of NbS. The effectiveness of NbS increases when they align with a country's SDG targets. For example, the case of Masdar City in the UAE, which was envisioned and is being built as a smart, sustainable urban area utilizing NbS to transform a desert landscape (Griffiths and Sovacool 2020). Since 2006, Masdar City's governance has evolved through several phases, from an initial focus on clean energy technology manufacturing to a sustainable eco-city that acts as a "holistic master integrator" of carbon-neutral solutions, fostered by partnerships, open collaborations, and research and development (Masdar 2017). Masdar City's responsive governance framework, aligned with the UAE's progressive sustainability policies like Energy Strategy 2050 and the Net-Zero by 2050 initiative, has driven its transformation. The authority granted to stakeholders such as the UAE, Mubadala, Khalifa University, NGOs, international partners, and citizens to implement NbS was crucial in Masdar City's case. This demonstrates a collaborative governance model that emphasizes consultation and co-creation (Frantzeskaki 2019), which is essential for managing and governing NbS to transform socio-environmental system.

18.2.2.2 Action Two: Accelerate upscale of proven nature-based practices and solutions

NbS need to be scaled up to be truly effective, but currently they are mostly limited to pilot projects or local government initiatives (Hartmann and Spit 2016). Involving citizen science (Fraisl et al. 2022) can help close this gap by engaging local communities in activities like data collection, monitoring, and adaptive management. This ensures NbS are adapted to specific local ecosystems and socioeconomic contexts while promoting wider adoption and support. Although NbS are typically customized to local conditions, increasing their scale offers the chance for broader impact and transformational change. A four-step framework for evaluating the potential and strategy for scaling NbS was proposed by Lebelt et al in 2023.

There are multiple pathways for scaling NbS, typically categorized into three approaches: "scaling out", "scaling up", and "scaling deep" (Salafsky et al. 2021). Examples include mangrove restoration in various coastal regions, expanding urban green infrastructure, adopting agroforestry across diverse agricultural landscapes, and conserving wetlands in different river basins. Scaling up specifically involves extensive replication of NbS across landscapes and seascapes, such as incorporating NbS into national climate policies, enacting legislation for urban planning, providing financial incentives for large-scale reforestation, integrating NbS into international development programmes, and securing corporate commitments to NbS. Addressing land restoration issues at a specific site exemplifies the scaling out of NbS. In contrast, scaling deep involves tackling the underlying socioeconomic drivers and barriers that cause ecosystem degradation, using appropriate leverage points. Ecosystem restoration must also be expanded spatially, to match the scale of widespread environmental damage, and temporally, to improve issue identification, enable adaptive management, and extend project longevity (Ren and Coffman 2023). Scaling deep of NbS entails integrating these solutions into national policies and laws, changing agricultural practices and cultural norms, and encouraging the private sector to incorporate NbS into their business models.

To create opportunities for system transformation, scaling deep requires addressing the root socioeconomic drivers of ecosystem degradation through relevant levers and by good governance. Scaling deep involves creating alternative livelihoods, addressing unemployment and integrating individual and collective action levers into NbS to reduce the drive of people to engage in illegal activities and increase participation and interests in conservation and restoration.

18.2.2.3 Action Three: Build resilience to create a self-sustaining socioecological system

Sustaining conservation, restoration, and ecosystem adaptation over the long term depends on enhancing the resilience of SES, enabling the development of self-sustaining and resilient ecosystems (Krievins et al. 2018). This is achieved by incorporating the seven principles (Biggs, Schlüter, and Schoon, 2015) into the four systematic steps for NbS (Albert et al. 2021).

To improve the effectiveness of NbS as a resilience pathway, measurable performance metrics should be incorporated into its implementation. These include ecosystem restoration targets, linked to solution

pathway 1, such as increasing vegetation cover and meeting KMGBF targets, as well as climate resilience metrics, including reduction of flood risk by a specified percentage and enhancement of water retention in NbS-managed landscapes. Socioeconomic benefits should be measured by tracking local job creation, improved livelihoods through ecotourism and sustainable agriculture, and the integration of citizen science in monitoring ecosystem health. Furthermore, carbon sequestration and climate mitigation can be evaluated through CO_2 absorption rates and expanded urban tree cover. To ensure accountability, NbS performance should be monitored using remote sensing, biodiversity surveys, and participatory approaches, aligning with international frameworks such as the Paris Agreement and SDGs.

18.2.3 Locally led adaptation and disaster risk management for enhancing socioecological system resilience

Building resilience is an ongoing process essential for a transformative shift in SES. CCA and resilience efforts require a combination of local initiatives supported by top-down policy measures, which are often missing in current state of practice. LLA actions and its eight principles (**Box 18.3**), endorsed by over 100 organizations including governments, development agencies, INGOs, and NGOs, call for a new paradigm. For genuine transformative adaptation, LLA solutions should be central to all sustainable development activities. Decades of CCA projects, often designed without considering local needs and priorities, have yielded mixed results—sometimes causing maladaptation—and have fallen short in mobilizing resources at the local level. This oversight also extends to the promotion and application of Indigenous Knowledge and Local Knowledge. These knowledge systems are deeply rooted in local contexts, often developed as NbS, and supported by scientific evidence gained over centuries through experimentation and accumulated learning. While Indigenous Knowledge and Local Knowledge are typically vital responses to climate change, they are also vulnerable to climatic impacts that could diminish their effectiveness. The LLA approach, which builds on Indigenous Knowledge and Local Knowledge might be more effective because it involves a gentler learning curve and carries a lower risk of failure or maladaptation, but the knowledge system requires identification and proper documentation, reinforced by integrating modern science, and creation of financial incentives for intergenerational transfer to youths.

LLA action, as a recent and evolving paradigm, can serve as a transformative solution if lessons are validated, standardized, and scaled across regions. It is envisioned as a model that co-achieves resilience for the human-nature nexus, adding a safety layer to prevent setbacks in conservation, restoration, and other human systems from severe climate change impacts. LLA encompasses not only CCA and DRR but also integrates net-zero energy systems, GHG mitigation, circular economy, sustainable food systems, ecosystem conservation, efficient financial pooling, and resilient critical infrastructure. For example, renewables can be deployed for climate adaptation while adaptation measures need to also account for energy security from climate risks, such as drought, heat stress and forest fires, floods, cyclones, landslides, to sustain the transformation of energy system mentioned in Chapter 16.

To implement this solution, this chapter suggests three sequences of actions to be undertaken over time by mobilizing sets of five levers. These actions are carried out by actors at various levels, based on available information, lessons learned, and common challenges faced in different regions. It is also crucial to incorporate the concerns of the most vulnerable groups and integrate a gender perspective to ensure that the needs and contributions of women, the elderly, children and youths, Indigenous Peoples, and other marginalized community members are fully addressed.

18.2.3.1 First Action: Enhance risk information and its communication in an inclusive manner

Risk information and communication are foundational for CCA, DRR, and minimizing loss and damage. As climate impacts are worsening and extreme multi-hazard situations, droughts, heat waves, forest fire, floods and landslides, cyclones and storm surges, become more frequent and complex, the importance of timely and correct risk information and communication has become critical for decision-making. Advances in information and communication technology, including rapid development and deployment of in situ and remote sensors, mobile apps, artificial intelligence solutions, has ushered a new era of technological and societal transformation that could be best utilized to speed-up the coverage of risk information and communication for all. International organizations, research community, governments at different levels,

private sector, as well as local communities are increasingly embracing the development, promotion, and uses of new innovations on information and communication.

Regional platform like SERVIR harnesses the power of satellite data and scientific collaboration to support healthy, sustainable communities, livelihoods and environments at local levels. The Intra-ACP Climate Services and Related Applications is an initiative for African, Caribbean, and Pacific States that aims to improve the production, access to and use of climate information, services and applications for decision makers. The Global Disaster Alert and Coordination System provides real-time alerts, impact assessments, mapping, weather forecasting, and standardized information exchange. Mobile apps and social media are connecting individuals, farmers, governments, and private sectors, providing key decision support and enabling robust feedback systems. In this regard, Early Warnings for All is an ambitious initiative by the UN Secretary-General that aims to protect everyone on

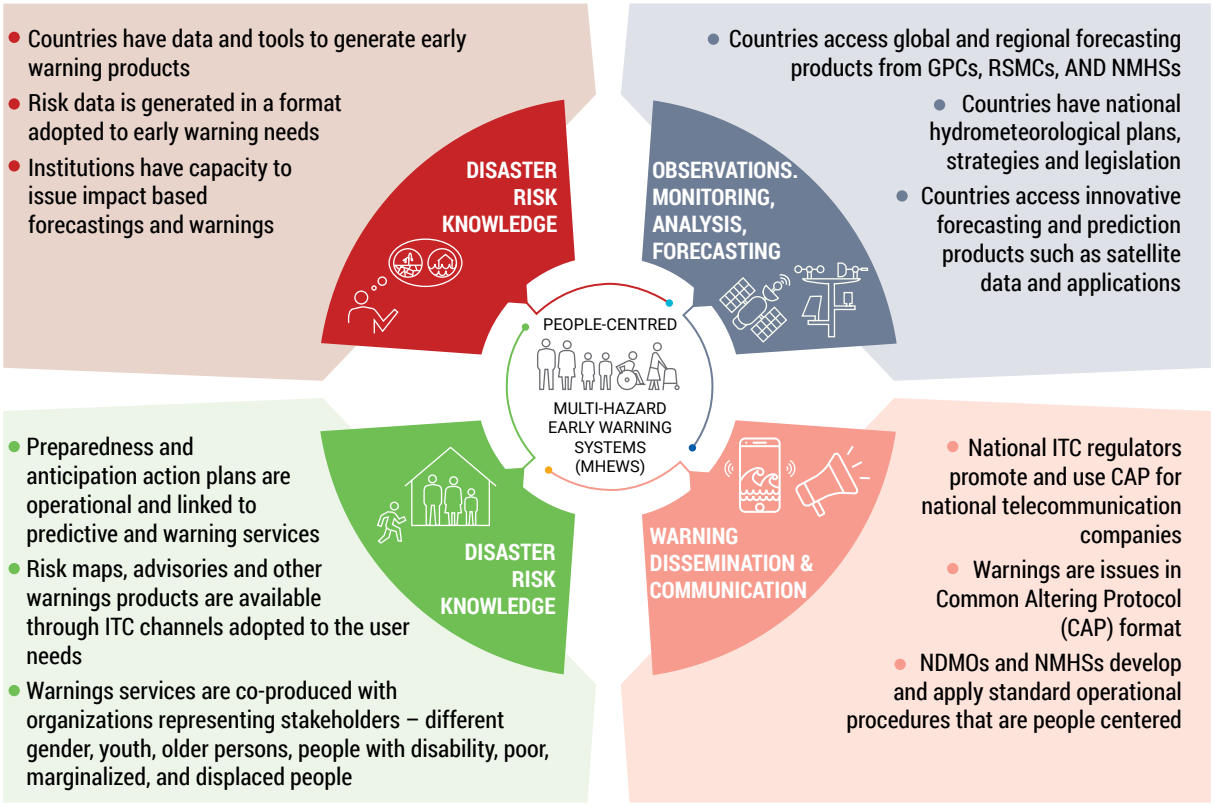
Box 18.3: Locally led adaptation actions

Local actors, including communities, Indigenous People, and local governments, are on the frontlines of climate change and other environmental problems. They often rely on their in-built responses, including Indigenous Knowledge and Local Knowledge, and frugal innovations. However, they often have a limited voice in important CCA decisions that directly affect them. LLA represents a shift from business as usual by prioritizing the involvement of local actors in all decision-making on CCA. This includes defining priorities, design of solutions and their implementation, as well as monitoring processes or evaluating successes and failures. LLA offers a transformative shift by positioning local stakeholders not as the sole bearers of adaptation responsibility, but as key drivers of catalytic adaptation solutions that are locally based, effective, equitable, and transparent.

While not all adaptation needs to be locally owned or led, initiatives like the LDC 2050 Vision, emphasize the need to channel more resources and capacity in the hands of local actors. Since social participation and ownership are not new in CCA-related interventions, LLA calls for consolidating proven best practices while addressing persistent barriers. To strengthen LLA, the Global Commission on Adaptation has developed eight principles:

- Devolving decision-making to the lowest appropriate level;
- Addressing structural inequalities faced by women, youth, children, people with disabilities, people who are displaced, Indigenous Peoples and marginalized ethnic groups;
- Providing patient and predictable funding that can be accessed more easily
- Investing in local capabilities to leave an institutional legacy;
- Developing a robust understanding of climate risk and uncertainty, drawing on a combination of local and Indigenous, generational and scientific knowledge;
- Promoting flexible programming and learning for adaptive management to address inherent uncertainty in adaptation;
- Ensuring transparency and accountability in all aspects of adaptation, including finance, design and implementation; and
- Promote collaborative action and investment to mobilize resources effectively from various sources and to enhance efficiencies and good practices (Global Commission on Adaptation 2021, Soanes et al. 2021).

Figure 18.4: Four pillars of Early-Warning-for-All initiative for effective multi-hazard early warning



Source: WMO (2022)

Earth from hazardous weather, water, or climate events through life-saving early warning systems by the end of 2027 (World Meteorological Organization [WMO] 2022) (**Figure 18.4**). Encouraging lessons are emerging on how regional cooperation in risk information and communication is essential in saving lives and property, including energy systems, from multiple hazards. However, there is a missing link between regional, national, and local capabilities when it comes to enabling reliable access to risk information and communication. For instance, farmers and pastoralists use Indigenous Knowledge or methods of weather forecasting alongside scientific forecasts for decision-making, such as through citizen science approach, to cope with climate change impacts (Nkuba et al. 2023). The knowledge and innovation levers play a significant role in transferring and adopting the latest innovations, such as providing satellite connectivity in remote or disaster-affected areas. Additionally, they promote Indigenous Knowledge and Local Knowledge that are grounded in science or have strong sociocultural support.

Meanwhile, economics and finance levers, like the Adaptation Fund or the newly established Fund for responding to Loss and Damage under the financial mechanism of UNFCCC, can be mobilized to finance technology adoption. This funding is crucial for activating other levers, including individual and collective action, knowledge and innovation, and capabilities, which generally take longer to implement. For example, successful deployment of an early warning system depends on clear protocols and mechanisms to turn warnings into timely, coordinated actions on the ground. Strengthening community-level response capacity ensures warnings are not only received but also effectively used for response to the events.

Similarly, regional organizations, research communities, and the private sector can focus on developing services, such as impact-based forecasting, centred on risk information and communication. Meanwhile, central and subnational governments, along with community-based organizations, can promote the adoption and use of the system. A two-way risk communication system should be established that is both responsive and adaptive to reduce losses and damages to people and nature. The faster progress is made on this action, the earlier significant progress on transformative adaptation will be made.

18.2.3.2 Second Action: Formulate integrated interventions to enhance the resilience of SES, while enabling climate-resilient development

Climate-resilient development can enhance capacity for climate action, including GHG reductions and the implementation of CCA options that boost social, economic, and ecological resilience to climate change (IPCC 2022). Therefore, climate-resilient development and strengthening the resilience of SES require integrating all synergistic approaches for CCA, net-zero strategies, DRR, addressing loss and damage, ecosystem conservation and restoration, sustainable bioeconomy, and related efforts. In addition to improving risk information and communication, it is important to acknowledge a combination of infrastructure and processes that have shown promising results but face barriers to widespread adoption. These include EbA and ecosystem-based DRR (UNEP 2021). These solutions should be tailored to the local context, designed for replication, and structured to encourage cross-fertilization, knowledge-sharing, and regional collaboration. Many initiatives and practices, both newly evolving and established, from local to regional levels, are available but still need consolidation. Available economics and finance levers, particularly the increasing number of large and small climate change funds under UNFCCC, the United Nations, multilateral development banks, governments, independent, and private sources require major consolidation to avoid duplication. Examples include the Green Climate Fund, Global Environmental Facility, Adaptation Fund, WB Climate Change Action Plan, ADB Climate Fund, Germany's International Climate Initiative, UK International Climate Finance, Climate Justice Resilience Fund, Patagonia Environmental Grants Program, Clean Technology Fund, and Amazon Climate Pledge Fund, among others.

LLA aims to facilitate a systematic flow of funds and resources from available sources to the local level efficiently. It is essential to prioritize a set of climate-smart interventions supported by existing financial instruments, which may be risky from a traditional cost-benefit perspective but are crucial for preventing the "soft limits" of adaptation from becoming "hard limits." These initiatives also lay the groundwork for inclusive climate-resilient development. Three key conditions are particularly relevant. First, addressing the immediate risks posed by climate change impacts, such as droughts, heat stresses and wildfires, that are widespread and affect sectors such as farming, health, transport, energy, and ecosystems. Second, implementing proper safeguard measures to compensate climate victims is vital to support building back better, promote transformation, and enhance resilience. Finally, climate-resilient development should broaden options for socioeconomic opportunities at the local level to enhance resilience and societal well-being in harmony with nature. Supported by economics and finance levers, much can be achieved through the effective use of knowledge and innovation levers, such as local innovation that integrates modern science to strengthen Indigenous Knowledge, traditional knowledge, and local knowledge, along with the rapid adoption and localization of interventions. Notable examples where knowledge and innovation levers have played a key role include NbS, community-based adaptation, climate-smart farming, solar panel use in agriculture (agrivoltaics) and rooftops, providing shading, decentralized access to clean energy, and creating additional income as prosumers, microcredits, crop or livestock insurance, and digital literacy.

Success often depends on local buy-in, primarily driven by effectively utilizing individual and collective levers. These levers are most effective when they motivate meaningful stakeholder participation across various levels. The capability and individual and collective levers are crucial for establishing frameworks that support monitoring, reporting, and evaluation. Capability lever not only facilitate the implementation of CCA interventions but also help generate socioeconomic opportunities, especially for youth. This includes promoting local entrepreneurship or start-ups related to CCA services, such as financial literacy, marketing skills, or local manufacturing of tools based on Indigenous Knowledge and Local Knowledge, extension, and advisory services. The successful implementation and replication of certain practices, such as climate-smart farming, is often determined by how well these capabilities are built, retained, used and embedded into local policy, planning, and decision-making.

18.2.3.3 Third Action: Rapid upscaling and institutionalizing of locally led adaptation interventions

The main challenge in transformation lies in implementing the identified LLA solutions quickly and at scale (Chapter 21), while ensuring sustainability. The approach is very adaptable, with all five levers and involved actors working together to overcome barriers, challenges, and trade-offs that may arise during implementation. It also aims to create synergies

that deliver sustainable benefits for people, nature, and the broader system economy.

Creative approaches are needed first to achieve the desired speed and scale of implementation. The previous two actions form the short- and medium-term focus, where a lot of innovation, trials, learning, and replication occur, laying the groundwork for long-term transformation.

In this third step, governance lever plays a crucial role by shaping the direction of change. Practical actions are needed to bridge the gap between upstream policy decisions on climate change – such as the National Adaptation Plans, National Climate Change Policies, and Nationally Determined Contributions – and the beneficiaries of these policies. Prioritizing capacity development alongside individual and collective action levers is vital for raising awareness and integrating national and international decisions at the local level. A clear example of this challenge is the difficulty in implementing adaptation communication to monitor Global Goal on Adaptation under the Paris Agreement, highlighting the disconnect between policy formulation and practical application. Mainstreaming must also include the localization of important biodiversity and SDG-related policies and targets in a coordinated way. This approach can benefit both governments and key stakeholders by aligning policies and actions across all levels. Firstly, it facilitates pooling resources for climate action, SDGs, DRR, biodiversity conservation, and ecosystem restoration. Secondly, it enables stakeholders, especially local beneficiaries, to align their priorities with national and international policies and to communicate their concerns and needs to decision makers upstream. While these considerations are often included during project and programme planning, they are frequently poorly executed due to time constraints and institutional barriers. Therefore, over time, a strong institution supported by capabilities, economics and finance, and knowledge and innovation levers will be necessary to improve coordination across different decision-making levels.

18.2.4 Acceleration of the circular economy transition through innovative bioresources and deployment of a sustainable bioeconomy infrastructure

Five actions are identified, along with levers and actors for transformational change as part of an effective solution pathway. These actions align with bioeconomy strategy development worldwide, with 23 countries already having an active bioeconomy strategy and 15 countries in the process of developing one (FAO 2024). See also **Box 18.4** for drivers and principles guiding a sustainable bioeconomy.

18.2.4.1 Action one: Accelerate the transition to a circular bioeconomy

The shift to a circular economy focuses on maintaining a continuous flow of resources within either technical or biological cycles. Its goal is to keep resources – such as energy, fuels, metals, plastics, and synthetic chemicals – within these cycles through recovery, restoration, and smart utilization using advanced technologies and effective regulation (**Figure 18.5**). This is especially critical for the mining industry, notably concerning energy transition minerals, as explained in Chapter 16.2.4. Developing a sustainable circular bioeconomy supported by suitable infrastructure is essential for reducing waste and maximizing resource efficiency (Geissdoerfer et al. 2017; IRENA 2020).

Likewise, food systems need to implement sustainable and regenerative practices that boost biodiversity, conserve Indigenous and local farming methods, lower GHG emissions, and enhance soil health (Chapter 17) (FAO 2018; IPCC 2019). Central to these efforts are knowledge and innovation and individual and collective levers. In the short term, developing and deploying technologies for resource recovery, biobased materials, and waste-to-resource conversion is vital to increase circularity. Additionally, collaborating with Indigenous Knowledge holders, who have extensive resource stewardship practices, is crucial to ensure bioeconomy strategies are effective and respectful of ecological limits. In the medium term, advanced technologies like artificial intelligence and blockchain can help monitor resource flows and increase transparency in supply chains. By harnessing diverse knowledge systems and scientific progress, society can establish resilient, circular economies that support both people and the planet in the long term.

The goal of reducing natural resource depletion by advancing a circular economy through innovative bioresources and bioeconomy infrastructure is to establish a sustainable system that minimizes waste, enhances resource efficiency, and helps restore natural

ecosystems. This strategy includes several vital components and strategies. The impact of production systems is profoundly local, as they influence nearby communities and their environments by depleting resources and using ecosystems as pollutant sinks via discharges and waste disposal (Geissdoerfer et al. 2017; Kirchherr, Reike, and Hekkert 2017). This degrades local ecosystems and damages the health and livelihoods of local populations (Rockström et al. 2009; Steffen et al. 2015).

Overall, accelerating the bioeconomy requires the combined action across knowledge and innovation, individual and collective and governance levers to enable effective transformational solutions. There is a significant policy commitment to the concept of the bioeconomy, with some technologies already in use, but deploying bioeconomy innovation at scale remains challenging.

18.2.4.2 Action Two: A regulatory environment to ensure biofeedstock supply is environmentally sustainable, avoids trade-offs with biodiversity, food and water resources

A strong and coherent regulatory environment, with central governance levers globally recognized and effectively implemented, is key to the successful deployment of a sustainable bioeconomy. Despite significant efforts, the regulatory environment is fragmented. This requires urgent short-term action. Sustainability metrics that quantify full life cycle impacts of direct and indirect effects of bioresource cropping, including on GHGs, biodiversity and ecosystems services are now well-understood, but require effective implementation. Direct effects refer to all life cycle effects on the immediate system in which the crop is grown, such as tractor operation and fuel used to grow the crop as well as environmental

Box 18.4: Drivers and principles to ensure a future sustainable bioeconomy

The bioeconomy refers to the production, utilization and conservation of biological resources, including plants, animals and microbes, alongside derived biomass and organic waste, across many economic sectors, including agriculture, energy, chemicals, and pharmaceuticals. It plays an essential part of the circular economy, detailed in Chapter 15. While bioeconomy pathways vary by sector, process and geography, they are linked using biological resources to support a low-carbon, sustainable economy (Tan and Lamers 2021). Five ecological principles to guide biomass use for a sustainable bioeconomy are:

- Safeguard and regenerate healthy ecosystems: source biomass sustainably, avoiding depletion of natural capital, through use of marginal land for bioeconomy development.
- Avoid non-essential products and reduce waste of essential ones.
- Prioritize biomass use appropriately. For example, avoiding the use of first-generation food crops for biofuel and avoiding direct and indirect land-use effects; thus, identifying land for food crops.
- Utilize co-products/waste from agroecosystems first: use by-products like straw or manure, and other resources, which may otherwise be lost or misused, such as straw burning.
- Minimize energy footprint and use renewable energy. Apply life cycle assessment methodology to ensure the energy and carbon footprint of the proposed bioeconomy system is significantly lower than fossil fuel-based alternatives (Muscat et al. 2021).
- Drivers enabling bioeconomy development and deployment:
- Low-carbon technologies to address climate change goals and climate mitigation

- More efficient use of planetary resources
- Integration into the circular economy
- Advances in biotechnology, such as engineering microbes, plants and animals are enabling new opportunities
- Regional governance driving innovation and deployment

Key barriers to sustainable bioeconomy deployment:

- Inconsistent biomass supply, especially year-round at a reasonable price
- Logistics of biomass transportation
- Infrastructure and storage limitations
- Technology scaling and gaps in chemical engineering knowledge
- Limited financial resources and financial models to enable investment and commercialization
- Capital investment requirements are high
- Immature regulatory environment and lack of global standards
- Weak market demand for products due to higher costs

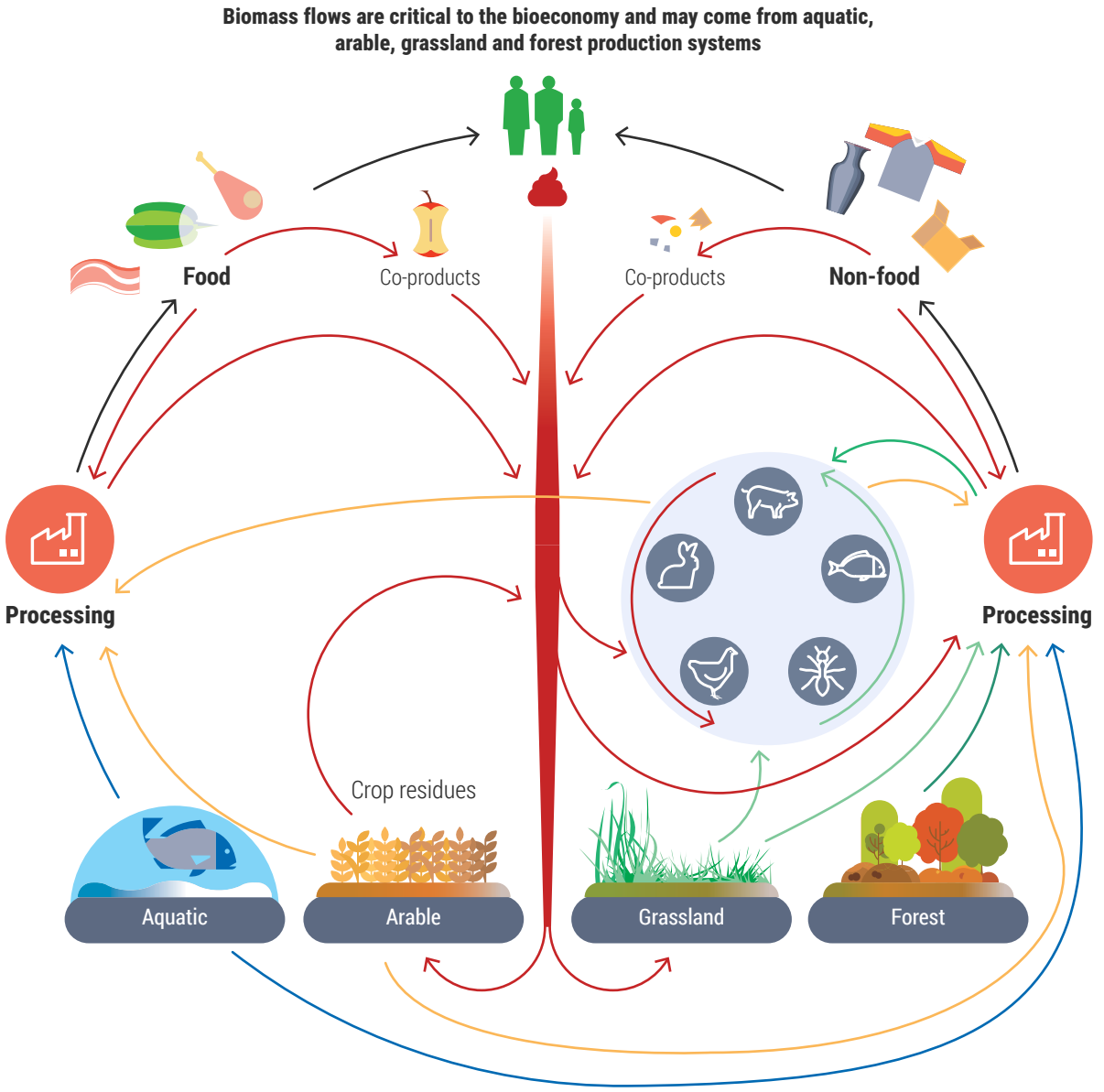
Absence of governance and policy support, ensuring sustainability standards are met, lack of skilled workforce, lack of public understanding and awareness

Bioeconomy case examples: The International Energy Agency provides a global summary of biorefinery research and deployment activities (IEA 2022).

One notable example is from the Kingdom of the Netherlands, where the company Avantium is advancing the use of plant-based resources for sustainable chemical production. Their vision includes production of plant-based plastics made from plant sugars, to replace glass bottles, aluminium cans and multilayer packaging, as well as capture of carbon dioxide and using it to produce formic acid, a preservative and antimicrobial chemical, and oxalic acid, a chemical derived from plants with use for cleaning. These high-value chemicals have a wide range of applications and are traditionally made from fossil fuels. The novel carbon-negative polymers are compostable, degradable, recyclable.

In linking such biorefinery deployments to restored natural capital, life cycle analysis demonstrates that, from cradle to grave, the GHG emissions of the biorefinery processes have significantly lower greenhouse gas emissions than their fossil- based alternatives, relative to alternative systems (Eerhart et al. 2012). It is widely acknowledged that to avoid potential conflicts around land for food and energy, the bioeconomy must shift to second generation non-food fibrous and woody crops. Equally important is to establish better links between the biorefinery activities and natural capital enhancement.

Figure 18.5: Biomass flows are critical to the bioeconomy



Source: modified from Muscat et al.(2021)

costs of fertilizer from which bioenergy resources are grown or extracted (IEA 2024). In contrast, indirect effects, recognized for several years (Bourguignon 2015) may occur as unintended consequence of bioresource cropping, for instance if food crops are displaced to high-biodiversity landscapes due to land conversion elsewhere (Sanchez et al. 2012).

However, the direct and indirect impacts of bioenergy cropping vary by geography, land availability, culture and management practices. Several regional and global standards for bioenergy cropping, such as the GBEP – the Global Bioenergy Partnership and the Roundtable on Sustainable Palm Oil, provide a framework to ensure sustainability criteria are met, particularly for direct land-based impacts, focused on GHG emissions reduction and ensuring sustainability. Recent technological expansion has been focused on non-food lignocellulosic (fibrous and woody crops)-fast-growing trees and grasses, with improved GHG balance (Harris, Spake, and Taylor 2015) and enhanced biodiversity (Donnison et al. 2021). However, these regulatory bodies are voluntary, leaving significant risk, given the increasing future demand for bioresources. There is a pressing need for explicit and enforceable frameworks for defining sustainable bioenergy crops, encompassing the management of natural resources, transparency and science-based carbon accounting, protecting and enhancing biodiversity and supporting and protecting communities, such as that proposed

by the Glasgow Declaration on Sustainable Bioenergy and IEA offer promising models.

In addition to biodiversity, a significant risk of water over-extraction remains for bioenergy, as well as for other crops. In the face of a changing climate, this should also be acknowledged, as identified by IPCC (2019). Levers required to ensure this action are governance and knowledge and innovation.

Evidence shows that poorly designed supply chains are an example of how bioenergy has the potential to go wrong and harm biodiversity, especially when bioenergy crops replace natural grasslands or forests (Desiree et al. 2013; Immerzeel et al. 2014; Núñez-Regueiro, Siddiqui, and Fletcher Jr 2021). Improved governance of bioresources is essential to ensure a sustainable bioeconomy and to protect biodiversity. A consensus is forming on designing biocropping systems that promote biodiversity across various landscape types. Sustainable bioenergy crops should be expanded and integrate innovative agricultural practices. These include:

- cover cropping
- shifting to perennial crops
- optimizing water and input use
- new crop varieties requiring fewer inputs
- adopting technology-driven practices as part of climate-smart agriculture

Cropping management should aim to stop biodiversity decline while incorporating transformative technologies like the widespread adoption of precision-engineered or gene-edited feedstocks. Most of these actions require better governance alongside individual and collective action levers. For instance, governance is essential to establish policies that incentivize changes in agricultural practices, such as payment for ecosystem services (Farley and Costanza 2010) and soil health initiatives (Eastburn et al. 2017). Farmers and communities must adopt change, reassess their environmental values, and produce goods in a new manner that promotes the flow of biomass from food to residues and processing.

The bioeconomy plays a crucial role in the sustainable circular economy (Chapter 15). It offers substantial potential to deliver transformative solutions – replacing fossil fuels with biomass-based energy, manufacturing, and processing – while also addressing climate change. This includes restoring natural capital, as well as advancing fuel, food, chemicals, and agricultural innovations, enhancing supply chain resilience, improving human health, and fostering cross-cutting advancements (The White House 2023). Achieving future success depends on rebuilding global natural capital (Tan and Lamers 2021). Future efforts should focus on identifying suitable land for bioenergy crops at the national level and streamlining fragmented global governance approaches to ensure the broad sustainability of this emerging resource (**Box 18.5**).

18.2.4.3 Action Three: Developing new and novel bioresources: plants, animals and microbes

The global demand for diverse types of bioresources will be substantial. For instance, in the United States of America alone, 1.2 billion tons of biomass annually are proposed for sustainable aviation fuel and to support a robust bioeconomy (Langholtz, Stokes, and Eaton 2016; The White House 2020). Recently, the fastest-growing biomass application is wood pellet production for low-carbon electricity, reaching over 44 million tons in 2021 and, up from 18.1 million tons in 2012 (World Bioenergy Association 2022). Effective crop and land management, along with crop breeding, can play a crucial role in supplying new bioresources for this expanding bioeconomy. A better understanding of the genetic and environmental factors influencing feedstock yield and quality is essential, especially through technological and future innovations. This highlights the need for developing crops that require less water, nitrogen, and phosphorus, while also lowering GHG emissions (Chen et al. 2019). Additionally, improving animal- and microbial-based systems is necessary to reduce their GHG footprint, which will require advances in biotechnology. Microbes play a crucial role in promoting a sustainable bioeconomy by enhancing biological carbon sequestration, facilitating more efficient microbial pathways for converting feedstock into fuel, remediating hazardous substances and wastes, and engineering crops with symbiotic bacteria for nitrogen fixation (Peixoto et al. 2024).

Waste-derived feedstocks should also be used, enabling the combined use of sustainable sources to produce environmentally friendly aviation, maritime, and other fuels that are difficult to supply through other technologies (Bioenergy Technologies Office

Box 18.5: Bioenergy and Carbon Capture and Storage: concerns for the environment

- Widescale deployment of bioenergy has the potential to deliver multiple low-carbon energy solutions, for heat, power and liquid biofuel, with or without associated carbon capture and storage. The demand for bioenergy is projected to increase in all GEO-7 scenarios (Chapter11), in line with other assessments. It is especially prominent in the GEO-7 Transformation Scenarios where bioenergy with carbon capture and storage (BECCS) is applied to help achieve the UNFCCC-Paris target of 1.5°C in 2050 without overshooting the target, or where the target is overshot and BECCS is used to return to the target. However, the amount of BECCS required is less in the behaviour-focused scenario compared to the technology-focused scenario. The unique and appealing feature of BECCS is that it produces both energy and negative emissions. The amount of BECCS required depends on several factors including the degree to which the energy system is decarbonized prior to 2050, and the amount of energy required after 2050 and how effectively biomass can be used for multiple purposes as part of an emerging bioeconomy (Chapter 15).

- The land use and potential consequences for the environment associated with this demand for BECCS is significant, but earlier estimates of the technical potential of over 2 billion hectares of land (Slade et al., 2014; Haberl et al., 2010; UKERC, 2011), has now been significantly reconsidered because of limitations associated with sustainability trade-offs. These trade-offs relate to loss of biodiversity, water use, and to conflicts with land needed for growing food, NbS, indirect land-use change, and conservation, according to recent estimates for land needed for effective bioenergy and BECCS purposes (IPCC, 2018, 2023; Chapters 16 and 17). The two scenarios of GEO-7 both commit less than 100 million hectares of land to BECCS, in contrast to earlier assessments that predicted much higher land demand.

- The use of land resources to address energy, food and nature is critical for effective transformative solutions identified throughout this GEO assessment. Potential supply of biomass for BECCS is also dependent on the emergence of new technologies, including biotechnologies that deliver highly productive non-food, fibrous and woody crops. Some biomass material is already available from agricultural and forestry residues and other waste materials that do not compete with food and feed. Governance and management of these trade-offs will be key to a future sustainable bioeconomy with BECCS as an appropriate technology.

Credit: ©UNEP

2024). Similarly, these feedstocks can be utilized to synthesize high-value chemicals, pharmaceuticals, and polymers, replacing traditional products and offering biotechnological solutions for a broad range of issues, such as bioengineered foods like milk and meat, and replacing fossil hydrocarbon-based materials with bioresource-based alternatives (Muscat et al. 2021).

Sustainably sourced and cultivated feedstocks are needed on a large scale, and this demand is expected to continue rising. Society is entering an era where more biomass has been harvested than ever before (Foley et al. 2011; Krausmann et al. 2013). It has been estimated that global biomass demand could triple in the coming decades. An essential solution pathway for establishing a sustainable bioeconomy involves identifying, sourcing, and managing new, sustainable global biomass resources. Consequently, biomass feedstocks will be increasingly needed for various applications in the future bioeconomy, as outlined in **Table 18.2**.

Engineering biology provides valuable knowledge and innovative prospects for the bioeconomy. Creating new and unique feedstocks and bioresources through biotechnology, as well as traditional methods like identification, sourcing, breeding, selection, collection, and pre-processing, is essential for advancing the bioeconomy. Traditional plant breeding typically yields about a 10 per cent increase per decade. However, the availability of new biotechnological approaches – such as engineered feedstocks from gene editing in plants, animals, and microbes – will enable paradigm-shifting developments. These include improvements in plant chemistry for bioprocessing, increased production of necessary chemicals, and yield enhancements, which are already beginning to emerge (Ricroch, Clairand, and Harwood 2017; Zhang et al. 2019).

Novel new sources of biomass are also needed to support the shift to more plant-based diets, including increased production in plant-based proteins from legumes such as peas, beans and chickpeas, as well as

Table 18.2: Projected biomass feedstock requirements

Bioproduct	Potential demand for feedstock biomass to 2050
Bioenergy heat and power	Global demand is increasing. 300-600 million ha of wood-based bioenergy cropping is possible (Lauri et al. 2014; Fuss et al., 2018), providing 5-250 Exajoules per year by 2050 (IPCC, 2023).
BECCS- Bioenergy with carbon capture and storage	Will be needed to meet the 1.5°C target for global warming by 2050. Requires 200-600 million hectares (IPCC 2023, IEA 2024). In the target-seeking scenarios of GEO-7, less than 100 million ha is required due to the extensive use of waste co-products.
Biogeochemical sequestration – carbon dioxide removal technologies	Fast-growing trees and afforestation, several hundred million to 1 billion hectares required, depending on tropical, temperate and boreal contributions.
Sustainable aviation fuel	Rapidly increasing demand with 400 million tons per year required by 2050. Significant amounts will come from waste and co-product streams but dedicated crops will become increasingly important. E.g. in the US, 10-12 million hectares required to supply 3 billion gallong per year by 2030.
Plastics, chemicals, pharma	Currently three million hectares for bioplastics (European Bioplastics 2024).
Protein production, plant-based meat, plant-based dairy, plant-based proteins in processing	A UNEP report cites land use as lowered, 100m2 per 100g protein in animal-based meat, versus 5-15 m^2 per 100g protein in plant-based (Santo et al. 2020).
Regenerative agriculture, mulches, better use of animal co-products, anaerobic digestion, biogas, biochar	With a goal to reduce GHG emissions by up to 30 per cent, these measures occur on land already allocated to food production and as such this is not additional land. This may be less than 1.5 per cent of total agricultural land of total agricultural land or approximately 5 billion hectares

grain crops, such as wheat and fast-growing duckweed (UNEP 2023). Novel bioprocessing are emerging, for example, cultured meat and milk, some of which are already available commercially in some parts of the world (The Economist 2023) and likely to become more widely acceptable (Kirsch 2023). Laboratory-based cultured milk, produced through precision fermentation without the use of grazed dairy livestock that emit significant methane, or plant-based milk alternatives made from almonds, which requires large amounts of water, may provide more sustainable alternatives. For example, the company Turtle Tree, is developing a novel process to mass produce lactoferrin, a key milk protein. Similarly, Shiok Meats in Singapore (Singapore Global Network 2021) is commercially producing cultured seafood by extracting stem cell from shrimps, prawn and lobster to generate cell-based laboratory protein. However, a note of caution remains that these ultra-processed foods may carry a significant environmental footprint, and current research is limited. Likewise, the impacts of lab-grown food on human health are unclear. There is limited peer-reviewed research in this rapidly evolving field, and regulatory frameworks are still being developed. Nevertheless, key technologies to watch for in the future include the knowledge and innovation lever, which remains essential for success. It works in conjunction with the capability lever, which is necessary for developing new skills.

18.2.4.4 Action Four: New infrastructures and technologies for the future bioeconomy

Bioeconomy infrastructure deployment encompasses establishing and executing essential systems, technologies, and frameworks that underpin the bioeconomy. This process involves constructing facilities, such as biorefineries, for converting biomass into valuable products, as well as developing supply chains, networks, and logistics that facilitate the efficient collection, processing, and distribution of biobased products.

Early investments from public and private sectors are essential for supporting high-potential solutions using economics and finance alongside governance levers. New sustainable biorefineries are crucial for scaling the bioeconomy. In the EU, over 130 woody biomass-based biorefineries are operating, with more planned. Financial investments are rising in these industries, and in the US, the Inflation Reduction Act in 2022 provided significant new government funding, totalling US$800 billion to help accelerate the development of the bioeconomy, including scaling up innovative technologies such as using municipal solid waste to produce sustainable aviation fuel, a sector that is difficult to decarbonize. A sustainable aviation fuel blending credit is available to encourage this market, provided the process achieves a 50 per cent reduction in GHG emissions compared to standard jet fuel. Many less favoured liquid biofuels can connect this technology to carbon capture and storage systems to reduce life cycle GHG emissions, thereby boosting the value of the fuel in states like California, Oregon, and Washington.

Despite these positive examples, action is needed to support the development of new infrastructures for the bioeconomy. The petroleum industry has benefited from over a century of research, which has shaped the development of a complex hydrocarbon chemical industry (Fitzgerald, 2017). This suggests that the transformational changes necessary to develop a new bioeconomy with such sophistication will take many decades unless concerted, solutions-focused actions are taken to enable rapid change. Biorefining is a key component of the circular bioeconomy, with multiple biorefining pathways identified, comprising four key elements: feedstocks, processes, platforms, and products (IEA, 2022). Multiple bespoke solutions are necessary to foster a circular economy and support the widespread deployment of commercial biorefineries globally. Overall, much of the infrastructure needed to establish these new biobased industries remains undeveloped. In this context, the economics and finance lever plays a central role alongside the governance lever. The sustainable biorefinery is central to the emerging concept of a circular economy, and multiple types of biorefineries are emerging. Some are at the conceptual and research scale, while others are already being deployed commercially (Budzianowski 2017). The International Energy Agency provides a global review of biorefinery research and deployment activity (IEA 2022).

18.2.4.5 Action Five: The bioeconomy that addresses wide societal issues with significant change in governance to support the circular economy to rebuild natural capital

Moving towards a new type of biobased industry is challenging, and stakeholders, including policymakers, innovation supporters, and others, need to explore and develop this space (Bioenergy Technology Office 2017; Schipfer 2024). Significant behavioural and social change, facilitated through the individual and

collective action lever, will be required to transition towards a circular economy, including the training and development of a newly skilled workforce via the capability lever. A strong and growing bioeconomy will need a new workforce with skill sets developed in the short term and deployed across the medium and long term. Technical educational qualifications may need to change, delivering graduates with less emphasis on academic knowledge and stronger technical skills to meet the rapid changes in skill sets required for the bioeconomy. As the demand for skilled workers grows, there will be a need to reskill and retain more people, which requires expanding capabilities. This new workforce should be diverse, supported by the creation of high-quality jobs, and often rooted in rural communities if biorefinery or bioprocessing hubs are established in the region. Developing this workforce will vary by location, and innovative partnerships are essential to ensure equitable access to the benefits of a future bioeconomy. Collaborations with local and Indigenous People and including Indigenous Knowledge can enhance opportunities for sustainable, long-term employment and improve well-being by promoting new skill sets in handling, transforming, and utilizing biomass resources, as well as operating new biobased infrastructure, shifting away from traditional fossil fuel-related skills.

External influences by companies can disrupt traditional methods of natural resource use in forest communities, potentially causing social tensions (Halonen, Näyhä, and Kuhmonen 2022). However, these influences also hold the potential to be positive and transformative, introducing new, innovative approaches through government regulations, altered financial mechanisms, and emerging technologies. Achieving this requires a clear social licence to operate, co-creation and active engagement with local communities. Innovation is essential for building a sustainable bioeconomy in the future. Educating consumers about the advantages of a circular economy and promoting sustainable consumption can increase demand for circular products and services (Hobson and Lynch 2016; Lieder and Rashid 2016).

18.2.5 Enabling adaptive and transformative governance of socioecological systems

Finally, upscaling and strengthening the resilience of SES, biodiversity conservation, and restoration, while advancing the bioeconomy, requires innovation in governance across and within multiple levels. It involves governance with multiple, overlapping decision-making centres that operate at different scales, promoting more adaptive and inclusive management of SES (Berkes 2007; Ostrom 2010) (**Box 18.6**). This model empowers local communities to participate in governance, ensuring that their knowledge and needs are integrated into broader policy frameworks (Folke et al. 2005; Armitage, Berkes, and Doubleday 2007). Collaboration among local, regional, and national levels, promotes adaptive, decentralized decision-making, fostering inclusive and context-specific solutions that enhance overall system resilience and sustainability (Folke et al. 2005; Ostrom 2009). These integrated solutions align biodiversity conservation, sustainable management of natural resources, climate adaptation, and innovative governance with a circular economic system to create a more resilient and sustainable future for all (Rockström et al. 2009; IPBES 2019).

18.2.5.1 Action One: Enhancing local decision-making through inclusive stakeholder engagement and capacity development

Local communities – including rural and urban neighbourhoods, local enterprises and businesses, and active participation from organizations such as non-governmental groups, civil society, Indigenous Peoples, women, and older people, among others – are central to improving decision-making at the local level through co-creation. Government institutions at the local, regional, and national levels serve as vital facilitators, providing the regulatory frameworks and oversight necessary for effective governance. Additionally, NGOs and civil society groups support and reinforce local decision-making processes.

Financial institutions, such as banks, microfinance organizations, and investment funds, are an EF lever that play a crucial role by providing funding mechanisms and financial tools to support local initiatives and ensure their long-term sustainability. Additionally, international organizations and donors contribute resources and technical support, helping to adapt global best practices to regional settings. Academia and research institutions also support the process by supplying data, research, and innovative ideas, which aid in evidence-based decision-making at the local level through the STDK lever.

The success of enhancing local decision-making capacity depends on the effective use of EF levers. In the medium

Box 18.6: Adaptive and transformative governance

Governance refers to the mechanisms and processes through which society makes collective decisions, sets shared goals, and takes coordinated action to achieve those goals. It encompasses the relationships between government and society, including the means through which private actors, markets, and interest-based networks influence policy decisions. Adaptive governance has emerged as a response to climate change and uncertainty, enabling societies to adapt to changing conditions. Transformative governance goes a step further, aiming for a fundamental reorganization of system's underlying structures and controlling mechanisms.

While adaptive governance and transformative governance differ in scope, these approaches share characteristics and can be considered different points on the same spectrum of governance. Both forms of governance require diverse individual and organizational actors operating at different levels of a SES, connected through formal and informal networks. Both require distributed structures such as polycentric governance, robust information exchange, consistent evaluation, and a culture of innovation, experimentation and learning. Transformative governance is needed when SES conditions reach adaptation limits, threshold is crossed, or a regime shift results in ecosystem degradation or increases social inequality. In such cases, governance needs to enable transition towards a more desirable system state with greater production of services and greater social equity (Chaffin et al. 2016).

term, public-private partnerships will be promoted, allowing local businesses to work with larger corporations and government agencies on mutually beneficial initiatives. Additionally, creating localized economic incentives, such as tax breaks or subsidies, will attract investment into sustainable, community-driven projects. In the long term, robust financial mechanisms, such as regional investment funds or climate resilience funds, will be established to provide ongoing financial support for local initiatives. National policies will be integrated with local financial frameworks to ensure the alignment of priorities. Some examples below.

- Short-term example: Microfinance programmes (1-2 years). In Kenya, microfinance institutions like Kenya Women Microfinance Bank offer small loans to women-led businesses and farmers, empowering local entrepreneurs to launch and expand small enterprises, which boosts local economic resilience.

- Medium-term example: Public-private partnerships (2-5 years). The Colombian project Agua Somos is a collaboration among local water utility companies, private firms, and community organizations aimed at promoting sustainable water management. By merging public funding with private sector expertise, this initiative ensures active community participation in decision-making and delivers efficient services.

- Long-term example: Regional investment funds (5+ years). The European Union's Cohesion Fund has consistently supported member states by funding regional projects aimed at reducing economic disparities. Regarding the SC levers, immediate short-term actions will focus on activating existing social networks and utilizing local cultural norms to encourage participation and acceptance of inclusive governance.

Public awareness campaigns will emphasize the advantages of multi-stakeholder involvement, employing culturally appropriate messaging for broad acceptance. In the medium term, ongoing efforts will focus on strengthening trust between local communities and external stakeholders, including businesses and government agencies. This will be accomplished through ongoing consultations and dialogues that respect local customs and traditions, ensuring that all voices are heard. Over time, these initiatives will foster the development of institutionalized multi-stakeholder platforms that encourage transparency, collaboration, and accountability in governance.

- Short-term example: Awareness campaigns and community mobilization (1-2 years). In Indonesia, community-based coastal management programmes, like those in Aceh, have successfully mobilized local fishing communities to participate in ecosystem conservation.

- Medium-term example: Building trust through consultation (2-5 years).

- In Brazil, the Chico Mendes Extractive Reserve involves local communities in sustainable forestry through formal consultation processes that guarantee their participation in decision-making. Trust is fostered by incorporating local knowledge and encouraging transparent dialogue between communities, businesses, and government, leading to stronger, more effective local governance.

- Long-term example: Establishing multi stakeholder platforms (over 5 years). The Philippine Local Development Councils are mandated bodies that unite civil society, government, and the private sector to promote participatory decision-making at the local level. Over time, these platforms have become an integral part of governance, embedding inclusivity into local policies.

A key focus is on developing capabilities that enable local actors to participate effectively in decision-making, such as improved leadership and facilitation skills, financial and entrepreneurial training, project management and monitoring skills, data and analytics skills. Training will highlight the importance of long-term planning, sustainability, and effective policy implementation to ensure a future, better-skilled workforce.

- In the short term (1-2 years), initial efforts will focus on leadership development and financial skills training for local actors. For instance, in Rwanda, the government's Umuganda programme encourages civic participation by training local leaders to oversee public projects, such as constructing infrastructure or implementing environmental conservation initiatives. Train local leaders in facilitation, conflict management, and leadership skills, empowering them to lead community development initiatives.

- Medium-term efforts (2-5 years) will focus on enhancing project management and data analysis skills. In India, the Smart Cities Mission educates local authorities on managing and tracking urban projects using data-driven decisions. The goal is to equip local actors with the skills needed to design, oversee, and monitor local initiatives.

- Long-term (5+ years) capabilities will concentrate on embedding policy and governance skills at the local level. For example, in Mexico, the National Institute for Federalism and Municipal Development offers ongoing training to local government officials, ensuring that governance remains participatory and efficient. Provide long-term governance training that enables local decision makers to incorporate local concerns within national policy frameworks.

18.2.5.2 Action Two: Vertical integration of local and higher governance levels for facilitating the flow of resources and support

Vertical integration between local governance structures and higher levels of government is vital for ensuring that resources, expertise, and policy support flow seamlessly to enable effective local decision-making. This integration requires collaboration among local communities, local and national governments, private sector actors, international organizations, NGOs, and research institutions. By linking the local level with regional, national, and international systems, local actors can access the financial, technical, and policy assistance needed to promote sustainable development initiatives aligned with broader strategies.

The flow of financial resources is a fundamental aspect of vertical integration. In the short term, local communities and governments require immediate access to funds that enable them to initiate small-scale development projects. National governments can provide this through community-based funds or national grants. An example of this is Nepal's Local Governance and Community Development Programme, which offers direct financial support to local governments to address infrastructure and social service needs. By supplying these initial funds, local governments can quickly tackle immediate challenges while laying the groundwork for larger, long-term projects.

Over the medium term, public-private partnerships become a crucial financial tool, allowing local governments to work with private sector actors on larger projects, such as infrastructure and energy development. Brazil's Minha Casa Minha Vida, My House-My Life, housing program is an excellent example of how national governments can collaborate with private developers to provide affordable housing, combining

public funding with private sector expertise. In the long run, institutionalizing funding pathways guarantees a steady flow of resources to underdeveloped regions. Mechanisms like the European Union's Cohesion Fund channel sustained investments into areas requiring economic development, bridging the gap between local and national disparities. Vertical integration also relies on harnessing social and cultural dynamics to build trust and cooperation between communities and government authorities.

In the short term, engaging local cultural leaders, such as community elders or religious figures, is essential for promoting dialogue between local communities and government representatives. For instance, in Indonesia, religious leaders have played a key role in promoting sustainable environmental practices, aligning local values with national conservation policies. These leaders act as trusted intermediaries, ensuring that government initiatives are accepted and understood by local populations. As integration advances in the medium term, regular consultations and participatory platforms become vital. Colombia's Participatory Rural Development Program provides a model for fostering social cohesion through ongoing dialogue between local farmers, Indigenous groups, and the national government. By institutionalizing regular policy forums and town hall meetings, local communities are empowered with a voice in decision-making, helping to align local practices with national policies while promoting a shared sense of responsibility.

In the long run, incorporating local knowledge systems into formal governance ensures that vertical integration remains culturally inclusive and sustainable. New Zealand's Te Mana o Te Wai framework exemplifies this approach by integrating Māori water governance practices into national water management policies. This formal acknowledgement of Indigenous Knowledge enhances local governance and ensures that national policies reflect the cultural values of Indigenous Peoples. Achieving effective vertical integration requires developing the necessary skills within local and national governance structures. In the short term, local leaders and government officials should receive training in communication and negotiation skills to advocate for their communities and engage with higher authorities.

In the medium term, local governments need strong policy alignment and administrative coordination skills to ensure their projects support national development goals. Morocco's National Initiative for Human Development illustrates how local governments can be trained to align with national poverty reduction strategies. Developing these skills enables local governments to effectively contribute to national plans, ensuring their local priorities are incorporated into broader policy frameworks.

In the long term, developing monitoring and evaluation capabilities is essential for assessing the effectiveness of vertical integration and making necessary adjustments over time. Kenya's National Integrated Monitoring and Evaluation System is a prime example of how monitoring and evaluation frameworks can be used to monitor development projects at all levels of government, ensuring that goals are achieved and improvements are implemented where needed. Establishing strong monitoring and evaluation systems enables governments to refine their strategies for resource allocation, policy support, and project execution, ensuring that vertical integration remains effective in the long term.

18.2.5.3 Action Three: Institutionalizing capacity-building at all levels to ensure long-term sustainability and impact

To achieve long-term success and sustainable growth, it is essential to institutionalize the capacities developed at local, regional, and national tiers. This involves integrating the skills, knowledge, and systems from capacity-building efforts into formal structures and processes across all levels of governance. Such an approach helps establish resilient institutions capable of adapting to shifting challenges and upholding effective governance practices.

The institutionalization process involves ensuring that local leaders, communities, governments, and stakeholders – including women, Indigenous Peoples, and other marginalized groups – can effectively manage resources, make decisions, and implement projects without relying on external interventions. This includes establishing permanent structures for training, knowledge-sharing, and skill development within local governments, integrating capacity-building into national governance frameworks, and fostering collaboration across sectors. The goal is to ensure that the skills and capacities acquired are retained and become an integral part of governance

Credit: ©UNEP

systems that support sustainable development well into the future.

Institutionalizing capacity-building requires dedicated EF levers to secure sustained support and ongoing improvement. In the short term, local governments and communities require immediate access to resources that can fund rapid-training programmes. For example, Rwanda's National Capacity Building Secretariat allocates funds to train local officials, enabling them to enhance service delivery. By establishing local and national training funds, communities can quickly acquire the skills needed to manage resources, lead development projects, and maintain effective governance systems. This approach ensures that capacity-building begins promptly and yields immediate results.

In the medium term, capacity-building should be incorporated into national development plans and budgets. Ghana's Decentralization Policy Framework is an example of how governments can mandate the inclusion of capacity-building within local governance. By consistently investing in local skills development, governments can ensure that capacity-building becomes an ongoing effort rather than a one-time initiative, integrating it into governance structures. Additionally, national governments should allocate specific funds annually to support local training programmes, helping local authorities enhance their governance capabilities on a continuous basis.

In the long run, establishing sustainable financial mechanisms is key. For instance, India's National Skill Development Fund provides long-term financial support for workforce and capacity development across various sectors. Besides EF levers, SC levers also play a vital role in integrating capacity-building into governance systems. In the short term, local leadership and community participation are crucial for effective governance.

In Kenya and Nepal, for example, Community Forest Associations or Community Forest User Groups bring local communities together to share knowledge on forest governance and management. These platforms not only promote a culture of learning but also ensure that the skills and knowledge shared are rooted in local practices and traditions. Creating similar knowledge-sharing platforms enables local leaders and community members to exchange insights and enhance their collective capacity to manage local governance effectively. Indigenous Knowledge and Local Knowledge systems, especially from Indigenous and rural communities, should be formalized within policy frameworks to ensure

capacity-building remains culturally relevant and widely accepted.

For instance, integrating Indigenous Knowledge systems into the national meteorological system should be considered (Nkuba et al. 2021), as this will involve documenting and validating Indigenous Knowledge systems (Nyadzi et al. 2022; Nkuba et al. 2022). In the long term, incorporating capacity-building into the educational system ensures that future generations are equipped with the skills necessary to address governance challenges effectively. Finland's education system incorporates sustainability, governance, and civic engagement into its national curriculum, preparing students from a young age to become future leaders in governance and sustainable development.

The success of institutionalizing capacity-building relies on developing the right capabilities within local and national governments, as well as within communities. In the short term, targeted training programmes in leadership, governance, and resource management are essential to equip local leaders and officials with the skills they need. Uganda's Local Government Development Programme demonstrates how short-term training can greatly enhance the leadership and governance capabilities of local officials, enabling them to provide better services to their communities. These programmes should be broadly adopted so local leaders can oversee governance and guide their communities towards sustainable development. In the medium term, it is essential to establish institutional knowledge transfer systems that preserve and pass on skills and knowledge within organizations, even as staff members change.

Developing strong monitoring and evaluation capabilities over the long term is crucial. It enables governments to monitor the progress of capacity-building programmes and adjust strategies as needed. Kenya's National Integrated Monitoring and Evaluation System monitors the effects of development initiatives across all levels of government, ensuring that capacity-building aligns with national development objectives. Implementing effective monitoring and evaluation systems enables local and national governments to enhance their capacity-building approaches, thereby supporting sustainable success over time.

18.3 Implication of the solution pathways for a resilient sustainable environment on other systems

The environment system is of underpinning importance to other system transformations in economics and finance (Chapter 14), materials/waste (Chapter 15), energy (Chapter 16) and food (Chapter 17). The environment system should be resilient to climate impacts to support the proposed circularity, as well as the transformations in food and energy systems (IPCC, 2023). Considering the solution pathways outlined here, key points of interaction with food, energy, and circularity systems emerge: land use, preventing biodiversity loss and maintaining soil health, and the widespread implications of transitioning away from fossil fuels alongside the use of various bioenergy technologies and carbon dioxide removal (CDR) technologies.

Of key concern is the use of land, alongside rivers and oceans as a limited natural resource in which to embed energy, food and circularity and the demands on landscape and seascape to deliver a range of ecosystem services as identified in the GEO-7 target seeking scenarios to enable transformations that deliver climate, biodiversity and pollution targets. The widespread deployment of bioenergy has the potential to provide multiple low-carbon energy solutions, including heat, power, and liquid biofuel, with or without associated carbon capture and storage. It serves as a key technology for achieving targets and limiting temperature increase to 1.5°C. However, the land use associated with this demand is significant, although the technical potential of over a billion hectares – once proposed –is considered unrealistic due to sustainability trade-offs related to biodiversity loss, water use, conflicts with land for food, NbS, indirect land-use change, and conservation. The two GEO-7 scenarios both allocate less than one hundred million hectares of land to BECCS and bioenergy, which is substantially less than earlier assessments and is effective in reaching Net Zero by 2050

Halting biodiversity loss is crucial for ensuring future environmental sustainability and achieving global targets. However, the intensification of agricultural systems threatens biodiversity. As discussed in Chapter 17, transforming the food system involves adopting sustainable intensification methods, such as breeding and selecting improved crops and livestock,

alongside a substantial increase in regenerative agriculture practices. Regarding energy systems, the effects of BECCS, bioenergy, and agrivoltaics should be carefully managed to prevent harm to biodiversity (Chapter 16). Additionally, promoting a circular flow of materials and resources can help reduce land degradation. Maintaining material stocks and a circular flow of resources in the economy will also contribute positively to socioeconomic development, while safeguarding Nature and people (Chapter 15). Economic transformation (Chapter 14), must integrate a nature-positive economy approach, recognizing that long-term prosperity depends on the health of ecosystems and policies should prioritize investments in biodiversity, ecosystem restoration, and NbSs to foster a regenerative, resilient, and inclusive economic future, aligned to global targets on biodiversity.

Soil health is key to ensuring stocks of carbon are preserved and soil biodiversity and functioning are enhanced, and it is central to several of the NbS approaches detailed in this chapter. Healthy soils are required for a transformed food system, where regenerative agriculture practices lead to reduced synthetic fertilizer use and improved soil carbon sequestration. For the energy system, linked to circularity, using organic waste to generate energy through anaerobic digestion as part of the circular economy, with residues returned to the soil (Chapters 15, 16), is an important goal for a future resilient environment system. Healthy soils are important for biogeochemical carbon sequestration, and their management remains a significant challenge to deliver multiple benefits of food, biodiversity and energy needs (IPCC, 2019).

References

Abson, D.J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U. et al. (2017). Leverage points for sustainability transformation. Ambio 46(1) 30-39. https://doi.org/10.1007/s13280-016-0800-y

Adger, W.N. (2006). Vulnerability. Global Environmental Change 16(3), 268-281. https://doi.org/10.1016/j.gloenvcha.2006.02.006

Agrawal, A. (2001). Common Property Institutions and Sustainable Governance of Resources. World Development 29(10), 1649-1672. https://doi.org/10.1016/S0305-750X(01)00063-8

Albert, C., Hack, J., Schmidt, S. and Schröter, B. (2021). Planning and governing nature-based solutions in river landscapes: Concepts, cases, and insights. Ambio 50(8), 1405-1413. https://doi.org/10.1007/s13280-021-01569-z

Altieri, M.A. and Nicholls, C.I. (2012). Agroecology Scaling Up for Food Sovereignty and Resiliency. In Sustainable Agriculture Reviews: Volume 11. Lichtfouse, E. (ed.). Dordrecht: Springer Netherlands. 1-29. https://doi.org/10.1007/978-94-007-5449-2_1

Altieri, M.A., Nicholls, C.I. and Montalba, R. (2017). Technological Approaches to Sustainable Agriculture at a Crossroads: An Agroecological Perspective. Sustainability 9(3), 349. https://doi.org/10.3390/su9030349

Armitage, D., Berkes, F. and Doubleday, N. (2007). Adaptive co-management: collaboration, learning and multi-level governance. D. Armitage, F.B.N.D. (ed.): Vancouver UBC Press, University of British Columbia. https://www.cabidigitallibrary.org/doi/full/10.5555/20083162303

Aronson, J., Goodwin, N., Orlando, L., Eisenberg, C. and Cross, A.T. (2020). A world of possibilities: six restoration strategies to support the United Nation's Decade on Ecosystem Restoration. Restoration Ecology 28(4), 730-736. https://doi.org/10.1111/rec.13170

Atmadja, S., Martius, C., Leonard, S. and Sanz Sanchez, M. (2021). Transformational change to reduce deforestation and climate change impacts–A review of definitions, concepts and drivers in scientific and grey literature. Rome, Italy: Food and Agriculture Organisation of the United Nations (FAO). https://doi.org/10.4060/cb7314en

Aryal, M. (2024). Phytoremediation strategies for mitigating environmental toxicants. Heliyon, 10(19). https://doi.org/10.1016/j.heliyon.2024.e38683

Balaguer, L., Escudero, A., Martín-Duque, J.F., Mola, I. and Aronson, J. (2014). The historical reference in restoration ecology: Re-defining a cornerstone concept. Biological Conservation 176, 12-20. https://doi.org/10.1016/j.biocon.2014.05.007

Baral, N. and Heinen, J.T. (2020). Regulatory Compliance of Community-Based Conservation Organizations: Empirical Evidence from Annapurna Conservation Area, Nepal. Sustainability 12(22), 9420 https://www.mdpi.com/2071-1050/12/22/9420

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C. and Silliman, B.R. (2011). The value of estuarine and coastal ecosystem services. Ecological Monographs 81(2), 169-193. https://doi.org/10.1890/10-1510.1

Barbosa, A., Martín, B., Hermoso, V., Arévalo-Torres, J., Barbière, J., Martínez-López, J. et al. (2019). Cost-effective restoration and conservation planning in Green and Blue Infrastructure designs. A case study on the Intercontinental Biosphere Reserve of the Mediterranean: Andalusia (Spain) – Morocco. Science of The Total Environment 652, 1463-1473. https://doi.org/10.1016/j.scitotenv.2018.10.416

Bass, M.S., Finer, M., Jenkins, C.N., Kreft, H., Cisneros-Heredia, D.F., McCracken, S.F. et al. (2010). Global Conservation Significance of Ecuador's Yasuní National Park. PLOS ONE 5(1), e8767. https://doi.org/10.1371/journal.pone.0008767

Bauer, T., de Jong, W., Ingram, V., Arts, B. and Pacheco, P. (2022). Thriving in turbulent times: Livelihood resilience and vulnerability assessment of Bolivian Indigenous forest households. Land Use Policy 119, 106146. https://doi.org/10.1016/j.landusepol.2022.106146

Beckley T. M. and Hall T. E. (2009). Editors' Note. Society & Natural Resources 22(10), 865-866. https://doi.org/10.1080/08941920903378820

Bedelian, C. and Ogutu, J.O. (2017). Trade-offs for climate-resilient pastoral livelihoods in wildlife conservancies in the Mara ecosystem, Kenya. Pastoralism 7(1), 10. https://doi.org/10.1186/s13570-017-0085-1

Benjamin K. Sovacool and Griffiths., S. (2020). The Cultural Barriers to a Low-Carbon Future: A Review of Six Mobility and Energy Transitions Across 28 Countries. Renewable & Sustainable Energy Reviews. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3532572

Berkes, F. (2007). Community-based conservation in a globalized world. Proceedings of the National Academy of Sciences 104(39), 15188-15193. https://doi.org/10.1073/pnas.0702098104

Berkes, F. (2017). Environmental Governance for the Anthropocene? Social-Ecological Systems, Resilience, and Collaborative Learning. Sustainability 9(7), 1232. https://doi.org/10.3390/su9071232

Berkes, F., Colding, J. and Folke, C. (2000). Rediscovery Of Traditional Ecological Knowledge As Adaptive Management. Ecological Applications 10(5), 1251-1262. https://doi.org/10.1890/1051-0761(2000)010[1251:ROTEKA]2.0.CO;2

Biggs, R., Schlüter, M. and Schoon, M.L. (2015). An introduction to the resilience approach and principles to sustain ecosystem services in social–ecological systems. In Principles for Building Resilience: Sustaining Ecosystem Services in Social-Ecological Systems. Cambridge: Cambridge University Press. https://www.cambridge.org/core/product/578EBCAA6C9A18430498982D66CFB042

Bioenergy Technologies Office (2017). Jobs & Economic Impact of a Billion-Ton Bioeconomy. Energy Efficiency and Renewable Energy,,United States Department of Energy. https://www.energy.gov/eere/bioenergy/articles/jobs-economic-impact-billion-ton-bioeconomy

Bourguignon, D. (2015). EU biofuelspolicy Dealing with indirect land use change Service, E.P.R. European Parliament, 10 https://www.europarl.europa.eu/RegData/etudes/BRIE/2015/548993/EPRS_BRI(2015)548993_REV1_EN.pdf

Bovill, W.D., Huang, C.Y. and McDonald, G.K. (2013). Genetic approaches to enhancing phosphorus-use efficiency (PUE) in crops: challenges and directions. Crop and Pasture Science, 64(3), 179-198.

Brierley, G. and Fryirs, K. (2022). Truths of the Riverscape: Moving beyond command-and-control to geomorphologically informed nature-based river management. Geoscience Letters 9(1), 14. https://doi.org/10.1186/s40562-022-00223-0

Budzianowski, W.M. (2017). High-value low-volume bioproducts coupled to bioenergies with potential to enhance business development of sustainable biorefineries. Renewable and Sustainable Energy Reviews 70, 793-804. https://doi.org/10.1016/j.rser.2016.11.260

Bugge, M.M., Hansen, T. and Klitkou, A. (2016). What Is the Bioeconomy? A Review of the Literature. Sustainability 8(7), 691. https://doi.org/10.3390/su8070691

Carus, M. and Dammer, L. (2018). The Circular Bioeconomy—Concepts, Opportunities, and Limitations. Industrial Biotechnology 14(2), 83-91. https://doi.org/10.1089/ind.2018.29121.mca

Chaffin, B.C., Garmestani, A.S., Gunderson, L.H., Benson, M.H., Angeler, D.G., Arnold, C.A. et al. (2016). Transformative Environmental Governance.

Annual Review of Environment and Resources 41, 399-423. https://doi.org/10.1146/annurev-environ-110615-085817

Intergovernmental Panel on Climate Change (2014). Summary for policymakers. In: Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir et al. (eds.). Cambridge, United Kingdom and New York, NY, USA: IPCC. https://www.ipcc.ch/site/assets/uploads/2018/02/ar5_wgII_spm_en.pdf

Chen, K., Wang, Y., Zhang, R., Zhang, H. and Gao, C. (2019). CRISPR/Cas Genome Editing and Precision Plant Breeding in Agriculture. Annual Review of Plant Biology 70(1), 667-697. https://doi.org/10.1146/annurev-arplant-050718-100049

Cherubini, F. (2010). The biorefinery concept: Using biomass instead of oil for producing energy and chemicals. Energy Conversion and Management 51(7), 1412-1421. https://doi.org/10.1016/j.enconman.2010.01.015

Cigolotti, V. (2012). Biomass and Waste as Sustainable Resources. In: Fuel Cells in the Waste-to-Energy Chain. Green Energy and Technology. Springer, London. https://doi.org/10.1007/978-1-4471-2369-9_2

Germany, Federal Ministry for the Environment Climate Action Nature Conservation und Nuclear Safety (BMUKN) (2012). Circular Economy Act. https://www.bmuv.de/en/law/circular-economy-and-safeguard-the-environmentally-compatible-management-of-waste

Coad, L., Watson, J.E., Geldmann, J., Burgess, N.D., Leverington, F., Hockings, M. et al. (2019). Widespread shortfalls in protected area resourcing undermine efforts to conserve biodiversity. Frontiers in Ecology and the Environment 17(5), 259-264. https://doi.org/10.1002/fee.2042

Comin, F.A., Romero, J.A., Astorga, V. and García, C. (1997). Nitrogen removal and cycling in restored wetlands used as filters of nutrients for agricultural runoff. Water Science and Technology, 35(5), 255-261. https://doi.org/10.1016/S0273-1223(97)00076-0

Convention on Biological Diversity (2022). Kunming-Montreal Global Biodiversity Framework Conference of the parties to the Convention on Biological Diversity. Conference of the parties to the Convention on Biological Diversity Conference of the parties to the Convention on Biological Diversity. Montreal, Canada, 7-19 December 2022. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf

Cutter, S.L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E. et al. (2008). A place-based model for understanding community resilience to natural disasters. Global Environmental Change 18(4), 598-606. https://doi.org/10.1016/j.gloenvcha.2008.07.013

Dhyani, S., Karki, M. and Gupta, A.K. (2020). Opportunities and Advances to Mainstream Nature-Based Solutions in Disaster Risk Management and Climate Strategy. In Nature-based Solutions for Resilient Ecosystems and Societies. Dhyani, S., Gupta, A.K. and Karki, M. (eds.). Singapore: Springer Singapore. 1-26. https://doi.org/10.1007/978-981-15-4712-6_1

Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Agard, J., Arneth, A. et al. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. Science 366(6471), eaax3100. https://www.science.org/doi/abs/10.1126/science.aax3100

Donnison, C., Holland, R.A., Harris, Z.M., Eigenbrod, F. and Taylor, G. (2021). Land-use change from food to energy: meta-analysis unravels effects of bioenergy on biodiversity and cultural ecosystem services. Environmental Research Letters 16(11), 113005. https://dx.doi.org/10.1088/1748-9326/ac22be

Dubo, T., Palomo, I., Zingraff-Hamed, A., Bruley, E., Collain, G. and Lavorel, S. (2023). Levers for transformative nature-based adaptation initiatives in the Alps. PLOS Climate 2(11), e0000193. https://doi.org/10.1371/journal.pclm.0000193

Eastburn, D.J., O'Geen, A.T., Tate, K.W. and Roche, L.M. (2017). Multiple ecosystem services in a working landscape. PLOS ONE 12(3), e0166595. https://doi.org/10.1371/journal.pone.0166595

Eerhart, A.J.J.E., Faaij, A.P.C. and Patel, M.K. (2012). Replacing fossil based PET with biobased PEF; process analysis, energy and GHG balance. Energy & Environmental Science 5(4), 6407-6422. https://doi.org/10.1039/C2EE02480B

Eisenberg, B., Chiesa, C., Fischer, L. K., Vera, K. J., Hans-Georg, P., & Schwarz-v. Raumer, H. (2022). Nature-based solutions – Technical handbook: Nature-based solutions technical handbook factsheets. Institut für Landschaftsplanung und Ökologie (ILPÖ). https://www.ilpoe.uni-stuttgart.de/files/UNaLab_Handbook.pdf

El-Chichakli, B., von Braun, J., Lang, C., Barben, D. and Philp, J. (2016). Policy: Five cornerstones of a global bioeconomy. Nature 535(7611), 221-223. https://doi.org/10.1038/535221a

Elmqvist, T., Redman, C.L., Barthel, S. and Costanza, R. (2013). History of Urbanization and the Missing Ecology. In Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Global Assessment. Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P.J., McDonald, R.I. et al. (eds.). New York, London: Springer Dordrecht. XXVIII, 755. https://doi.org/10.1007/978-94-007-7088-1

Engström, R., Howells, M., Mörtberg, U. and Destouni, G. (2018). Multi-functionality of nature-based and other urban sustainability solutions: New York City study. Land Degradation & Development 29(10), 3653-3662. https://doi.org/10.1002/ldr.3113

Tan, E., & Lamers, P. (2021). Circular bioeconomy concepts—A perspective. Frontiers in Sustainability 2, 701509. https://doi.org/10.3389/frsus.2021.701509

European Commission (2020). European green deal – Delivering on our targets. Directorate-General for Communication. Publications Office of the European Union. https://data.europa.eu/doi/10.2775/373022

European Environment Agency (2024). What is the current state of the ozone layer?. https://www.eea.europa.eu/en/topics/in-depth/climate-change-mitigation-reducing-emissions/current-state-of-the-ozone-layer?activeAccordion=16764f62-ff77-4bec-b56d-2a30a8e315ea

Schipfer, F. (2024). Bioeconomy Synergies (BioSyn) Initiative 2022-2024: Synergies for bioenergy supply chains in bioeconomy networks Lange, N. (ed.)IEA Bioenergy. https://www.ieabioenergy.com/wp-content/uploads/2025/03/IEA_Bioenergy-Task-40_Report_Synergies-for-bioenergy-supply-chains-in-bioeconomy-networks-1.pdf

Farley, J. and Costanza, R. (2010). Payments for ecosystem services: From local to global. Ecological Economics 69(11), 2060-2068. https://doi.org/10.1016/j.ecolecon.2010.06.010

Fischer, J., Riechers, M., Loos, J., Martin-Lopez, B. and Temperton, V.M. (2021). Making the UN Decade on Ecosystem Restoration a Social-Ecological Endeavour. Trends in Ecology & Evolution 36(1), 20-28. https://doi.org/10.1016/j.tree.2020.08.018

Fitzgerald, N.D. (2017). Chemistry challenges to enable a sustainable bioeconomy. Nature Reviews Chemistry 1(10), 0080. https://doi.org/10.1038/s41570-017-0080

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M. et al. (2011). Solutions for a cultivated planet. Nature 478(7369), 337-342. https://doi.org/10.1038/nature10452

Folke, C., Biggs, R., Norström, A.V., Reyers, B. and Rockström, J. (2016). Social-ecological resilience and biosphere-based sustainability science. Ecology and Society 21(3). https://doi.org/10.5751/ES-08748-210341.

Folke, C., Hahn, T., Olsson, P. and Norberg, J. (2005). Adaptive Governance of social-ecological systems. Annual Review of Environment and Resources 30(30), 441-473. https://doi.org/10.1146/annurev.energy.30.050504.144511.

Folke, C., Österblom, H., Jouffray, J.-B., Lambin, E.F., Adger, W.N., Scheffer, M. et al. (2019). Transnational corporations and the challenge of biosphere stewardship. Nature Ecology & Evolution 3(10), 1396-1403. https://doi.org/10.1038/s41559-019-0978-z

Food and Agriculture Organisation of the United Nations (2018). The future of food and agriculture – Alternative pathways to 2050: Summary version. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/2c6bd7b4-181e-4117-a90d-32a1bda8b27c/content

Food and Agriculture Organisation of the United Nations (2021). Transformational change to reduce deforestation and climate change impacts - A review of definitions, concepts and drivers in scientific and grey literature. Rome, Italy: FAO. https://doi.org/10.4060/cb7314en

Food and Agriculture Organisation of the United Nations (2022). The State of the World's Forests 2022. Forest pathways for green recovery and building inclusive, resilient and sustainable economies. The State of the World's Forests (SOFO). Rome, Italy: FAO. https://doi.org/10.4060/cb9360en

Food and Agriculture Organisation of the United Nations (2024). Climate-Smart Agriculture. Rome, Italy: FAO. https://www.fao.org/climate-smart-agriculture/en

Food and Agriculture Organisation of the United Nations (2024). FAO launches the Global Bioeconomy Dashboard. Rome, Italy: FAO. https://www.fao.org/climate-change/news/news-detail/fao-launches-the-global-bioeconomy-dashboard/en

Food and Agriculture Organization of the United Nations (2021). Restoring the Environment and Livelihoods of Smallholder Farmers Affected by Illegal Mining in Ghana. Rome, Italy: FAO. https://www.fao.org/3/cb6353en/cb6353en.pdf

Fraisl, D., Hager, G., Bedessem, B., Gold, M., Hsing, P.-Y., Danielsen, F. et al. (2022). Citizen science in environmental and ecological sciences. Nature Reviews Methods Primers 2(1), 64. https://doi.org/10.1038/s43586-022-00144-4

Frantzeskaki, N. (2019). Seven lessons for planning nature-based solutions in cities. Environmental Science & Policy 93, 101-111. https://doi.org/10.1016/j.envsci.2018.12.033

Frost, H. and Andersen, P. (2006). The Common Fisheries Policy of the European Union and fisheries economics. Marine Policy 30(6), 737-746. https://doi.org/10.1016/j.marpol.2006.01.001

Future Earth, The Earth League and World Climate Research Programme (2023). 10 New Insights in Climate Science 2023/2024. Stockholm. https://doi.org/10.5281/zenodo.10034364

Geissdoerfer, M., Savaget, P., Bocken, N.M.P. and Hultink, E.J. (2017). The Circular Economy – A new sustainability paradigm? Journal of Cleaner Production 143, 757-768. https://doi.org/10.1016/j.jclepro.2016.12.048

Geldmann, J., Coad, L., Barnes, M.D., Craigie, I.D., Woodley, S., Balmford, A. et al. (2018). A global analysis of management capacity and ecological outcomes in terrestrial protected areas. Conservation Letters 11(3), e12434. https://doi.org/10.1111/conl.12434

Gill, S.E., Handley, J.F., Ennos, A.R. and Pauleit, S. (2007). Adapting cities for climate change: The role of the green infrastructure. Built Environment 33(1), 115-133. https://doi.org/10.2148/benv.33.1.115

Global Commission on Adaptation (2021). Principles for Locally Led Adaptation Action. https://gca.org/reports/principles-for-locally-led-adaptation-action/?_gl=1*y5k31a*_ga*MTQ2MzQyNDQzNy4xNzI5NDg3OTgy*_up*MQ

Government of Western Australia (2012). Mining Rehabilitation Fund The Department of Energy, M., Industry Regulation and Safety. The Department of Energy, Mines, Industry Regulation and Safety, Perth. https://www.wa.gov.au/organisation/resource-and-environmental-regulation/mining-rehabilitation-fund

Great Barrier Reef Foundation (2023). Year in review 2022-23. Great Barrier Reef Foundation. https://www.barrierreef.org/uploads/GBRF-Year-In-Review-2022-23-FINALweb.pdf

Whitesides, G. (2020). Learning from Success: Lessons in Science and Diplomacy from the Montreal Protocol. Science and Diplomacy, American Association for the Advancement of Science https://www.sciencediplomacy.org/article/2020/learning-success-lessons-in-science-and-diplomacy-montreal-protocol

Griffiths, S. and Sovacool, B.K. (2020). Rethinking the future low-carbon city: Carbon neutrality, green design, and sustainability tensions in the making of Masdar City. Energy Research & Social Science 62, 101368. https://doi.org/10.1016/j.erss.2019.101368

Gupta, J., Liverman, D., Prodani, K., Aldunce, P., Bai, X., Broadgate, W. et al. (2023). Earth system justice needed to identify and live within Earth system boundaries. Nature Sustainability 6(6), 630-638. https://doi.org/10.1038/s41893-023-01064-1

Halonen, M., Näyhä, A. and Kuhmonen, I. (2022). Regional sustainability transition through forest-based bioeconomy? Development actors' perspectives on related policies, power, and justice. Forest Policy and Economics 142, 102775. https://doi.org/10.1016/j.forpol.2022.102775

Haberl, H., Erb, K-H., Krausmann, F., Running, S., Searchinger, T.D., Smith W.K. (2013). Bioenergy: how much can we expect for 2050? Environmental Research Letters, 8, 031004

Harris, Z.M., Spake, R. and Taylor, G. (2015). Land use change to bioenergy: A meta-analysis of soil carbon and GHG emissions. Biomass and Bioenergy 82, 27-39. https://doi.org/10.1016/j.biombioe.2015.05.008

Hartmann, T. and Spit, T. (2016). Legitimizing differentiated flood protection levels – Consequences of the European flood risk management plan. Environmental Science & Policy 55, 361-367. https://www.sciencedirect.com/science/article/pii/S1462901115300666

Hecker, L.P., Sturm, A., Querhammer, L. and Wätzold, F. (2024). Cost-effectiveness of state-dependent versus state-independent agri-environment schemes for biodiversity conservation. Ecological Economics 217, 108088. https://doi.org/10.1016/j.ecolecon.2023.108088

Hill, R., Adem, Ç., Alangui, W.V., Molnár, Z., Aumeeruddy-Thomas, Y., Bridgewater, P. et al. (2020). Working with Indigenous, local and scientific knowledge in assessments of nature and nature's linkages with people. Current Opinion in Environmental Sustainability 43, 8-20. https://doi.org/10.1016/j.cosust.2019.12.006

Hilty, J.A. and Laur, A.T. (2021). Ecological networks and corridors in the context of global initiatives. Parks Stewardship Forum 37(3). https://doi.org/10.5070/P537354730

Hoban, S., Campbell, C.D., da Silva, J.M., Ekblom, R., Funk, W.C., Garner, B.A. et al. (2021). Genetic diversity is considered important but interpreted narrowly in country reports to the Convention on Biological Diversity: Current actions and indicators are insufficient. Biological Conservation 261, 109233. https://doi.org/10.1016/j.biocon.2021.109233

Hobson, K. and Lynch, N. (2016). Diversifying and de-growing the circular economy: Radical social transformation in a resource-scarce world. Futures 82, 15-25. https://doi.org/10.1016/j.futures.2016.05.012

Hou-Jones, X., Roe, D. and Holland, E. (2021). Nature-based Solutions in Action: Lessons from the Frontline. London: International Institute for Environment and Development [IIED], Bond. https://www.bond.org.uk/wp-content/uploads/2022/03/bond_-_nbs_case_studies_-_v4.pdf

Hubble, T.C.T., Docker, B.B. and Rutherfurd, I.D. (2010). The role of riparian trees in maintaining riverbank stability: a review of Australian experience and practice. Ecological Engineering, 36(3), 292-304. https://doi.org/10.1016/j.ecoleng.2009.04.006

Immerzeel, D.J., Verweij, P.A., van der Hilst, F. and Faaij, A.P.C. (2014). Biodiversity impacts of bioenergy crop production: a state-of-the-art review. GCB Bioenergy 6(3), 183-209. https://doi.org/10.1111/gcbb.12067

Intergovernmental Panel on Climate Change (2019). Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts. et al. (eds.). Cambridge: Cambridge University Press. 1-36. https://www.cambridge.org/core/books/climate-change-and-land/summary-for-policymakers/BACDCBE9CB0F9F0729BE006926569FDB

Intergovernmental Panel on Climate Change (2022). Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. https://www.cambridge.org/core/product/2929481A59B59C57C743A79420A2F9FF

Intergovernmental Panel on Climate Change (2023). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. et al. (eds.). Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056. https://doi.org/10.1017/9781009325844

Intergovernmental Panel on Climate Change (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, Lee, H. and Romero, J. (eds.). Geneva, Switzerland: IPCC. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). IPBES (2019): Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES Secretariat: Bonn, Germany. Brondizio, E.S., Settele, J., Díaz, S. and Ngo, H.T. (eds.). https://doi.org/10.5281/zenodo.3831673

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services - Food (2016). From Uniformity to Diversity: A paradigm shift from industrial agriculture to diversified agroecological systems. Jacobs, N. (ed.): International Panel of Experts on Sustainable Food Systems. https://www.ipes-food.org/_img/upload/files/UniformityToDiversity_FULL.pdf

International Energy Agency (2022). Global biorefinery status report 2022. IEA Bioenergy: Task 42 Biorefining in a circular economy. Annevelink, B., Chavez, L.G., Ree, R.v. and Gursel, I.V. (eds.)The IEA Bioenergy Technology Collaboration Programme. https://www.ieabioenergy.com/wp-content/uploads/2022/09/IEA-Bioenergy-Task-42-Global-biorefinery-status-report-2022-220712.pdf

International Energy Agency (2024) Bioenergy. https://www.iea.org/energy-system/renewables/bioenergy#overview

International Finance Corporation (2017). Liquefied Natural Gas Facilities:The Environmental, Health, and Safety (EHS) Guidelines. Washington International Finance Corporation. https://www.ifc.org/content/dam/ifc/doc/2010/2017-lng-ehs-guidelines-en.pdf

International Fund for Agricultural Development (2024). The three types of biodiversity: explained. https://www.ifad.org/en/w/explainers/the-three-types-of-biodiversity-explained#:~:text=In%20fact%2C%20there%20are%20three,their%20part%20to%20protect%20it.&text=Every%20individual%20plant%20or%20animal%20has%20a%20distinct%20combination%20of%20genes

International Renewable Energy Agency (2020). Recycle: Bioenergy. Circular Carbon Economy. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Sep/CC_05_Recycle_bioenergy_2020.pdf

International Union for Conservation of Nature (2020). IUCN Global Standard for Nature-based Solutions : a user-friendly framework for the verification, design and scaling up of NbS : first edition. Gland, Switzerland: International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2020.08.en

IPBES (2024). Summary for Policymakers of the Thematic Assessment Report on the Underlying Causes of Biodiversity Loss and the Determinants of Transformative Change and Options for Achieving the 2050 Vision for Biodiversity. O'Brien, K., Garibaldi, L., Agrawal, A., Bennett, E., Biggs, O., Calderón Contreras, R. et al. (eds.). Bonn, Germany: IPBES Secretariat. https://doi.org/10.5281/zenodo.11382230

Islam, M.A. and Ashilenje, D.S. (2018). Diversified forage cropping systems and their implications on resilience and productivity. Sustainability, 10(11), 3920. https://doi.org/10.3390/su10113920

Jayachandran, S., De Laat, J., Lambin, E.F., Stanton, C.Y., Audy, R. and Thomas, N.E. (2017). Cash for carbon: A randomized trial of payments for ecosystem services to reduce deforestation. Science, 357(6348), 267-273. https://doi.org/10.1126/science.aan0568

Kabisch, N., Frantzeskaki, N. and Hansen, R. (2022). Principles for urban nature-based solutions. Ambio 51(6), 1388-1401. https://doi.org/10.1007/s13280-021-01685-w

Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M. et al. (2016). Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. Ecology and Society 21(2). http://dx.doi.org/10.5751/ES-08373-210239

Kinol, A.D., Arango-Quiroga, J. and Kuhl, L. (2023). Opportunities for nature-based solutions to contribute to climate-resilient development pathways. Current Opinion in Environmental Sustainability 62, 101297. https://doi.org/10.1016/j.cosust.2023.101297

Kirchherr, J., Reike, D. and Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling 127, 221-232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kirsch, M., Morales-Dalmau, J. and Lavrentieva, A. (2023). Cultivated meat manufacturing: Technology, trends, and challenges. Engineering in Life Sciences 23(12), e2300227. https://doi.org/10.1002/elsc.202300227

Koh, H.L., Teh, S.Y., Kh'Ng, X.Y. and Raja Barizan, R.S. (2018). Mangrove forests: Protection against and resilience to coastal disturbances. Journal of Tropical Forest Science, 30(5), 446-460. https://www.jstor.org/stable/26514436

Krausmann, F., Erb, K.-H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V. et al. (2013). Global human appropriation of net primary production doubled in the 20th century. Proceedings of the National Academy of Sciences 110(25), 10324-10329. https://www.pnas.org/doi/abs/10.1073/pnas.1211349110

Krievins, K., Plummer, R. and Baird, J. (2018). Building Resilience in Ecological Restoration Processes: A Social-Ecological Perspective. Ecological Restoration 36(3), 195-207. https://doi.org/10.3368/er.36.3.195

Kumar, S. et al. (2020). Legumes for Carbon and Nitrogen Cycling: An Organic Approach. In: Datta, R., Meena, R., Pathan, S., Ceccherini, M. (eds) Carbon and Nitrogen Cycling in Soil. Springer, Singapore. https://doi.org/10.1007/978-981-13-7264-3_10

Lafortezza, R., Chen, J., van den Bosch, C.K. and Randrup, T.B. (2018). Nature-based solutions for resilient landscapes and cities. Environmental Research 165, 431-441. https://doi.org/10.1016/j.envres.2017.11.038

Lalavanua, W., Govan, H. and Steenbergen, D. (2021). Scaling-up community-based fisheries management in the Pacific: Key outcomes of subregional workshops. https://api.semanticscholar.org/CorpusID:271270940}

Langholtz, M.H., Stokes, B.J. and Eaton, L.M. (2016). 2016 Billion-ton report: Advancing domestic resources for a thriving bioeconomy. Oak Ridge: Oak Ridge National Laboratory. https://www.fs.usda.gov/research/treesearch/53253#:~:text=Citation,1%3A%20Economic%20availability%20of%20feedstock

Lebelt, L., Breil, M., Ballinas, M.B.P., Castellani, C., Keesstra, S.D., Veerkamp, C., Veerkamp. et al. (2023). Scaling nature-based solutions for climate resilience and nature restoration. European Environment Agency. https://research.wur.nl/en/publications/scaling-nature-based-solutions-for-climate-resilience-and-nature-

Lavell, A., Oppenheimer, M., Diop, C., Hess, J., Lempert, R., Li, J. et al. (2012). Climate Change: New Dimensions in Disaster Risk, Exposure, Vulnerability, and Resilience. In Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change. Field, C.B., Barros, V., Stocker, T.F. and Dahe, Q. (eds.). Cambridge: Cambridge University Press. 25-64. https://www.cambridge.org/core/product/BB084965B525470AE958E68BAFEC133F

Lieder, M. and Rashid, A. (2016). Towards circular economy implementation: a comprehensive review in context of manufacturing industry. Journal of Cleaner Production 115, 36-51. https://doi.org/10.1016/j.jclepro.2015.12.042

Li, M., Ge, S., Zhang, J., Wu, S., Wu, H. and Zhuang, L.L. (2022). Mechanism and performance of algal pond assisted constructed wetlands for wastewater polishing and nutrient recovery. Science of the Total Environment, 840, 156667. https://doi.org/10.1016/j.scitotenv.2022.156667

Lindorfer, J., Zeilerbauer, L. and Hrbek, J. (2022). Technical, Economic and Environmental (TEE) Assessment of Integrated Biorefineries IEA Bioenergy. https://task42.ieabioenergy.com/wp-content/uploads/sites/10/2022/10/IEA-Bioenergy_TEE_Gasificatio n_Final.pdf

Ma, B., Zhang, Y., Hou, Y. and Wen, Y. (2020). Do Protected Areas Matter? A Systematic Review of the Social and Ecological Impacts of the Establishment of Protected Areas. International Journal of Environmental Research and Public Health 17(19), 7259. https://doi.org/10.3390/ijerph17197259

Mammides, C., Zotos, S. and Martini, F. (2024). Quantifying the amount of land lost to artificial surfaces in European habitats: A comparison inside and outside Natura 2000 sites using a quasi-experimental design. Biological Conservation 293, 110556. https://doi.org/10.1016/j.biocon.2024.110556

Masdar (2017). Pioneering the Future of Sustainability. Masdar City Masdar https://masdar.ae/-/media/corporate/downloads/media/masdar-corporate-brochure-english.pdf

Matson, P., Clark, W.C. and Andersson, K. (2016). Pursuing Sustainability: A Guide to the Science and Practice: An essential guide to sustainable development for students and practitioners. Princeton University Press. https://press.princeton.edu/books/hardcover/9780691157610/pursuing-sustainability

Mganga, K.Z., Bosma, L., Amollo, K.O. et al. (2022). Combining rainwater harvesting and grass reseeding to revegetate denuded African semi-arid landscapes. Anthropocene Science, 1(1), 80-90. https://doi.org/10.1007/s44177-021-00007-9

Miller, A.B., Cox, C. and Morse, W.C. (2023). Ecotourism, wildlife conservation, and agriculture in Costa Rica through a social-ecological systems lens. Frontiers in Sustainable Tourism 2. https://doi.org/10.3389/frsut.2023.1179887

Ministry of Environment Forestry and Tourism and Namibian Association of CBNRM Support Organizations (2021). The State of Community Conservation in Namibia: Annual Report 2012. A review of Communal Conservancies, Community Forests and other community-based natural resource management initiatives. Windhoek: Ministry of Environment, Forestry and Tourism, Namibian Association of CBNRM Support Organizations. https://www.nacso.org.na/sites/default/files/The%20State%20of%20Community%20Conservation%20Report%202020%20book.pdf

Molotoks, A., Kuhnert, M., Dawson, T.P. and Smith, P. (2017). Global Hotspots of Conflict Risk between Food Security and Biodiversity Conservation. Land 6(4), 67. https://doi.org/10.3390/land6040067

Mossop, J. (2020). Marine Protected Areas and Area-Based Management in New Zealand. Asia-Pacific Journal of Ocean Law and Policy 5(1), 169-185. https://doi.org/10.1163/24519391-00501009

Munagala, M., Shastri, Y., Nalawade, K., Konde, K. and Patil, S. (2021). Life cycle and economic assessment of sugarcane bagasse valorization to lactic acid. Waste Management 126, 52-64. https://doi.org/10.1016/j.wasman.2021.02.052

Muscat, A., de Olde, E.M., Kovacic, Z., de Boer, I.J.M. and Ripoll-Bosch, R. (2021). Food, energy or biomaterials? Policy coherence across agro-food and bioeconomy policy domains in the EU. Environmental Science & Policy 123, 21-30. https://doi.org/10.1016/j.envsci.2021.05.001

Muscat, A., de Olde, E.M., Ripoll-Bosch, R., Van Zanten, H.H.E., Metze, T.A.P., Termeer, C.J.A.M. et al. (2021). Principles, drivers and opportunities of a circular bioeconomy. Nature Food 2(8), 561-566. https://doi.org/10.1038/s43016-021-00340-7

Nature-based Solutions for supporting sustainable development : resolution / adopted by the United Nations Environment Assembly, 2022 (United Nations Environment Programme Environment Assembly). https://digitallibrary.un.org/record/3999268?v=pdf

Nick Salafsky, Varsha Suresh, Rosina Bierbaum, Ella Clarke, Mark Stafford Smith, Christopher Whaley et al. (2021). Taking Nature-Based Solutions Programs to Scale. Foundations of Success (FOS), the Science and Technical Advisory Panel (STAP) to the Global Environmental Facility (GEF), and the Gordon and Betty Moore Foundation (GBMF). https://cdn.unenvironment.org/stapgef/public/2022-02/Taking%20Nature%20Based%20Solutions%20to%20Scale%202021-01_0.pdf

Nkuba, M.R., Chanda, R., Mmopelwa, G., Kato, E., Adedoyin, A., Mujuni, G. et al. (2023). Factors that influence pastoralists' estimation of onset and cessation of rains in Rwenzori region in Western Uganda. Environmental Development 47, 100901. https://doi.org/10.1016/j.envdev.2023.100901

Nkuba, M.R., Chanda, R., Mmopelwa, G., Kato, E., Mangheni, M.N., Lesolle, D. et al. (2022). Factors associated with farmers' use of indigenous and scientific climate forecasts in Rwenzori region, Western Uganda. Regional Environmental Change 23(1), 4. https://doi.org/10.1007/s10113-022-01994-0

Nkuba, M.R., Chanda, R., Mmopelwa, G., Mangheni, M.N., Lesolle, D., Adedoyin, A. et al. (2021). Determinants of pastoralists' use of indigenous knowledge and scientific forecasts in Rwenzori region, Western Uganda. Climate Services 23, 100242. https://doi.org/10.1016/j.cliser.2021.100242

Norström, A.V., Cvitanovic, C., Löf, M.F., West, S., Wyborn, C., Balvanera, P. et al. (2020). Principles for knowledge co-production in sustainability research. Nature Sustainability 3(3), 182-190. https://doi.org/10.1038/s41893-019-0448-2

Núñez-Regueiro, M.M., Siddiqui, S.F. and Fletcher Jr, R.J. (2021). Effects of bioenergy on biodiversity arising from land-use change and crop type. Conservation Biology 35(1), 77-87. https://doi.org/10.1111/cobi.13452.

Nyadzi, E., Werners, S.E., Biesbroek, R. and Ludwig, F. (2022). Towards weather and climate services that integrate indigenous and scientific forecasts to improve forecast reliability and acceptability in Ghana. Environmental Development 42, 100698. https://doi.org/10.1016/j.envdev.2021.100698

Nyirenda, H. and Balaka, V. (2021). Conservation agriculture-related practices contribute to maize yield and soil improvement in Central Malawi. Heliyon 7(3). https://doi.org/10.1016/j.heliyon.2021.e06636

Ochieng, G., Ngugi, K., Wamalwa, L.N., Manyasa, E., Muchira, N., Nyamongo, D. and Odeny, D.A. (2021). Novel sources of drought tolerance from landraces and wild sorghum relatives. Crop Science, 61(1), 104-118. https://doi.org/10.1002/csc2.20300

Onkangi, R., Abouelhamd, I., Madadi, V., Maina, P., Mwangi, P., Wanjohi, J. et al. (2023). The Legacy of urban sprawl on wildlife conservation: A case study of Nairobi National Park. Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES) 9, 305-312. http://dx.doi.org/10.5109/7157994

Ostrom, E. (1990). Governing the Commons: The Evolution of Institutions for Collective Action. Political Economy of Institutions and Decisions. Cambridge: Cambridge University Press. https://www.cambridge.org/core/product/7AB7AE11BADA84409C34815CC288CD79

Ostrom, E. (2009). A General Framework for Analyzing Sustainability of Social-Ecological Systems. Science 325(5939), 419-422. https://doi.org/10.1126/science.1172133

Ostrom, E. (2010). Polycentric systems for coping with collective action and global environmental change. Global Environmental Change 20(4), 550-557. https://doi.org/10.1016/j.gloenvcha.2010.07.004

Palomo, I., Locatelli, B., Otero, I., Colloff, M., Crouzat, E., Cuni-Sanchez, A. et al. (2021). Assessing nature-based solutions for transformative change. One Earth 4(5), 730-741. https://doi.org/10.1016/j.oneear.2021.04.013.

Peixoto, R., Voolstra, C.R., Stein, L.Y., Hugenholtz, P., Salles, J.F., Amin, S.A. et al. (2024). Microbial solutions must be deployed against climate catastrophe. npj Sustainable Agriculture 2(1), 23. https://doi.org/10.1038/s44264-024-00033-1

Pretty, J., Benton, T.G., Bharucha, Z.P., Dicks, L.V., Flora, C.B., Godfray, H.C.J. et al. (2018). Global assessment of agricultural system redesign for sustainable intensification. Nature Sustainability 1(8), 441-446. https://doi.org/10.1038/s41893-018-0114-0

Ramesh, R., Chen, Z., Cummins, V., Day, J., D'Elia, C., Dennison, B. et al. (2015). Land–Ocean Interactions in the Coastal Zone: Past, present & future. Anthropocene 12, 85-98. https://doi.org/10.1016/j.ancene.2016.01.005

Ramieri, E., Bocci, M. and Markovic, M. (2019). Linking Integrated Coastal Zone Management to Maritime Spatial Planning: The Mediterranean Experience. In Maritime Spatial Planning: past, present, future. Zaucha, J. and Gee, K. (eds.). Cham: Springer International Publishing. 271-294. https://doi.org/10.1007/978-3-319-98696-8_12

Ren, J.W.F. and Coffman, G.C. (2023). Integrating the resilience concept into ecosystem restoration. Restoration Ecology 31(5), e13907. https://doi.org/10.1111/rec.13907

Rhodes, C.J. (2014). Mycoremediation (bioremediation with fungi)–growing mushrooms to clean the earth. Chemical Speciation & Bioavailability, 26(3), 196-198. https://doi.org/10.3184/095422914X14047407349335

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F. et al. (2023). Earth beyond six of nine planetary boundaries. Science Advances 9(37), eadh2458. https://www.science.org/doi/10.1126/sciadv.adh2458

Ricroch, A., Clairand, P. and Harwood, W. (2017). Use of CRISPR systems in plant genome editing: toward new opportunities in agriculture. Emerging Topics in Life Sciences 1(2), 169-182. https://doi.org/10.1042/ETLS20170085

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F. et al. (2009). Planetary boundaries. Exploring the safe operating space for humanity. Ecology and Society 14(2), 32. http://www.ecologyandsociety.org/vol14/iss2/art32/

Romero Antonio, M.E., Faye, A., Betancur-Corredor, B., Baumüller, H. and von Braun, J. (2025). Productivity effects of agroecological practices in Africa: insights from a systematic review and meta-analysis. Food Security, 17(1), 207-229. https://doi.org/10.1007/s12571-024-01504-6

Ronchi, S. and Salata, S. (2022). Insights for the Enhancement of Urban Biodiversity Using Nature-Based Solutions: The Role of Urban Spaces in Green Infrastructures Design. In Nature-based Solutions for Sustainable Urban Planning: Greening Cities, Shaping Cities. Mahmoud, I.H., Morello, E., Lemes de Oliveira, F. and Geneletti, D. (eds.). Cham: Springer International Publishing. 47-68. https://doi.org/10.1007/978-3-030-89525-9_3

Salvador, R., Barros, M.V., Donner, M., Brito, P., Halog, A. and De Francisco, A.C. (2022). How to advance regional circular bioeconomy systems? Identifying barriers, challenges, drivers, and opportunities. Sustainable Production and Consumption 32, 248-269. https://doi.org/10.1016/j.spc.2022.04.025

Sanchez, S.T., Woods, J., Akhurst, M., Brander, M., O'Hare, M., Dawson, T.P. et al. (2012). Accounting for indirect land-use change in the life cycle

assessment of biofuel supply chains. Journal of The Royal Society Interface 9(71), 1105-1119. https://doi.org/10.1098/rsif.2011.0769

Scarlat, N., Dallemand, J.-F., Monforti-Ferrario, F. and Nita, V. (2015). The role of biomass and bioenergy in a future bioeconomy: Policies and facts. Environmental Development 15, 3-34. https://doi.org/10.1016/j.envdev.2015.03.006.

Schröter, B., Gottwald, S., Castro-Arce, K., Hartkopf, E., Aguilar-González, B. and Albert, C. (2023). Virtual participatory mapping of nature-based solutions in the Grande de Tárcoles River basin, Costa Rica: Connecting diverse knowledge systems in a context of physical immobility. Science of The Total Environment 872, 162195. https://doi.org/10.1016/j.scitotenv.2023.162195

Sène, A.L. (2024). Justice in nature conservation: limits and possibilities under global capitalism. Climate and Development 16(9), 838-847. https://doi.org/10.1080/17565529.2023.2274901

Serra-Llobet, A., Jähnig, S.C., Geist, J., Kondolf, G.M., Damm, C., Scholz, M. et al. (2022). Restoring rivers and floodplains for habitat and flood risk reduction: experiences in multi-benefit floodplain management from California and Germany. Frontiers in Environmental Science, 9, 778568. https://doi.org/10.3389/fenvs.2021.778568

Shrawat, A.K., Carroll, R.T., DePauw, M., Taylor, G.J. and Good, A.G. (2008). Genetic engineering of improved nitrogen use efficiency in rice by the tissue-specific expression of alanine aminotransferase. Plant biotechnology journal, 6(7), 722-732. https://doi.org/10.1111/j.1467-7652.2008.00351.x

Singapore Global Network (2021) Cultivating Meats with Science: How Shiok Meats' Founder Ka Yi Ling Grows Sustainable Seafood with Cell Technology. https://singaporeglobalnetwork.gov.sg/stories/sustainability/cultivating-meats-with-science-how-shiok-meats-founder-ka-yi-ling-grows-sustainable-seafood-with-cell-technology/

Slade, R, Bauen A, Gross, R (2014). Global Bioenergy Resources, Nature Climate Change 4, 99-105.

Soanes, M., Bahadur, A., Shakya, C., Smith, B., Patel, S., Rumbaitis del Rio, C. et al. (2021). Principles for locally led adaptation - A call for action. London: International Institute for Environment and Development. https://www.iied.org/10211iied

Soubry, I., Doan, T., Chu, T. and Guo, X. (2021). A Systematic Review on the Integration of Remote Sensing and GIS to Forest and Grassland Ecosystem Health Attributes, Indicators, and Measures. Remote Sensing 13(16), 3262. https://doi.org/10.3390/rs13163262

Stechemesser, A., Koch, N., Mark, E., Dilger, E., Klösel, P., Menicacci, L. et al. (2024). Climate policies that achieved major emission reductions: Global evidence from two decades. Science 385(6711), 884-892. https://doi.org/10.1126/science.adl6547

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M. et al. (2015). Planetary boundaries: Guiding human development on a changing planet. Science 347(6223), 1259855. https://www.science.org/doi/abs/10.1126/science.1259855

Sustainable Bioenergy Glasgow Declaration on Sustainable Bioenergy. 26th Conference of the Parties to the UNFCCC 26th Conference of the Parties to the UNFCCC 26th Conference of the Parties to the UNFCCC Glasgow, Glasgow, November 2021. https://sustainablebioenergy.org/wp-content/uploads/Glasgow-Declaration-on-Sustainable-Bioenergy.pdf

Tan, E.C.D. and Lamers, P. (2021). Circular Bioeconomy Concepts—A Perspective. Frontiers in Sustainability 2. https://doi.org/10.3389/frsus.2021.701509

The Economics of Ecosystems and Biodiversity (2010). Mainstreaming the Economics of Nature: A Synthesis of the Approach, Conclusions and Recommendations of TEEB. The Economics of Ecosystems and Biodiversity. The Economics of Ecosystems and Biodiversity the Economics of Ecosystems and Biodiversity. 2010. https://www.teebweb.org/wp-content/uploads/Study%20and%20Reports/Reports/Synthesis%20report/TEEB%20Synthesis%20Report%202010.pdf

The Economist (2023). Singapore is the world leader in selling cultivated meat. The Economist https://www.economist.com/asia/2023/07/20/singapore-is-the-world-leader-in-selling-cultivated-meat

The Montreal Protocol on Substances that Deplete the Ozone Layer, 1987 (Programme, U.N.E.). https://ozone.unep.org/treaties/montreal-protocol.

The White House (2023). Bold Goals for U.S. Biotechnology and Biomanufacturing Harnessing Research and Development to Further Societal Goals the White House Office of Science and Technology (ed.). Washington. https://www.whitehouse.gov/wp-content/uploads/2023/03/Bold-Goals-for-U.S.-Biotechnology-and-Biomanufacturing-Harnessing-Research-and-Development-To-Further-Societal-Goals-FINAL.pdf

Townsend, P.V., Harper, R.J., Brennan, P.D., Dean, C., Wu, S., Smettem, K.R.J. and Cook, S.E. (2012). Multiple environmental services as an opportunity for watershed restoration. Forest policy and Economics, 17, 45-58. https://doi.org/10.1016/j.forpol.2011.06.008.

Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kaźmierczak, A., Niemela, J. et al. (2007). Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. Landscape and Urban Planning 81(3), 167-178. https://doi.org/10.1016/j.landurbplan.2007.02.001

Ünal, V., Kızılkaya, Z., Krueger, C.C., Taylor, W.W. and Youn, S.J. (2019). A long and participatory process towards successful fishery management of Gökova Bay, Turkey. In Catastrophe to Recovery: Stories of Fishery Management Success. American Fisheries Society. https://medpan.org/en/resource-center/mpa-success-story-gokova-example-co-management-small-scale-fishers-restore-marine

United Nations Environment Programme and DHI (2017). Soil moisture conservation techniques. https://www.ctc-n.org/technologies/soil-moisture-conservation-techniques

United Nations Environment Programme (2022). Doubling finance flows into nature-based solutions by 2025 to deal with global crises – UN report. https://www.unep.org/news-and-stories/press-release/doubling-finance-flows-nature-based-solutions-2025-deal-global#main-content

United Nations (2019). Global Sustainable Development Report - The Future is Now - Science for Achieving Sustainable Development. New York: United Nations. https://doi.org/10.18356/5d04ad97-en

United Nations (2023). Global Sustainable Development Report - Times of Crisis, Times of Change - Science for Accelerating Transformations to Sustainable Development. New York: United Nations. https://doi.org/10.18356/9789213585115

United Nations Development Programme (2021). Mangrove restoration leads to greater resilience in Bangladesh: report. https://www.undp.org/bangladesh/press-releases/mangrove-restoration-leads-greater-resilience-bangladesh-report Accessed 1 April 2025

United Nations Educational Scientific and Cultural Organization (1971). Man and the Biosphere Programme (MAB). https://www.unesco.org/en/mab?hub=66369 Accessed 8 May 2025

United Nations Environment Programme (2021). Guidelines for Integrating Ecosystem-based Adaptation into National Adaptation Plans: Supplement to the UNFCCC NAP Technical Guidelines. https://wedocs.unep.org/20.500.11822/36703

United Nations Environment Programme (2023). Turning off the Tap: How the world can end plastic pollution and create a circular economy. Nairobi. https://www.unep.org/resources/turning-off-tap-end-plastic-pollution-create-circular-economy

United Nations Environment Programme (2023). What's Cooking? An assessment of the potential impacts of selected novel alternatives to conventional animal products. Frontiers 2023 Special Issue. Nairobi. https://doi.org/10.59117/20.500.11822/44236

United Nations Environment Programme and Food and Agriculture Organization of the United Nations (2020). The UN Decade on Ecosystem Restoration (2021-2030): Flagship Initiatives. https://wedocs.unep.org/20.500.11822/37848

Vasconcellos, M. and Unal, V. (2022). Transition towards an ecosystem approach to fisheries in the Mediterranean Sea: Lessons learned through selected case studies. Rome, Italy: Food and Agriculture Organisation of the United Nations. https://books.google.co.in/books?id=hMNfEAAAQBAJ

Vernooy, R., Sthapit, B., Otieno, G., Shrestha, P. and Gupta, A. (2017). The roles of community seed banks in climate change adaption. Development in Practice, 27(3), 316-327. https://doi.org/10.1080/09614524.2017.1294653

Visit Norway (2024). National parks in Norway: Explore untouched nature. https://www.visitnorway.com/things-to-do/nature-attractions/national-parks/2024

Reid, W. V., Mooney, H. A., Cropper, A., Capistrano, D., Carpenter, S. R., Chopra, K. et al. (2005). Ecosystems and human well-being: Synthesis. Millennium Ecosystem Assessment. World Resources Institute. https://www.millenniumassessment.org/documents/document.356.aspx.pdf

Webber, J.L., Fletcher, T.D., Cunningham, L., Fu, G., Butler, D. and Burns, M.J., (2020). Is green infrastructure a viable strategy for managing urban surface water flooding?. Urban Water Journal, 17(7), 598-608. https://doi.org/10.1080/1573062X.2019.1700286

Whitesides, G. (2020). Learning from Success: Lessons in Science and Diplomacy from the Montreal Protocol. Science and Diplomacy, American Association for the Advancement of Science. https://www.sciencediplomacy.org/article/2020/learning-success-lessons-in-science-and-diplomacy-montreal-protocol

World Bioenergy Association (2023). Global Bioenergy Statistics Report. https://www.worldbioenergy.org/uploads/231219%20GBS%20Report.pdf

World Meteorological Organization (2022). EARLY WARNINGS FOR ALL: The UN Global Early Warning Initiative for the Implementation of Climate Adaptation Executive Action Plan 2023-2027. Geneva: WMO. https://library.wmo.int/viewer/58209/download?file=Executive_Action_Plan_en.pdf&type=pdf&navigator=1

Wu, J. (2014). Urban ecology and sustainability: The state-of-the-science and future directions. Landscape and Urban Planning 125, 209-221. https://doi.org/10.1016/j.landurbplan.2014.01.018

Wu, S., Bashir, M.A., Raza, Q.U.A., Rehim, A., Geng, Y. and Cao, L. (2023). Application of riparian buffer zone in agricultural non-point source pollution control—A review. Frontiers in Sustainable Food Systems, 7, 985870. https://doi.org/10.3389/fsufs.2023.985870

Zhang, J., Ström, A., Bordes, R., Alminger, M., Undeland, I. and Abdollahi, M. (2023). Radial discharge high shear homogenization and ultrasonication assisted pH-shift processing of herring co-products with antioxidant-rich materials for maximum protein yield and functionality. Food Chemistry 400, 133986. https://doi.org/10.1016/j.foodchem.2022.133986

Zhang, Y., Massel, K., Godwin, I.D. and Gao, C. (2019). Applications and potential of genome editing in crop improvement. Genome Biology 19(1), 210. https://doi.org/10.1186/s13059-018-1586-y

Zhu, C., Ji, P. and Li, S. (2017). Effects of urban green belts on the air temperature, humidity and air quality. Journal of Environmental Engineering and Landscape Management, 25(1), 39-55. https://doi.org/10.3846/16486897.2016.1194276

Zinzi, M. and Agnoli, S. (2012). Cool and green roofs. An energy and comfort comparison between passive cooling and mitigation urban heat island techniques for residential buildings in the Mediterranean region. Energy and buildings, 55, 66-76. https://doi.org/10.1016/j.enbuild.2011.09.024

Credit: NASA Visible Earth

PART E

Implications for Regions and Groups of Countries and Driving the Transformations

Indigenous Knowledge and Local Knowledge Chapeau E

Chapter 19
Implications for Different Economic Development Contexts

Chapter 20
Regional Dimensions of the Transformative Solutions for the Global Environmental Crises

PAG. 01

Chapter 21
Driving the Transformations

PAG. 01

PAG. 01

Credit: SKY-Stock/Envato

Indigenous Knowledge and Local Knowledge Chapeau E

Studies consistently illustrate how Indigenous ontologies, knowledge, values, and ways of being offer pathways for sustainability transformation. Across diverse biocultural regions, Indigenous Knowledge and local knowledge are being deployed through various livelihood strategies and place-based adaptation and mitigation processes to address environmental change (Thornton and Manasfi 2010; Huntington et al. 2017; Orozco-Ramírez et al. 2020). Indigenous Peoples are also contributing to our collective understanding of the dynamic and existential dimensions of global change at local and regional scales (López-Maldonado et al. 2024; Reyes-García et al. 2024). For instance, Indigenous Arctic communities are building detailed observations of sea ice growth, decay and thickness, which are essential for assessing ice mass balance and its implications for climate and human well-being in the region (Ashjian et al. 2010; Krupnik et al. 2010). Also, Indigenous dryland communities in Australia and elsewhere are showing the value of cultural burning practices, honed over millennia, to sustain biodiversity and mitigate disastrous wildfires (Nursey-Bray et al. 2019).

However, GEO-7 is organized by large UN regions or by income-class countries rather than by biocultural regions or livelihood modes. Further, most studies of the role of Indigenous Knowledge and local knowledge in adaptation and sustainability are based at the landscape or cultural region scale. Biocultural and livelihood perspectives illustrate the complexities and contingencies in the relationships between social and ecological change over time at these scales. For example, scientists have long puzzled over the factors that contributed to the so-called collapse of the Maya civilization, particularly the role of climate change (Haug et al. 2003) Studies indicate that climatic change, especially severe drought, played a significant role in the decline of Mayan cities circa 800–1000 A.D. Mayan people endured by adaptively reorganizing to decentralize and de-urbanize in response to these environmental changes (Clayton 2016), while maintaining a mosaic of productive, biodiverse landscapes, such as the milpa system (Ford and Nigh 2010), that still flourish where permitted. To avoid misreading the historical-ecological record and recognizing the underlying causes of unsustainability which can result in ecocide, ethnocide, or other adverse consequences for Indigenous Peoples and their lands, it is essential to have Indigenous perspectives in environmental assessments (Brondízio et al. 2021). Indigenous-led research and social movements can support sustainability transformations, including adaptation to climate change, advancing understanding of the causes, effects and responses to environmental change across the seven UN-recognized sociocultural

Credit: thanyapatm/Envato

regions of Indigenous Peoples. Expanding Indigenous leadership in intergovernmental environmental assessments will enhance Indigenous insights and strategies for sustainability.

Using Indigenous-led results to inform future scenarios of stewardship and adaptation at meaningful biocultural scales can lead to important breakthroughs. For example, a recent study using data on soils in 703 tribal land areas in the United States, reveals how Indigenous Knowledge can shape sustainable agricultural futures (Chesnais et al. 2024). The analysis makes clear the high potential for Indigenous regenerative agroecological practices to transform food systems, addressing global environmental crises and local issues of sustainability, food sovereignty, biocultural diversity and health. The study also demonstrates how the benefits of Indigenous Knowledge are obscured by data biases. The findings reinforce the need to amplify Indigenous perspectives and leadership roles in the conceptualization, collection, use and management of data on human-environmental systems, including medicinal plants to avoid biases that lead to suboptimal solutions, environmental harms or other injustices. More equitable processes for developing transformation pathways are already being considered or implemented in select biocultural regions with Indigenous inhabitants to strengthen their rights and stewardship capacities (Turner and Spalding 2013; Chesnais 2022; Forest Peoples Programme 2024). International governance organizations can assist with this by partnering with Indigenous Peoples to address environmental crises and just sustainability transitions in multicentric and bioculturally integrated ways (Indigenous Summit Just Transition 2024; Muthukrishnan and Datta 2024; IK & LK Dialogues 2025).

References

Ashjian, C.J., Braund, S.R., Campbell, R.G., George, J.C.C., Kruse, J., Maslowski, W. et al. (2010). Climate Variability, Oceanography, Bowhead Whale Distribution, and Iñupiat Subsistence Whaling near Barrow, Alaska. Arctic 63(2). http://www.jstor.org/stable/27821962

Brondízio, E.S., Aumeeruddy-Thomas, Y., Bates, P., Carino, J., Fernández-Llamazares, Á., Ferrari, M.F. et al. (2021). Locally Based, Regionally Manifested, and Globally Relevant: Indigenous and Local Knowledge, Values, and Practices for Nature. Annual Review of Environment and Resources 46, 481-509. https://doi.org/10.1146/annurev-environ-012220-012127

Chesnais, A.K. (2022). The double data movement towards the ecological pluriverse: The case of the native land information system. In Routledge handbook of the digital environmental humanities. Routledge. 143-156. https://doi.org/10.4324/9781003082798

Chesnais, A.K., Brewer II, J.P., Whyte, K.P., Saposhnik, R.S. and Johnson, M.K. (2024). Reform Federal Policies to Enable Native American Regenerative Agriculture: Centering the goals and knowledge of Native land stewards in federal data and definitions of" climate smart" agriculture could nourish communities while incentivizing carbon sequestration across millions of acres. Issues in Science & Technology 40(3), 50–54. https://doi.org/10.58875/YQYW4711

Clayton, S.C. (2016). After Teotihuacan: A View of Collapse and Reorganization from the Southern Basin of Mexico. American Anthropologist 118(1), 104-120. https://doi.org/10.1111/aman.12522

Fairhead, J. and Leach, M. (1996). Misreading the African Landscape: Society and Ecology in a Forest-Savanna Mosaic. Cambridge University Press. https://doi.org/10.1017/CBO9781139164023

Ford, A. and Nigh, R. (2016). The Maya Forest Garden: Eight Millennia of Sustainable Cultivation of the Tropical Woodlands. Routledge. https://doi.org/10.4324/9781315417936

Forest Peoples Programme (2024). Forest Peoples Programme Webpage. https://www.forestpeoples.org/. Accessed 4 October of 2024

Haug, G.H., Günther, D., Peterson, L.C., Sigman, D.M., Hughen, K.A. and Aeschlimann, B. (2003). Climate and the Collapse of Maya Civilization. Science 299(5613), 1731-1735. https://doi.org/10.1126/science.1080444

Huntington, H.P., Begossi, A., Fox Gearheard, S., Kersey, B., Loring, P.A., Mustonen, T. et al.. (2017). How small communities respond to environmental change: patterns from tropical to polar ecosystems. Ecology and Society 22(3). http://www.jstor.org/stable/26270171

IK & LK Dialogues (2025). Indigenous Knwoledge and Local Knowledge Dialogues. Global Environment Outlook 7. Mexico City: Indigenous Knowledge and Local Knowledge Dialogues - Copit Arxives (2025)

Indigenous Summit Just Transition. (2024). Indigenous Peoples Principles and Protocols for Just Transition Just Transition: Indigenous Peoples' Perspectives, Knowledge, and Lived Experiences. Geneva, Switzerland, October 8-10. https://www.indigenoussummit.org/summit-outcome

Krupnik, I., Aporta, C., Gearheard, S., Laidler, G.J. and Holm, L.K. (2010). SIKU: knowing our ice: Documenting Inuit Sea Ice Knowledge and Use. Krupnik, I., Aporta, C., Gearheard, S., Laidler, G.J. and Holm, L.K. (eds.). Dordrecht: Springer. https://doi.org/10.1007/978-90-481-8587-0

López-Maldonado, Y., Anstee, J., Neely, M.B., Marty, J., Mastracci, D., Ngonyani, H. et al. (2024). The contributions of Indigenous People's earth observations to water quality monitoring. Frontiers in Water 6. https://doi.org/10.3389/frwa.2024.1363187

Muthukrishnan, R. and Datta, R. (2024). Indigenous Practice and Community-Led Climate Change Solutions: The Rele-vance of Traditional Cosmic Knowledge Systems. London: Routledge. https://www.routledge.com/Indigenous-Practice-and-Community-Led-Climate-Change-Solutions-The-Relevance-ofTraditional-Cosmic-Knowledge-Systems/Muthukrishnan-Datta/p/book/9781032484365?srsltid=AfmBOopoN7G80fzdz-2Z0oRPDEc41g0FfHaXUkMLzqIL5X3QwHKjAkfWp

Orozco-Ramírez, Q., Bocco, G. and Solís-Castillo, B. (2020). Cajete maize in the Mixteca Alta region of Oaxaca, Mexico: adaptation, transformation, and permanence. Agroecology and Sustainable Food Systems 44(9), 1162-1184. https://doi.org/10.1080/21683565.2019.1646374

Nursey-Bray, M., Palmer, R., Smith, T.F. and Rist, P. (2019). Old ways for new days: Australian Indigenous peoples and climate change. Local Environment, 24(5). The International Journal of Justice and Sustainability 24, 473–486. https://doi.org/10.1080/13549839.2019.1590325

Reyes-García, V., García-del-Amo, D., Álvarez-Fernández, S., Benyei, P., Calvet-Mir, L., Junqueira, A.B. et al.. (2024). Indigenous Peoples and local communities report ongoing and widespread climate change impacts on local social-ecological systems. Communications Earth & Environment 5(1), 29. https://doi.org/10.1038/s43247-023-01164-y

Thornton, T.F. and Manasfi, N. (2010). Adaptation—Genuine and Spurious: Demystifying Adaptation Processes in Relation to Climate Change. Environment and Society 1(1), 132–155. https://doi.org/10.3167/ares.2010.010107

Turner, N. and Spalding, P.R. (2013). "We Might Go Back to This"; Drawing on the Past to Meet the Future in Northwestern North American Indigenous Communities. Ecology and Society 18(4). http://dx.doi.org/10.5751/ES-05981-180429

19 Implications for Different Economic Development Contexts

Coordinating Lead Authors: Heinz Schandl (CSIRO), Lynette Cheah (University of the Sunshine Coast)

Lead Authors: Alaa Al Khourdajie (Imperial College London), Pankaj Kumar (Institute for Global Environmental Strategies), Steve Arquitt (Millennium Institute)

Contributing Authors: Isa Elegbede (Lagos State University), Estee Miltz (Millennium Institute)

Fellow: Estee Miltz (Millennium Institute)

Chapter summary

Credit: Dmitry_Rukhlenko/Envato

Countries at different stages of economic development face distinct challenges and opportunities in the transformation towards sustainability goals.

High-income countries (HICs) are well-positioned to influence multilevel and multilateral governance, macroeconomic and fiscal policy to support sustainable financing in the global economic transition *(well established)*. This involves strengthening international tax norms, advancing the effectiveness of the development bank system, operationalizing the Fund for responding to Loss and Damage (FRLD), debt relief, and stimulating the development of green technologies {19.3.1}.

By investing in green technologies and sectors, HICs can diversify their economies, reduce resource dependency, and generate employment opportunities in sustainable industries. With access to advanced technologies, HICs are well-positioned to develop and implement effective strategies for resource management and waste reduction *(well established)* {19.4.1}. Growing renewable energy deployment, supported by policy frameworks and offering socio-economic benefits like job creation, illustrates this potential *(established but incomplete)* {19.5.1}.

Beyond renewable energy deployment, electrifying transport and heating, supported by financial markets capable of mobilizing substantial private investment, and effective policy frameworks that provide robust regulatory support, will be critical in HICs *(well established)*. However, challenges persist in managing the socioeconomic impacts of phasing out fossil fuels. Coal-dependent communities, in particular, will require just-transition measures and comprehensive social programmes. Additionally, renewable energy infrastructure development may raise environmental concerns, including the potential degradation of protected areas, key biodiversity zones, and wilderness regions from onshore and offshore wind, hydropower, and solar photovoltaic installations, though these impacts are generally limited. Nevertheless, these developments can contribute to broader environmental issues, including

biodiversity loss, air pollution, and land degradation *(established but incomplete)* {19.5.1}.

Transforming the food system in HICs will require promoting sustainable agricultural practices. This includes pursuing organic farming, improving livestock productivity, and promoting afforestation *(established but incomplete)* {19.6.1}.

Imposing carbon tariffs in HICs can prevent producers from shifting polluting operations to countries with weaker environmental standards. By targeting carbon-intensive imports, such as steel and cement, these tariffs can help overcome the limitations of production-based, or polluter-pays, emissions accounting, which can falsely suggest environmental progress while potentially increasing overall global emissions *(established but incomplete)*. As of this writing, no carbon tariff programmes have yet been fully implemented {19.7.1}.

On the demand side, HICs can reduce consumption and improve resource efficiency *(well established)*. As major consumers of global materials, doing so offers considerable economic savings by reducing raw material demand, energy use, and waste management costs. By leading in resource efficiency and environmental stewardship, HICs can shape international policies and practices {19.4.1}.

Changing consumer behaviour and preferences around energy and food consumption can yield significant benefits *(well established)*. Policy incentives and infrastructure investments can promote energy-efficient technologies and discourage carbon-intensive lifestyles. Both market-based and voluntary approaches are required to encourage sustainable diets. Minimizing food waste, encouraging dietary changes and promoting regional food products can enhance self-sufficiency and reduce food insecurity {19.6.1, 19.7.1}.

Industrializing and urbanizing middle-income countries (MICs) need to ramp up investments in sustainable infrastructure to address significant service gaps, particularly in housing and transportation *(well established)*. Strategic public investments can support the development of durable, resource-efficient infrastructure. This includes adaptable and sustainable residential and commercial buildings, integrated public transportation networks, and cities designed for active mobility. Incorporating secondary materials into manufacturing and construction also demands substantial investments in waste management and resource recovery infrastructure. Making economies more circular and mitigating associated risks will require institutional reforms and innovation in resource governance and material management strategies {19.3.2, 19.4.2}.

Proactive industrial and innovation policies tailored to local contexts can support the development of green technologies *(established but incomplete)*. MICs can adopt sustainable industrial practices from the outset, framing the transition as a growth opportunity. Realizing benefits from green technologies will require a sustained focus on human capital and capacity building {19.4.2}.

Careful planning for coal phase out, fossil fuel subsidy reform, and renewable energy development will be critical for MICs in the energy transition *(well established)*. Addressing existing fossil fuel dependencies and infrastructure challenges, particularly in rapidly urbanizing areas, remains a key concern *(established but incomplete)*. Integrated policymaking can accelerate the adoption of renewable energy while mitigating environmental impacts, such as climate change and air pollution. With sufficient human and economic resources, the MIC countries have the opportunity to leapfrog to a green economy by promoting clean technology and removing fossil fuel subsidies {19.5.2, 19.7.2}.

Incorporating environmental and health externalities in national development planning could support sustainable development pathways *(established but incomplete)*. Middle-income countries face the challenge of striking a balance between economic development and environmental protection. Raising public awareness of pollution and the related health risks can help to create public demand for more decisive action against pollution. Finally, all countries need to develop legislation and enforcement mechanisms that guarantee access to justice for all citizens who bear the brunt of pollution's consequences {19.7.2}.

For low- and middle-income countries, ensuring effective waste management and resource recovery systems, especially in fast-growing cities, is a key priority *(well established)*. The informal sector plays a significant role in repair, reuse and resale, offering valuable opportunities. However, more research is needed to understand and realize this potential fully {19.4.2} {19.4.3}.

Foreign direct investment and targeted renewable energy subsidies, alongside policies addressing

Credit: bilanol/Envato

institutional barriers, are crucial to overcome resource constraints and enable energy transition in low-income countries (LICs) *(established but incomplete)*. While LICs hold substantial renewable energy potential, financial barriers, especially high upfront costs, limit the adoption of renewable energy and energy-efficient technologies. While renewable energy subsidies can support environmental goals, it will be critical to balance economic development with energy efficiency as per capita energy use continues to rise. Maintaining this balance requires an enabling environment that attracts investment in renewable projects while supporting a gradual shift from fossil fuels to cleaner energy sources {19.5.3}.

In LICs, sustainable agricultural approaches such as agroecology and agroforestry can help restore and nurture the natural capital of ecosystem services, sustain yields, protect biodiversity and reduce pollution from chemical fertilizers and pesticides *(well established)*. Achieving this will require government investment in farmer training and support for sustainable production methods, while discouraging unsustainable practices {19.6.3} {19.7.3}.

International action and cooperation in science, technology, innovation and sustainable financing are highly beneficial. In both middle- and low-income countries, building capacity and supporting technology transfer are essential for driving system transformation *(well established)*. Strengthening local research capacities and developing a skilled workforce will reap long-term benefits. Participation in international green innovation initiatives can facilitate the transfer of technology, knowledge and financial resources, while strong local capabilities can ensure successful integration into local contexts {19.4.3, 19.7.3}.

19.1 Introduction

Countries at different stages of development face distinct challenges and opportunities in their transition towards sustainability goals. This chapter examines solution pathways tailored to varying economic contexts, highlighting examples of best practice with key challenges and opportunities. Recognizing that one size does not fit all, this chapter emphasizes the importance of context-specific approaches to support transformative change.

In designing an effective response to the environmental crises, it is essential to recognize the diverse contexts of countries, ranging in economic development, environmental health, and resource endowments, that shape the distinct outlooks of nations across the globe. While some countries grapple with limited resources and fragile ecosystems, others boast strong economies and relatively healthy environments. Tailoring strategies to these differences is key to leveraging each country's strengths while addressing their specific challenges.

19.2 Country groupings

The focus throughout this chapter is on three economic country groupings adapted from the World Bank country classification system. The World Bank classifies countries into four per capita income bands: low, lower-middle, upper-middle, and high-income countries (World Bank 2023a). However, for the purposes of this chapter and to simplify the solution pathways by system and country, three country-economic groups are defined: High-income, industrializing and urbanizing middle-income, and financially constrained low-income countries. Additional details about the countries in each group are provided in Appendix 19.1 (**Figure 19.1**), including information on population density and trade status to inform the analysis.

High-income countries (HICs) are those with a gross national income (GNI) per capita exceeding US$13,845 (World Bank 2023a). For these nations, the transformation involves strengthening existing sustainability efforts, managing and maintaining infrastructure, encouraging responsible consumption, and addressing potential environmental impacts they cause beyond their borders.

Industrializing and urbanizing middle-income countries (MICs) are classified as having a GNI per capita between US$4,466 and US$13,845 (World Bank 2023a). In this group, countries experience rapid urbanization, a quick increase in energy use, and higher consumption of animal protein. These

Credit: BGStock72/Envato

transformations present a unique opportunity to shape urban planning, energy infrastructure, and economic growth in a sustainable manner.

Financially constrained low-income countries (LICs) are those with a GNI per capita below US$4,466 (World Bank 2023a). These countries often possess abundant natural resources but have limited economic capacity, facing unique challenges in managing their transitions. For this group of countries, it is essential to balance the exploitation of natural resources for economic growth with sustainable practices.

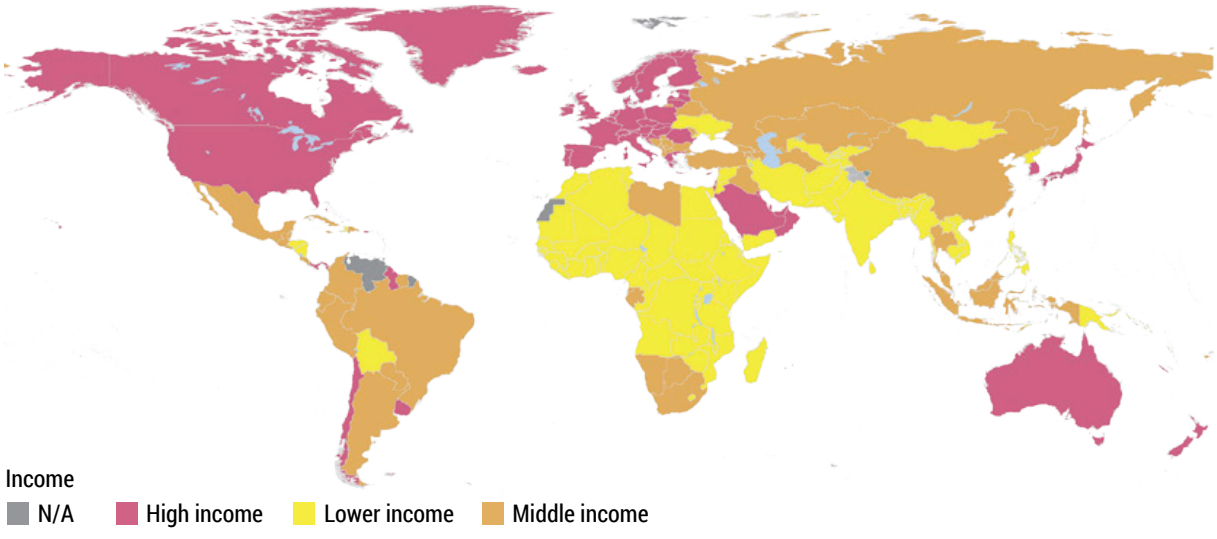
While other grouping approaches and country classifications exist, such as the International Monetary Fund's classification of advanced, emerging, and developing economies, this analysis recognizes the financial capacity of different countries to ensure that proposed solutions are realistic. This does not suggest a "one-size-fits-all" solution per country group but recognizes that solution pathways can be contextualized based on other sociocultural and political characteristics of countries. Chapter 20 further supports this analysis by providing solution pathways from a regional country perspective to capture nuanced development features.

This chapter explores the diverse nature of the three economic groups and interprets system transformations across different stages of economic development. Selected case studies highlight best practices to support solution pathways within each group. Where

Credit: dotshock/Envato

relevant, results from the two modelled scenarios are discussed. More details about these scenarios are available in Chapter 11. In short, Chapter 11's Technology-focused Transformation Scenario relies on technological development, particularly aimed at a green economy, while the Behaviour-focused Transformation Scenario involves societal changes in values, beliefs, and norms, moving away from dominant cycles of consumerism (11.2). The model outputs for these two scenarios across the five systems (Economic, Materials/Waste, Energy, Food, and Environment) are also presented, broken down by country grouping (High-, Middle-, and Low-income).

Figure 19.1: World map with adapted country groupings defined according to the World Bank's economic classification



Source: World Bank 2022

19.3 Transformation of economic Systems

The current economic paradigm, along with population growth, is pushing countries further away from sustainability. It is widely recognized that economic growth alone cannot attain environmental sustainability (Cumming and von Cramon-Taubadel 2018). Projections of GDP per capita are expected to increase based on current trends and in the two transformation scenarios, as shown in **Figure 19.2**. However, high-, middle-, and low-income countries display distinct economic and consumption patterns and opportunities. These differences influence how they use natural resources and respond to population growth, requiring tailored approaches during the transition to sustainable governance and finance.

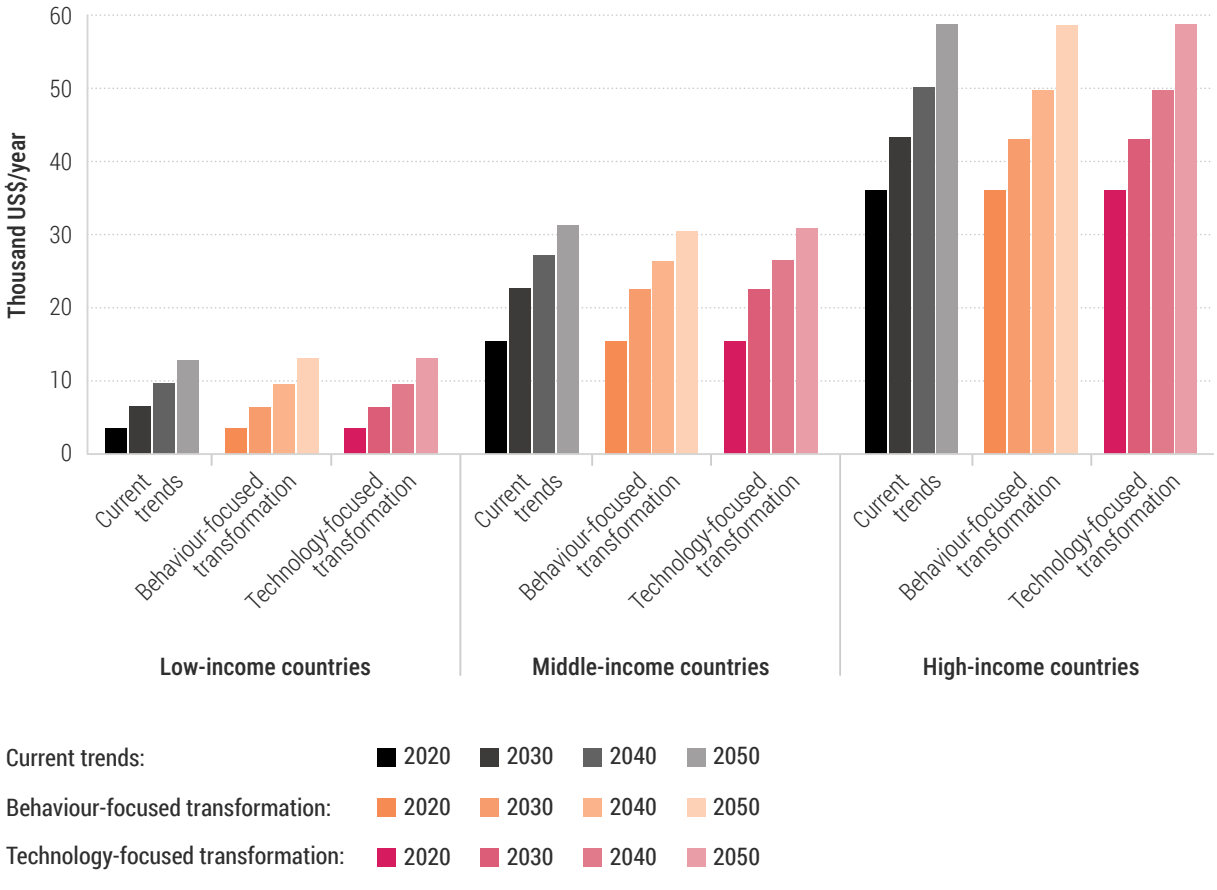
19.3.1 High-income countries: Steering sustainable financing

Countries with high incomes have higher material consumption and waste per capita (United Nations 2023a). The increasing use of natural resources leads to greater environmental impacts, which are often transferred to other nations through imported products (Cumming and von Cramon-Taubadel 2018).

HICs can steer multilevel and multilateral governance, as well as macroeconomic and fiscal policies, towards sustainable financing. This includes efforts to strengthen international tax standards, particularly for digitalized and globalized businesses, as well as to reassess the role of development banks. Key initiatives involve operationalizing the Fund for responding to Loss and Damage (FRLD), facilitating debt relief, reforming the international debt resolution framework, and addressing tensions over green subsidies through revised trade rules (United Nations 2023a).

While sustainable finance is expanding rapidly, most resources are still concentrated in HICs, which control 80 per cent of global finance. However, less than 3 per cent of sustainable investments are directed to low-income countries. HICs play a key role in removing barriers

Figure 19.2: GDP per capita (2010 US$) across the three country groups



Note: These projections take into account the policy costs for the transformation pathways as well as climate damages.

Credit: SouthworksStock/Envato

that restrict financing for sustainable development in low-income regions (Organisation for Economic Cooperation and Development [OECD] 2022) (**Box 19.1**).

Within their borders, HICs can revise policies and regulations to better align private sector profits with sustainability goals (United Nations 2023b). Encouraging businesses to adopt resource recovery initiatives and resource circularity is essential. Moving toward a less resource-intensive system of production and consumption, while developing workforce skills for low-carbon technologies, will facilitate this transition (World Bank and International Monetary Fund 2014). International cooperation in science, technology, and innovation is vital for sustainability (Stamm 2023). Several key donor countries have committed at least 40 per cent of their development aid to green innovation (OECD 2019). Developing human capital and transferring knowledge are crucial for integrating sustainable technologies into local contexts, driving structural change, and ensuring lasting impact (Hansen et al. 2018).

Countries with high incomes can move beyond traditional GDP growth targets and metrics, exploring alternatives like "post-growth" and "degrowth." By redefining economic narratives, these nations can adopt a more comprehensive view of socio-economic progress (European Parliamentary Research Service 2023). Additionally, encouraging behavioural and lifestyle shifts, partly motivated by awareness of climate and ecological crises, can help decrease energy demand and resource use in HICs.

Making sure that sustainable options are accessible and practical will be essential for encouraging lasting change (OECD 2022).

Box 19.1: Case study: France's development cooperation profile

France ranks highly among the main providers of official development assistance (ODA), with a strong emphasis on Africa. The donor country allocated US$15.9 billion in ODA in 2022, which amounts to 0.56 per cent of its GNI. Sixty-six per cent of its aid goes towards supporting the environment and the Rio Conventions, while 56 per cent focuses on climate change (OECD 2024).

19.3.2 Balancing economic growth and environmental impact in middle-Income countries

In MICs, rapid economic growth results in increased consumption and spending needs relative to GDP (McKinsey and Company 2022). These countries are also catching up to HICs in energy demand. Simultaneously, rising living standards and rapid urbanization present significant environmental challenges.

The main challenge for MICs is to create a growth model that balances economic development with energy saving and environmental protection (Li and Lin 2019). Using existing technologies and innovations can support sustainable development while reducing the risks of resource depletion and environmental degradation.

MICs also face pressing infrastructure challenges. As these countries experience urban growth, they need to increase investments in infrastructure to fill existing gaps and replace ageing, polluting systems. Public-private partnerships can help fund infrastructure projects when suitable. Additionally, investing in resilient infrastructure as a climate change adaptation strategy offers a green growth opportunity. These investments can deliver high economic returns by minimizing long-term climate-related damages. For MICs, every dollar invested in adaptation can generate up to four dollars in economic benefits (Global Commission on Adaptation 2019).

Other essential measures for MICs involve planning for coal phase-outs, reforming and gradually eliminating fossil fuel subsidies, promoting renewable energy sources, encouraging circular economy practices, and enhancing waste management, sustainable agriculture, and land use (Deutsche Gesellschaft für Internationale Zusammenarbeit [GIZ] 2021).

Moreover, proactive policies in the industry and innovation can accelerate the adoption of green technologies. Framing the transition as a development opportunity that emphasizes quality is crucial (Rodrik and Stiglitz 2024). Investing in capacity building, especially in human capital, will help create pathways to sustainable growth (**Box 19.2**).

19.3.3 Aligning financial flows with sustainability goals in low-Income countries

Countries with low incomes experience significant financial limitations and often depend heavily on ecosystems for their livelihoods (Cumming and von Cramon-Taubadel 2018). This group of countries is disproportionately impacted by ecological crises, and their scarce financial and human resources restrict their ability to invest in sustainable changes (United Nations 2023b). Consequently, LICs rely more on foreign technology, knowledge, and financial aid compared to other nations.

Investment in sustainable activities continues to be constrained in LICs because of the high risks from conflict, natural disasters, and disease outbreaks. Additionally, there are few sustainable finance options for firms in LICs or small and medium-sized enterprises (SMEs). These businesses frequently lack the necessary expertise and capital to obtain green loans or to engage in green bond markets (Global Sustainable Finance Working Group 2022).

Innovative options like concessional financing can speed up achievement of development objectives. Debt-for-nature swaps present a promising strategy, providing both sovereign debt relief and opportunities for environmental conservation (Losos, Pfaff and Pimm 2024). This approach is especially relevant where limited fiscal resources restrict environmental

Box 19.2: Sustainable Banking and Finance Network

The Sustainable Banking and Finance Network (SBFN) is a global initiative focused on building sustainable finance capabilities. Launched in 2012, it is a voluntary community of financial sector regulators, central banks, ministries, and industry associations from emerging markets. SBFN encourages knowledge exchange and capacity building to help align sustainable finance with national development goals. These efforts enhance risk management and support increased capital flows directed at environmental and social objectives. As of August 2024, SBFN includes 96 member institutions from 72 countries, covering both middle and low-income nations (SBFN 2024).

investments. Additionally, LICs can enhance their role in international arenas to build capacity in sustainable finance. Governments, financial regulators, and other stakeholders should participate in global platforms to better coordinate financial flows with sustainability targets.

Finally, it is crucial to address power dynamics between governments and extractive industries. In many LICs, sectors like mining and industrial fishing hold significant sway over environmental policies due to lobbying efforts and their economic contributions to the national economy (Teixidó-Figueras et al. 2016; Childs 2020). Tackling these deeply rooted power dynamics is essential for driving meaningful systemic change.

19.4 Transformation towards circularity and sustainable materials management

Since the 1970s, global living standards have significantly improved, but this progress has also led to notable increases in material demand, waste generation, and emissions. From 1970 to 2024, worldwide material extraction, including biomass, fossil fuels, metal ores, and non-metallic minerals, rose from 30 billion tons (8.4 tons per person) to 106 billion tons (13.2 tons per person) (United Nations Environment Programme [UNEP] 2024).

Material extraction accounts for 50 per cent of climate change impacts, 90 per cent of biodiversity loss and water scarcity, and 30 per cent of air and water pollution (UNEP 2024). While middle-income countries now represent 60 per cent of global material consumption, high-income nations still use materials at a rate six times greater than low-income countries (Schandl et al. 2018).

The Sustainable Development Goals (SDGs) emphasize the importance of resource efficiency and sustainable materials management. A circular economy presents a practical solution by reducing resource consumption through maintaining the value of materials and by increasing the lifespan of infrastructure and products (Geissdoerfer et al. 2017). Nonetheless, as of 2024, only 7.5 per cent of material demand is met through secondary sources (UNEP 2024), highlighting significant potential for further advancements.

There are many economically appealing opportunities for resource efficiency and circular economy measures in the housing, mobility, food, and energy sectors in the short term. Over the long term, investing in circularity and conserving natural resources proves to be the most economically advantageous approach, as current trends **(Figure 19.3)** indicate.

If the global economy stays on its current trajectory, material consumption is expected to increase from 106 billion tons in 2024 to 165 billion tons by 2050. However, both the Technology-focused Transformation Scenario and the Behaviour-focused Transformation Scenario, explained in Chapter 11, could significantly lower global material demand. The technology-focused approach would cut material use to 104 billion tons, about 60 billion tons less than the baseline, while the behaviour-focused approach could bring it down to 81 billion tons, a reduction of 84 billion tons.

Choosing either of the two transformation scenarios would have the most significant impact on domestic material consumption, a key indicator in material flow accounting, in MICs and the least impact in HICs **(Figure 19.3)**.

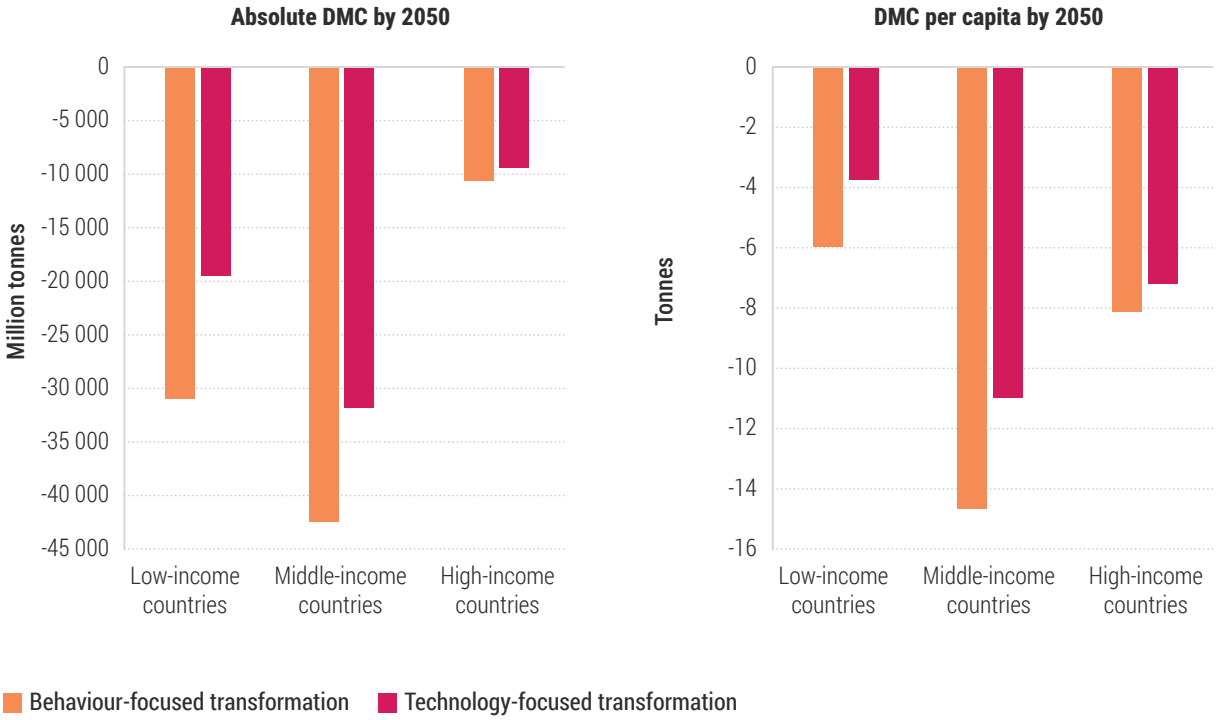
Approximately half of the projected decrease in material demand is expected to happen in middle-income countries, which are also likely to experience the largest decline in per capita material availability. This could limit their capacity to invest in infrastructure crucial for reaching SDG goals focused on people and prosperity.

A similar challenge applies to low-income countries, where there is an even greater need for basic infrastructure, such as buildings, transportation, communication, energy, and water and sanitation systems. These factors emphasize the importance of balancing environmental goals with socio-economic development priorities. Achieving this balance will require a coordinated global effort to facilitate a fair transition that ensures no one is left behind.

19.4.1 Unlocking technological and economic leadership through circularity in high-income countries

Countries with high incomes maintain a high per capita material footprint, indicating both high living standards and significant environmental impacts. Historically,

Figure 19.3: Reduction in Domestic Material Consumption (DMC) by 2050 in the behaviour-focused and technology-focused transformation pathways compared to the baseline, absolute values and per capita



these nations depended heavily on material imports to support their economies (Schandl et al. 2018). Over the past decade, this pattern has evolved. Some HICs, especially those with low population densities, abundant natural resources, and economies rooted in agriculture and mining, such as Australia, Canada, and, to a lesser extent, the United States of America, have transitioned into net exporters of biomass, fossil fuels, and metal ores. Meanwhile, HICs in Europe and Asia, such as Japan and the Republic of Korea, continue to depend on imported materials to maintain their economic functions.

Shifting toward enhanced resource efficiency, waste reduction, and emission management requires deliberate and strategic policymaking (Hatfield-Dodds et al. 2017). Countries with high incomes that rely on importing materials have implemented proactive policies to enhance resource use efficiency, reduce waste, and promote circular economy practices, aiming to strengthen their economic resilience (Haas et al. 2015). Conversely, resource-rich HICs with vast fossil fuel and mineral deposits often prioritize economic gains over sustainable production and consumption, exhibiting a reluctance to implement environmental sustainability policies.

HICs draw advantages through access to cutting-edge technologies, allowing them to develop and apply efficient resource management strategies. Advances in renewable energy, recycling, and materials science can significantly reduce resource consumption and waste (Roy and Tarafdar 2022). By investing in green tech and sustainable industries, these countries can diversify their economies, reduce the dominance of resource-intensive sectors, and create employment opportunities within sustainable fields.

This approach depends on innovative business models (Geissdoerfer et al. 2018) and on training both new and existing workers to acquire the skills needed for a circular economy (Buyukyazici and Quatraro 2025). It also involves supporting women's entrepreneurship in recycling and waste management sectors and ensuring women have access to training and resources (Crespo-Rosas and Franco-Garcia 2023). Regarding per capita material consumption and the significant share of global resource use, it is essential for HICs to reduce their material demand, thereby creating space for middle- and low-income countries to develop their infrastructure (Hickel 2021). Efficient resource use reduces costs, including those for raw materials, energy, and waste management, and helps HICs lead in global sustainability initiatives (Schandl et al. 2016).

Credit: vectorfusionart/Envato

By setting strong resource and environmental standards and leveraging their experience with circular economy policies in Europe, Japan, and China (McDowall et al. 2017), HICs can influence international policymaking and promote sustainable practices worldwide.

19.4.2 Building resilient economies through circular infrastructure in middle-income countries

Middle-income countries stand at a crucial juncture, confronting both challenges and opportunities as they move toward a future characterized by high resource efficiency, low waste, and a circular economy. These countries have higher material demand than both low- and high-income countries, primarily due to rapid economic growth and heavy reliance on imports (Wang et al. 2022a). However, their per capita material consumption stays comparatively modest, and they need to meet urgent infrastructure needs to support expanding populations and achieve the SDGs.

The construction of new buildings and infrastructure, especially for housing and transportation, presents a unique opportunity for MICs. Large-scale public investments can be strategically focused on creating resilient and resource-efficient infrastructure (Hebb 2019). This includes opting for sustainable architecture in and commercial structures, extensive public transit systems, and urban designs that encourage active mobility. These investments not only promote sustainable development but also support lower-income communities by offering shared mobility options and enhancing the quality of life in cities. As MICs experience rapid industrialization and urbanization, they are well-positioned to incorporate circular economy practices into their infrastructure, potentially setting an example in environmental responsibility and economic resilience.

The transition of middle-income countries is characterized by a surge in material demand, resulting in higher waste generation across various categories and a shift from biomass to predominantly non-renewable resources (Schandl et al. 2016). Governments and industries need to invest significantly in waste management and resource recovery infrastructure to meet rising demand while reducing landfill waste by incorporating secondary materials into manufacturing and construction.

Effectively managing this transition and reducing related risks will likely require institutional reforms and innovations in resource governance and sustainable material management strategies (Lockwood et al. 2010). Scenario analysis indicates an alternative development path that departs from the conventional model of industrialization followed by environmental remediation. Instead, it favours a trajectory that emphasizes sustainable industrial practices from the outset (Gerst, Raskin and Rockström 2014).

For countries with high population density, it is crucial to secure access to affordable materials on the global

market. These nations can enhance their economic resilience by strengthening recycling and resource recovery efforts. Meanwhile, countries with lower population densities in this group should implement proactive environmental policies and follow best practices, guiding extractive industries toward practices and outcomes that support sustainability and minimize environmental impact. (Measham, Fleming and Schandl 2015).

19.4.3 Harnessing local potential and global support for circular economies in low-income countries

Since the 1970s, LICs have experienced little benefit from the growing global demand for materials (UNEP 2019[a]). Their per capita material supply has remained stagnant, reflecting a lack of essential services such as energy, transport, water, sewerage, and waste management infrastructure. These countries often struggle with weak institutional frameworks and lack effective governance over their natural resources, which hampers their economic development.

To overcome these issues, low-income countries will need substantial support from high- and middle-income nations, especially in developing environmentally sustainable infrastructure for housing, transportation, food, and energy. A crucial focus is on establishing effective waste management and resource recovery, particularly in rapidly expanding cities (Aleluia and Ferrão 2016) (**Box 19.3**). Enhancing living conditions remains a key objective,which suggests that, even within a circular economy approach, their demand for materials will likely increase considerably until the mid-21st century.

Densely populated countries in this group face compounded challenges. They need to expand infrastructure to support their large populations amid ongoing urbanization. Ensuring access to essentials like food, shelter, and utilities is uncertain and requires substantial investments and international aid. (Ahmed, Mahmud and Acet 2022).

On the other hand, countries with low population density in this group, though rich in natural resources, encounter development issues tied to an extractive economy (Vilaysouk, Schandl and Murakami 2019). Nevertheless, they could capitalize on their natural resource wealth, especially if these resources are managed well and for the broader benefit of their populations.

The informal sector offers a valuable area for exploration, as it is a common hub for repair, reuse, and resale activities. However, there is limited data on these practices, which are crucial for fostering circularity. More research is needed to understand the potential of such activities. Promoting and strengthening these activities can generate more value for these countries and bring additional benefits to the workers engaged in them.

19.5 Transformation of energy systems

This section examines the unique challenges and opportunities involved in transforming energy systems across three economic groups. It explores how specific characteristics of each group influence key components of the energy system, including sources, conversion processes, system integration, end-use needs, the roles of various end users including

Box 19.3: Circular economy approaches for the electronics sector in Nigeria

Nigeria lacks sufficient recycling infrastructure to handle e-waste, relying heavily on the informal sector for metal recovery. About 100,000 people are engaged in informal e-waste processing, handling around half a million tons of discarded appliances each year (UNEP 2019b). Although laws exist to ban e-waste imports and promote responsible management practices, weak enforcement remains a major obstacle (GIZ 2021). In 2019, the Nigerian government, with support from the Global Environment Facility and UNEP, launched a US$15 million initiative to develop a circular electronics system. This effort united government, private sector, and civil society to foster a financially sustainable circular economy for electronics. The approach aims to safeguard the environment while creating safer jobs for informal workers. Key steps include implementing Extended Producer Responsibility legislation and encouraging regional and global sharing of knowledge on circular economy practices.

women, and policy frameworks. A range of economic, environmental, resource, and technological indicators is evaluated (Clarke et al. 2022). Whenever relevant, the discussion also considers public acceptance and health impacts, along with institutional aspects, including political feasibility and governance capacity.

19.5.1 Managing the energy transition in high-income countries

Countries with high incomes show different levels of renewable energy adoption. In Europe, renewables make up 19 per cent of the total energy supply, supported by policies and investments (Roth et al. 2022; International Energy Agency [IEA] 2023a). In contrast, HICs in Asia and the Pacific and North America have lower shares, around 11 per cent (IEA 2023a). Though most HICs actively incorporate renewables and electrify sectors like transportation and heating (Lin and Okoye 2023), some HICs in the Middle East have renewable shares below 1 per cent, heavily depending on fossil fuels (Adun, Ishaku and Ogungbemi 2022; IEA 2023a; International Renewable Energy Agency [IRENA] 2020).

Electricity generation from renewables also varies: Europe leads with 40 per cent, followed by Asia and the Pacific and North America at 27 per cent (IEA 2023a). The Gulf Cooperation Council (GCC) countries are well-positioned for renewable energy growth, benefiting from significant private investment aligned with national targets. However, additional policy measures are needed to improve financing for renewables (Krupa, Poudineh and Harvey 2019).

The transition to sustainable energy systems in HICs involves key components. Initially, expanding renewable energy capacity depends on strong regulatory policies and higher investment returns (Dalei and Joshi 2023). Countries that remain reliant on fossil fuels need to diversify their economies to support this transition. Solar and wind power are particularly promising options for meeting growing energy needs (Zhang et al. 2017). Expanding renewable energy capacity provides socio-economic benefits, including job creation in the renewable sector (Azarpour et al. 2022). Some countries are exploring green hydrogen as a low-emission alternative to natural gas. However, its application remains limited (for domestic heating) and is currently not cost-competitive. (Hristescu 2022; IEA 2023a).

Figure 19.4 shows future power generation through two transformation scenarios, either Technology-focused or Behaviour-focused (see Chapter 11). Both scenarios assume that non-biomass renewables will lead electricity production in HICs by 2050. However, the Behaviour-focused Scenario anticipates lower overall electricity demand due to lifestyle changes and increased efficiencies.

The transition in HICs also projects a decrease in final energy demand per person by 2050, as shown in **Figure 19.5**. This decline is especially significant in the scenario focused on behavioural changes, mainly due to lower demand in residential, transportation, and industrial sectors. These projections emphasize the importance of energy-efficient technologies and sustainable policies (De Angelo et al. 2021). However, even with the financial means to adopt sustainable technologies, carbon-intensive lifestyles still pose a challenge to lowering demand-side emissions. Robust policy incentives and infrastructure investments are crucial for achieving the targeted emission reductions (Mi et al. 2020; Rajput et al. 2023; Starr et al. 2023; IEA 2023b).

The energy transition in HICs presents both challenges and opportunities. Phasing out fossil fuels, particularly coal, requires careful management of the socioeconomic effects on workers and local communities. Many countries have already pledged coal phase-outs, highlighting a growing momentum for change. For instance, members of the Powering Past Coal Alliance (PPCA) have pledged to phase out unabated coal by 2030, while Germany has set a later deadline of 2038 to allow more time for society and the economy to adjust. In North America, the decline of coal has been primarily driven by the availability of inexpensive shale gas and the ageing of coal infrastructure, complementing the Biden Administration's goal of achieving carbon-free electricity by 2035. Canada also plans to phase out by 2030. These transitions underscore the need for just-transition measures and robust social programmes to support affected workers, invest in alternative livelihoods and strengthen local economies during the shift to cleaner energy (Jewell et al. 2019; Blondeel, Van de Graaf and Haesebrouck 2020; United States Energy Information Administration [US EIA] 2023). From an environmental standpoint, transitioning to renewable energy reduces carbon emissions but it also brings new challenges. Building renewable energy infrastructure, including onshore and offshore wind,

Figure 19.4: Projected power generation (including heat) across income groups

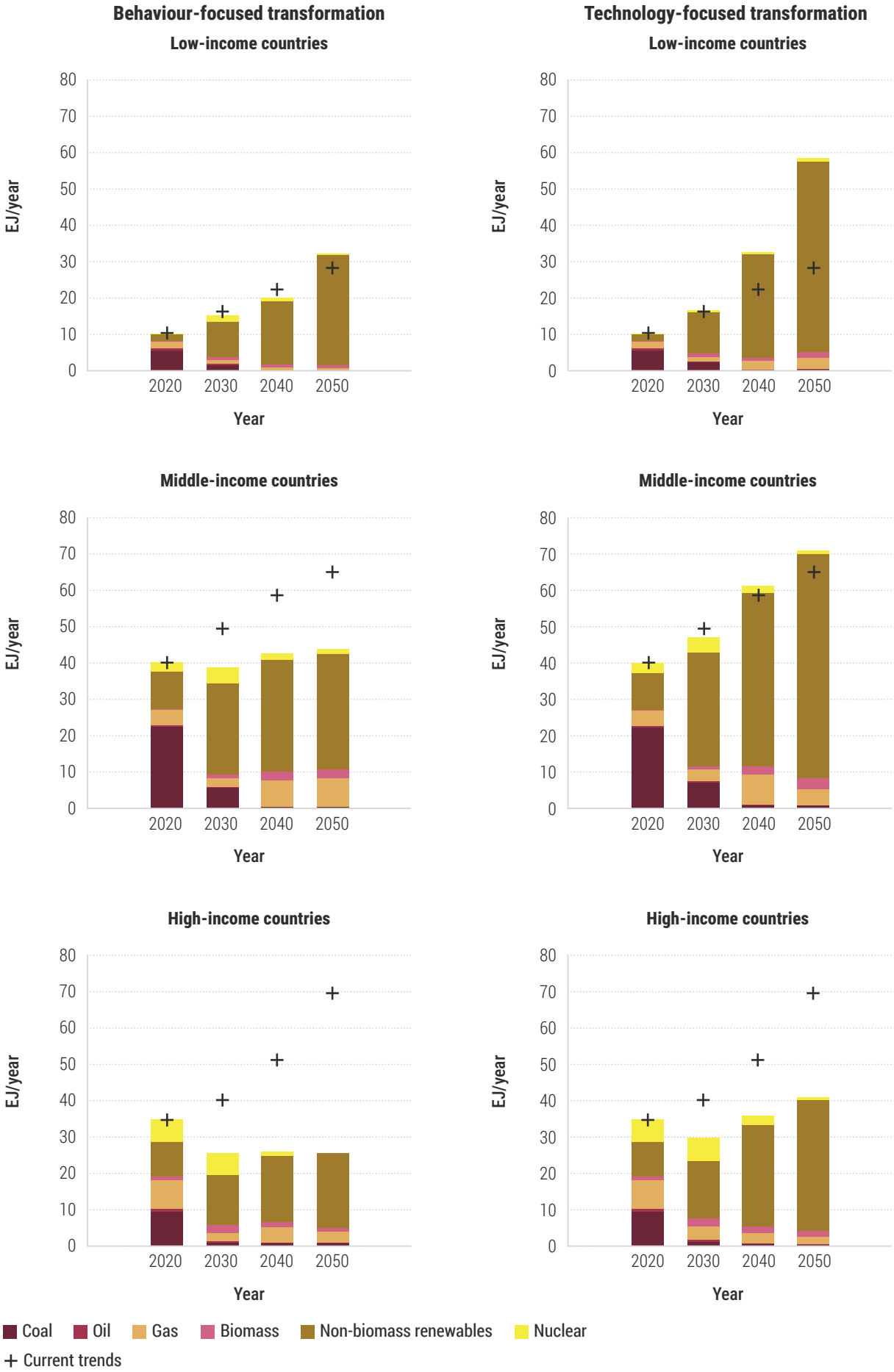
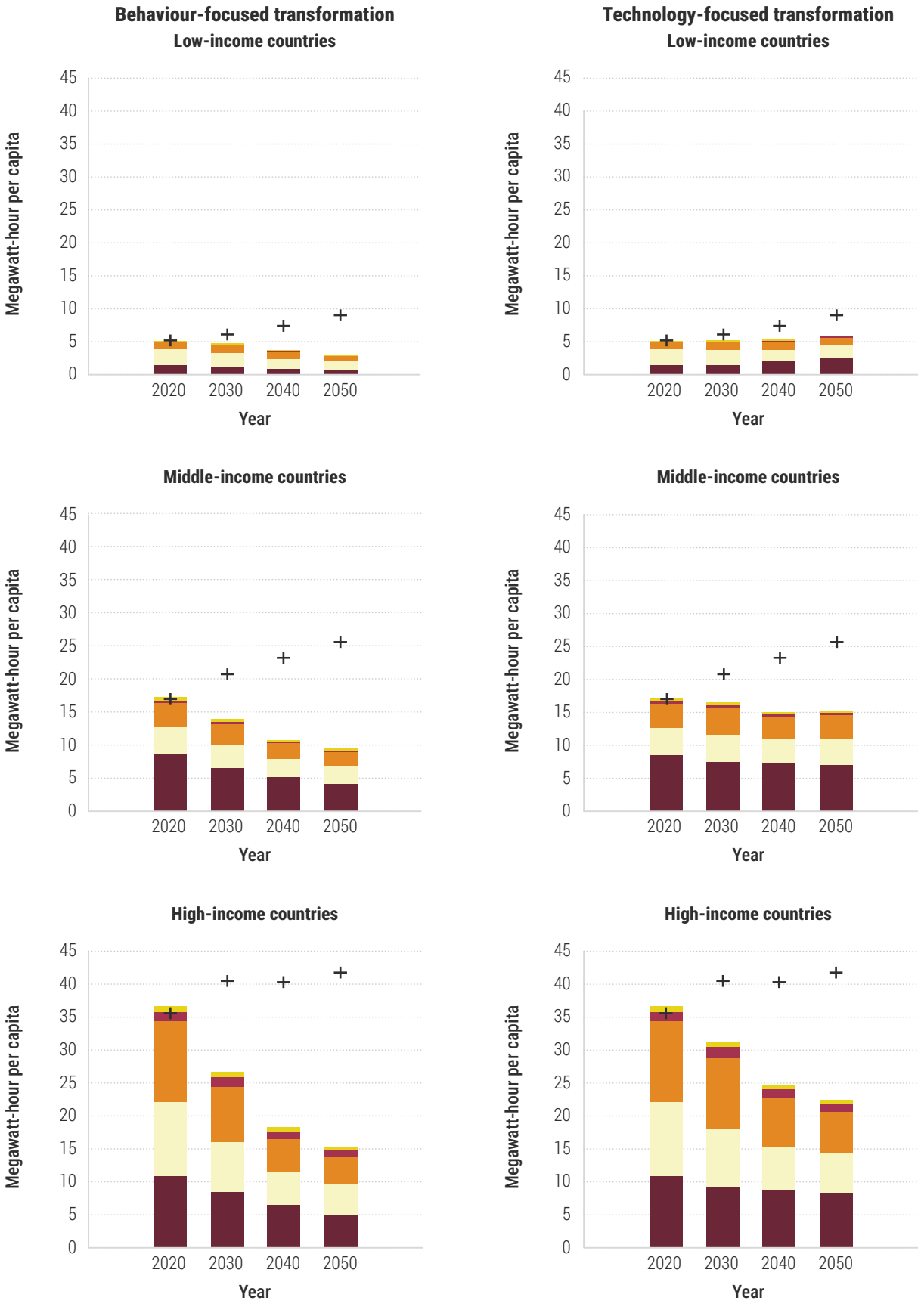


Figure 19.5: **Projected final energy demand per capita across income groups under behaviour-focused and technology-focused transformation pathways**



hydropower, and solar photovoltaic, can adversely affect protected regions, key biodiversity hotspots, and wilderness areas, though these impacts are generally limited (Rehbein et al. 2020). Such developments also contribute to larger environmental and societal problems like biodiversity decline, air pollution, and land degradation (Wang et al. 2022a).

19.5.2 Energy challenges and opportunities for middle-income countries

Energy systems in MICs vary widely. In Brazil, renewable energy makes up about 50 per cent, mainly from hydropower and biofuels, backed by strong regulations (Simon et al. 2018; Denny 2020; IEA 2023a). In contrast, renewable energy share in China is roughly 9 per cent, with expansion driven by carbon reduction targets (Song, Jia and Jiao 2022; Wang et al. 2022b; IEA 2023a). Despite growth in renewables, coal still supplies 60 per cent of energy in China, though demand growth is slowing (Lamb et al. 2021). In Southeast Asia, renewables constitute 20 per cent of the energy mix, indicating a gradual transition (Lau et al. 2022; IEA 2023a).

The difference is even more pronounced in electricity generation. In Brazil, 88 per cent of electricity comes from renewable sources, mainly hydroelectric power, aligning with Central and South America's average of 73 per cent. Meanwhile, the share of renewable electricity in China stands at 30 per cent, and Southeast Asian MICs average 28 per cent (Kroposki et al. 2017; Azhgaliyeva and Mishra 2022; Feng, Song and Chen 2023; IEA 2023a).

Several key factors are essential to enabling the energy transition in MICs. First, speeding up the shift toward renewables while managing existing fossil fuel dependencies requires addressing infrastructure challenges, especially in rapidly urbanizing areas. Regulation is also crucial, as shown by China's efforts to expand clean energy under its carbon reduction goals (Feng, Song and Chen 2023). Additionally, building an enabling environment for investment in renewable energy projects is also key. In Southeast Asian MICs, for instance, insufficient incentives have slowed progress despite new subsidy proposals (Johnson, du Pont and Gueguen-Teil 2021; Azhgaliyeva and Mishra 2022). Managing existing and planned fossil fuel infrastructure, particularly coal power plants, remains another critical challenge.

Figure 19.4 shows projections for power generation in MICs under the Technology-focused and Behaviour-focused Transformation Scenarios. The Behaviour-focused Scenario suggests a stabilization in total power generation through to 2050, with non-biomass renewables becoming the dominant source. Meanwhile, the Technology-focused Transformation Scenario shows a continued increase in power generation, also accompanied by a significant shift to non-biomass renewables. The Behaviour-focused Transformation Scenario reflects improved energy efficiency and reduced demand through lifestyle changes.

The energy transition involves more than just electricity generation; it also includes the energy directly consumed by end users. Figure 19.5's middle panels show these changes. The Behaviour-focused Transformation Scenario predicts a decline in final energy demand per person across all sectors by 2050, mainly due to reduced activity, increased efficiency, and lifestyle shifts. The Technology-focused Transformation Scenario also indicates lower final energy demand per capita compared to the Current Trends baseline. However, changing lifestyles will require targeted policy efforts, a challenge shared with high-income countries (Mi et al. 2020; Wang et al. 2022c). Regional differences in energy needs and resource availability, like the uneven distribution of oil, gas, coal, and hydropower in middle-income countries in East and Southeast Asia, further complicate the transition (Wiedenhofer et al. 2017; Bhattacharyya 2017).

The transition to renewable energy in MICs has both socioeconomic and environmental impacts. On the positive side, renewable energy initiatives can help reduce poverty. For instance, the Income and Energy Generation Programme in Brazil and Photovoltaic Poverty Alleviation programme in China have demonstrated how renewables can promote social progress (Barroco Fontes Cunha et al. 2021; Liu et al. 2023). However, expanding renewables can also lead to conflicts. 'Green' narratives may be exploited to justify land acquisitions, leading to tensions (Backhouse and Lehmann 2020).

Environmentally, the transition provides opportunities to reduce CO_2 emissions, but it also brings challenges. Like HICs, MICs' renewable energy infrastructure can impact protected areas and key biodiversity zones (Wang et al. 2025). Expansion of such renewables as hydropower and biofuels has caused biodiversity losses and habitat fragmentation (Pratiwi and Juerges 2020). Moving towards non-biomass renewables offers a more sustainable route, balancing electricity needs with CO_2 reduction goals. (Hausman 2012; Siala et al. 2021).

19.5.3 Energy challenges and opportunities for low-income countries

Countries with low incomes face distinct energy challenges and opportunities. Their energy systems have a relatively high share of renewables in total energy supply and unique electricity generation patterns, influenced by socioeconomic conditions that increase energy demand. These countries are expected to undergo significant changes in their energy systems, with the potential for widespread adoption of cleaner technologies while balancing economic development needs.

In many LICs, particularly in Africa and India, renewables make up about 15 per cent of the total energy supply (IRENA and African Development Bank [AfDB] 2022; IEA 2023a). This share is relatively high compared to high- and middle-income countries, due to the abundance of untapped renewable resources. In electricity generation, LICs in Africa and India have a renewable share of around 23 per cent, while LICs in the Middle East lag behind with only 3.5 per cent (IEA 2023a). Hydropower is the main source of renewable electricity in Sub-Saharan Africa, leaving significant potential for expanding solar and wind energy (Olanrele and Fuinhas 2022).

Achieving a successful energy transition in LICs depends on several crucial actions. It is vital to speed up the move to renewables, while managing fossil fuel dependencies is essential. India aims to install 500 gigawatts of renewable capacity by 2030 demonstrates this ambition (Government of India 2022). However, substantial infrastructure issues need to be overcome, particularly in urban regions where underdeveloped distribution networks slow down the adoption of renewable energy (Shrestha and Kakinaka 2023).

In many LICs in Africa the slowdown in coal power development since 2016, excluding South Africa and Zimbabwe, mirrors shifting global attitudes against coal financing and offers a chance to adopt cleaner technologies (Diluiso et al. 2021). The energy transition's success hinges on implementing supportive low-carbon policies and enhancing the efficiency of foreign direct investment in renewable projects. Creating an enabling environment that eliminates institutional barriers and attracts investment is crucial to driving renewable energy adoption (Olanrele and Fuinhas 2022; Rashed, Yong and Soon 2022).

As shown in the bottom panels of **Figure 19.4**, both the Technology-focused and the Behaviour-focused Scenarios forecast an increase in power generation by 2050. This growth is more significant in the Technology-focused Transformation Scenario, while the Behavior-focused Transformation Scenario emphasizes efficiency and demand measures. In both cases, this expansion aims to satisfy increasing demand, with non-biomass renewables becoming the main energy source. Although the Technology-focused Scenario shows much higher total generation compared to current trends, the Behavior-focused Transformation Scenario remains closer to today's levels.

In LICs, energy transition must go beyond electricity to meet overall energy needs. Resource limitations on demand-side measures can be addressed through innovative financing, which helps reduce the high initial costs of energy-efficient technologies (Wolske and Stern 2018). As rising incomes and poverty reduction are expected to drive higher per capita energy use, it is essential to implement strategies that balance economic growth with energy efficiency (DeAngelo et al. 2021).

Figure 19.5 compares the differences in final energy demand per capita between the two scenarios. The Behaviour-focused Scenario predicts a gradual decline in energy demand per person from 2020 to 2050, highlighting the importance of behavioural changes and energy efficiency in supporting economic development. Conversely, the Technology-focused Scenario indicates an increase in per capita energy demand, emphasizing that clean and efficient technologies will be crucial to meet this growing demand. Both scenarios show lower overall final demand per capita than the Current Trends Scenario. While high- and middle-income countries are projected to see a decrease in per capita energy demand over time, low-income countries show a more complex pattern: the Behaviour-focused Scenario forecasts declining demand, whereas the Technology-focused Scenario shows increasing demand to support development needs, though both remain significantly lower than those of countries in other income groups.

The energy transition in LICs has wider socioeconomic and environmental effects. It presents substantial opportunities to enhance air quality, with research indicating that renewable energy subsidies help decrease environmental degradation (Abdulwakil et al. 2022). Additionally, higher renewable energy use

has been shown to improve sustainable development outcomes in low-income countries (Tweneboah-Koduah, Arah, and Botchway 2023).

19.6 Transformation of food systems

The global food system faces systemic challenges that require a fundamental shift in how food is produced, consumed, and approached overall. Each region faces distinct problems: HICs deal with obesity, land abandonment, and meat-heavy diets; LICs face malnutrition, hunger, and stunted growth; and MICs encounter a combination of these challenges.

With global food demand expected to rise by 2050, implementing sustainable solutions like reducing meat consumption, supporting local food production, minimizing food waste, and adopting innovative agricultural methods is crucial (van Vuuren et al. 2017). However, changing food systems requires coordinated, long-term efforts spanning technical, economic, cultural, behavioural, and social dimensions. Additionally, disparities in income levels and lifestyles across countries require tailored regional strategies. This section explores the challenges and opportunities for food system transformations across various economic settings.

19.6.1 Sustainable food production and consumption for greater resilience in high-income countries

Despite having access to natural resources and advanced technologies, HICs face significant food-related issues, including land degradation, obesity, and resource-intensive diets (Pollard and Booth 2019). While high-income countries face a lower risk of food insecurity, individuals in these countries report a significant decline in subjective well-being when they do experience it (Frongillo et al. 2019). Additionally, their heavy dependence on food imports weakens resilience, increasing risks of supply disruptions and price fluctuations, as seen during the COVID-19 crisis. In response, HICs often adopt short-term food relief strategies that may not fully address nutritional needs or align with dietary preferences (Godrich et al. 2023).

Improving food system resilience is crucial for many high-income countries, especially given the high risks associated with global supply chain disruptions (Vicente et al. 2021). Regionalizing diets, supporting organic farming, and boosting food self-sufficiency can help shorten supply chains and strengthen resilience. The Metropolitan Foodshed and Self-sufficiency Scenario, or the "foodshed model", as applied to Vienna and Bristol, demonstrates high potential for self-sufficiency based on regional and sustainable production. However, its implementation requires diversifying regional crops, reducing food waste and shifting consumption patterns.

Organic farming plays a crucial role in sustainable food systems, benefiting human health, animal welfare, and ecosystem health by minimizing external inputs (Basnet et al. 2023). Yet, fully realizing the foodshed model and organic practices requires broader transformative strategies.

A major challenge for HICs is aligning stakeholders on essential changes in agrifood systems. Reaching agreement on environmental and social goals can promote agronomic innovation and sustainable development, whereas conflicting economic interests might obstruct progress. Wojtynia et al. (2021) highlight that agricultural sustainability studies should explore how current economic models prevent sustainable solutions. For example, a transdisciplinary approach helped Dutch dairy farmers successfully lower greenhouse gas emissions.

Röös et al. (2020) highlight that shifting from meat-heavy to plant-rich diets can help address environmental and health concerns. However, cutting back significantly on meat may lead to nutritional deficiencies, requiring an increased cultivation of locally grown grains and legumes to maintain a balanced diet.

Several HICs have launched national initiatives aimed at reducing food waste, including public awareness campaigns and improved food labelling. For instance, some supermarkets now provide storage tips for products to help consumers extend the shelf life of fruits and vegetables (World Resources Institute [WRI] 2019).

Promoting a bioeconomy requires well-designed policy frameworks that address key drivers, such as GDP growth, demographic shifts, trade dynamics, and land-use policies (Sturm and Banse 2021). On the supply side, boosting agricultural productivity and reducing post-harvest losses are vital, while on the demand side, changing consumer behaviour and preferences

are equally important. A balanced policy strategy also needs to support sustainable biomass use for energy and materials, reduce environmental impacts, and transform societal attitudes towards consumption. (Sturm and Banse 2021).

However, this transition also requires advancements in production technologies and carefully addressing broader environmental pressures, including water and land use. In this regard, modelling tools and scenario analysis can offer critical insights for policymakers (Sturm and Banse 2021) (**Box 19.4**). Through multi-regional input-output modelling, Mangir and Şahin (2022) help to understand the emission intensity of imported goods, highlighting the significance of a consumption-based perspective and connecting final demand to the production processes across global supply chains.

19.6.2 Food challenges and opportunities for middle-income countries

For MICs, the primary challenge lies in the dominance of economic paradigms, where environmental considerations are often given lower priority. Several major factors pose significant risks to food security in this context. These include rapid land-use changes, especially the conversion or degradation of farmland, intensive crop production without sufficient soil recovery, an ageing farming population, increasing climate variability, spatial and temporal mismatches between water and land resources and grain production, as well as spatial imbalances between population, land, and the grain system. (Liu and Zhou 2021).

These challenges are further exacerbated by the decreasing share of household spending on food, while the makeup of food consumption remains mostly steady, especially in urban areas. This trend is driven by increased spending on non-food items such as housing, transportation, water, and energy (Putra, Tong and Pribadi 2020). The unchanged structure of food consumption provides limited financial motivation, leading farmers to be hesitant about adopting diverse or innovative cropping methods (Putra, Tong and Pribadi 2020). As a result, this may lead to land abandonment, which also raises equity concerns, as many farmers lack access to basic amenities and a decent standard of living (Waha et al. 2022).

Globalization has led to a dietary shift in MICs, moving away from traditional fresh foods like rice, lentils, millets, and local staples toward processed and ultraprocessed foods. There is also a noticeable difference in how food security is understood. While national Food Security Indexes often measure food security using infrastructure-related indicators, institutional stakeholders usually define it based on the consistent availability and accessibility of food for consumers (Nurhasan et al. 2022).

Box 19.4: Modelling food and land system in Australia

Due to the complexity of the food system, exploring scenarios that capture the relationship between all variables and account for future uncertainties is challenging. Neglecting these uncertainties may lead to ineffective sustainability issues, e.g., wrong timing or scale of efforts. To better manage land use for both agriculture and livestock, a model of the Australian food and land system has been developed (Navarro-Garcia et al. 2023). The FABLE (Food, Agriculture, Biodiversity, Land-use, Energy) Calculator enables scenario-based analysis, allowing systematic examination of how different parameter ranges influence model outcomes and helping to design resilient pathways towards sustainability with a broad portfolio of solutions. Among these solutions, livestock productivity and density, afforestation, and dietary shifts are crucial for meeting sustainability goals. Investing in these areas could have wide-reaching knock-on effects, helping countries with extensive pasturelands improve their export performance and environmental outcomes. For instance, increasing livestock productivity (or reducing demand) means more land for biodiversity protection and vegetation recovery in Australia. A mix of institutional policies and market incentives can promote afforestation needed to meet food and land system objectives. This could involve enforcing effective land-clearing regulations to safeguard primary forests, support forest regrowth and stimulate demand for land-based emission offsets.

Credit: wirestock/Envato

Encouragingly, many of these countries possess valuable resources, such as human capital and economic capacity, that can facilitate investment in more sustainable technologies and practices (Rother et al. 2022).

Another potential solution worth considering is promoting the acceptance and cultivation of neglected and underutilized species, which can enhance agrobiodiversity and support food and nutrition security (Siddique and Cuong 2018). In this context, designating Globally Important Agricultural Heritage Systems (GIAHS) sites capable of supporting traditional farming and addressing problems such as land abandonment could be a crucial step (Siddique and Cuong 2018).

To improve food system policies, particularly in terms of institutional collaboration, a series of reforms is necessary. These include the horizontal and vertical integration of institutions, promoting citizen science, ensuring meaningful stakeholder participation, and implementing smart agriculture to support sustainable farming (Hoey et al. 2021; Ahsan et al. 2024).

Advanced technologies, widely used in plant genome editing and crop improvement, hold great promise for achieving food security and zero hunger (Ahmad et al. 2021).

Addressing equity issues in the food system requires broader systemic change. Governments should focus on enhancing rural living standards by supporting rural transitions and smart agriculture, aiming to make farming a more appealing and viable career option. Substantial efforts are also needed from institutional, social, and behavioural angles to change existing perceptions and reposition farming as a respected and dignified occupation (Ahsan et al. 2024).

To tackle the challenges associated with mass food production, it is essential to cultivate a new food production culture that more effectively addresses issues of equity and vulnerability. Although proposed solutions often include advanced technologies and changes in consumption habits, these alone are insufficient. A greater emphasis should be on enhancing equity and good governance within food

Credit: ThanhTN90/Envato

systems (Turner et al. 2020). Conducting thorough vulnerability assessments and using their findings to influence policy reform, backed by financial investments and actionable plans, can play a vital role in reducing rural poverty, transforming food systems, addressing inequalities, and supporting livelihood diversification (Woodhill et al. 2022).

Given the rising demand for livestock-based foods in low- and middle-income countries, it is critical to anticipate the associated environmental impacts and adopt both soft and hard mitigation strategies to support food security. A promising method is targeted investment in the livestock sector. Boosting livestock productivity through market-oriented investments can help these countries improve food and financial security while lowering their environmental impact (Nurhasan et al. 2022).

Institutional stakeholders have shown support for reverting to traditional diets and decreasing reliance on processed foods as a food security strategy. Many countries are promoting traditional staples like millets and sago (Nurhasan et al. 2022).

19.6.3 Enhancing food security in low-income countries

Malnutrition – both macronutrient and micronutrient deficiencies – and limited dietary diversity continue to be major challenges in LICs. These problems hinder growth and development (Li, Yadav, and Siddique 2020; Picchioni, Goulao, and Roberfroid 2022). Recent data shows that food security challenges have led to a 19.5 per cent rise in malnutrition in Sub-Saharan Africa and a 14.6 per cent increase in Southern Asia (Cho 2022; FAO 2021).

Food insecurity in these areas is frequently connected to poor environmental conditions that impact agriculture, along with insufficient infrastructure (Pawlak and Kołodziejczak 2020). These infrastructure gaps lead to increased food waste and limit the adoption of smart farming techniques due to a lack of technical skills and trained workers. In many LICs, agriculture constitutes a high share of gross domestic product (GDP), which exacerbates economic instability. Furthermore, agricultural systems in these contexts are especially vulnerable to the effects of climate

change. The lack of government support, ongoing dependence on traditional farming methods, and limited access to modern agricultural technologies weaken the ability to adapt, reduce impact, and build resilience against the pressures of population growth and climate change (Ceesay and Ndiaye 2022).

Population density significantly influences food security, as higher population concentrations increase the demand for land, water, and fertilizers to sustain food production (Agyemang, Kwofie and Fabrice 2022; Miladinov 2023). Although some low-income countries with lower population densities have abundant natural resources, they often struggle to achieve sustainable food production due to limitations in technical expertise, institutional capacity, and access to modern agricultural methods. Addressing food security in rural areas, especially in terms of availability and access, involves improving agricultural infrastructure and increasing household purchasing power (Wudil et al. 2022). Mekonnen et al. (2021) highlight the need for policymakers to carefully balance dietary guidelines with economic realities. For instance, promoting dairy over more affordable, locally available foods like vegetables, starchy staples, and fruits can be financially unsustainable for low-income families. At the same time, encouraging the intake of affordable, protein-rich foods should be prioritized over catering to household taste preferences to ensure sustainable food system management.

Households with limited financial means and insufficient knowledge of dietary and crop diversity are especially prone to food insecurity. Therefore, promoting access to decent work and launching basic education programmes to enhance food and nutrition literacy are essential components of public health strategies targeting the reduction of household food insecurity and malnutrition in low-income settings (Militao et al. 2023).

In low-lying delta regions like Bangladesh, water salinity and frequent flooding pose increasing threats to food security. In such areas, shifting emphasis from traditional farming, both crop cultivation and aquaculture, to livestock farming (such as cattle, sheep, and poultry) offers a promising strategy for developing climate-resilient livelihoods (Verhagen et al. 2022). This change may not only boosts adaptive capacity but also can improve nutrition by increasing access to protein-rich foods. While enhancing crop yields remains important, there's ongoing debate about whether it's sustainable to keep maximizing harvests with high-yield crop varieties, especially in areas that might have already reached their biophysical or ecological limits. Nevertheless, Popp et al. (2017) note that many decision makers in low-income regions still see potential to close current and future yield gaps by adopting advanced scientific agricultural methods, which could significantly increase crop production. Complementary approaches like capacity building for local agricultural officers and transferring suitable technologies from high-income countries are effective strategies to close yield gaps and support more sustainable agricultural growth.

The future challenges and opportunities for food system transition or food security are be reflected in land-use changes, serving as an indicator. The implications of these land-use changes on land availability across three income groups are depicted in Figures 19.6 and 19.7. Two transformation scenarios – a Technology-focused and a Behaviour-focused – are used to model future trends. The projections estimate and compare land cover changes from 2020 to 2050, focusing on shifts in intensive land uses, such as cropland and pasture, and extensive land uses, including forests and other natural lands, across both scenarios.

Figure 19.6 illustrates that high-income countries experience a slight decrease in pasture, compensated by gains in cropland and modest improvements in forest and natural land under the Technology-focused Scenario. In contrast, the Behaviour-focused Scenario shows a notable shift, with a substantial replacement of pasture by forest and natural land. Middle-income countries see an expansion of cropland, forest, and natural land at the expense of pasture in both scenarios. Low-income countries, however, experience a significant reduction in cropland in favour of forest and natural land in the Technology-focused Scenario, and a reduction in both cropland and pasture in the Behaviour-focused Scenario.

Figure 19.7 shows that high-income countries have twice the land per person compared to middle-income countries and three times that of low-income countries. However, in all future scenarios, as the population in HICs grows, rising from 955 million in 2020 to 1,080 million in 2050, the amount of land available per person is expected to shrink. In the technology-

Figure 19.6: Changes in land cover for intensive land use (cropland and pasture) vs extensive land use (forest and other natural lands) comparing the current trends to the behaviour-focused and technology-focused transformation pathways from 2020 to 2050

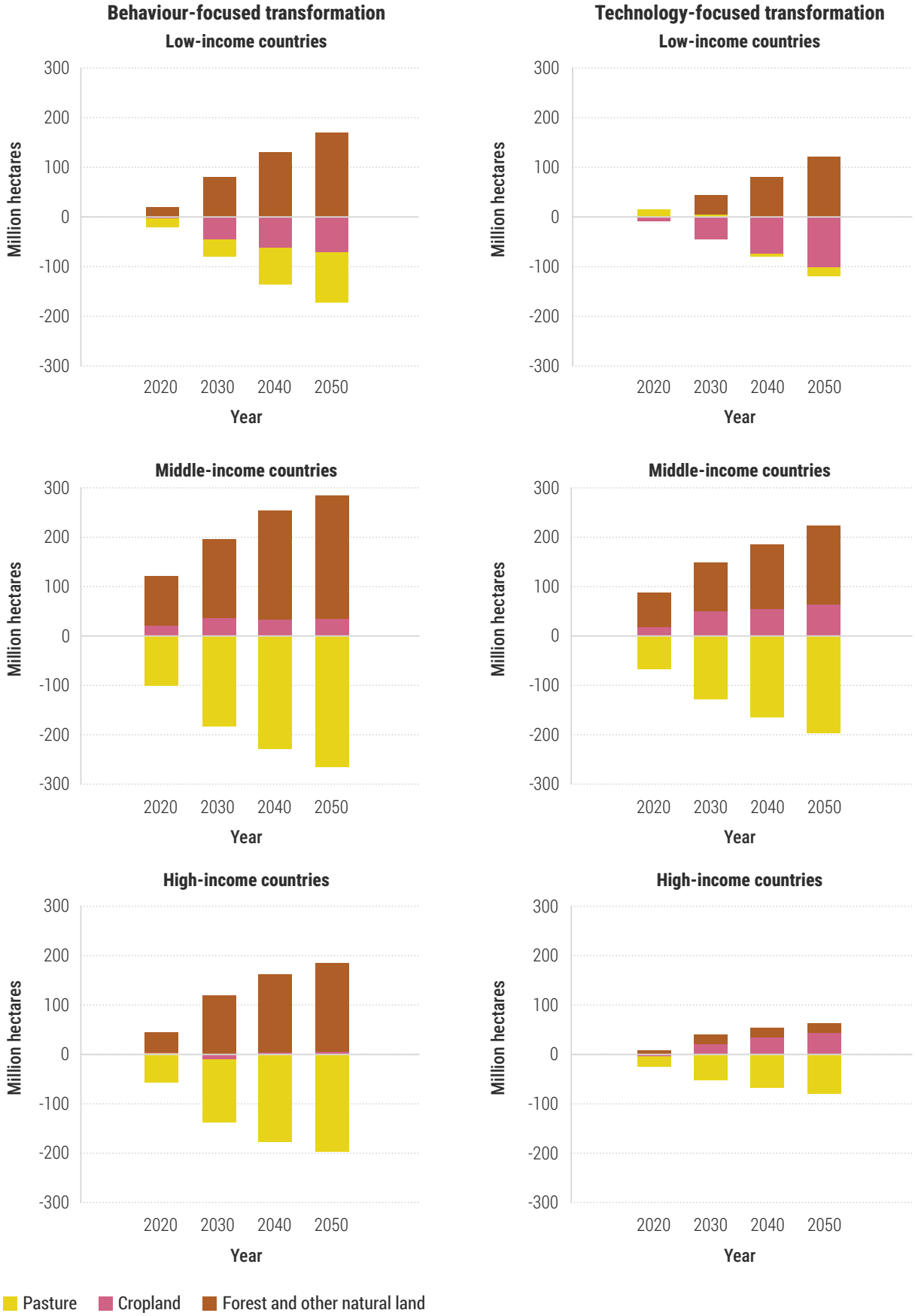


Figure 19.7: Land availability of cropland, pasture, and forest and other natural lands for the current trends, technology-focused and behavioural-focused scenarios from 2020 to 2050

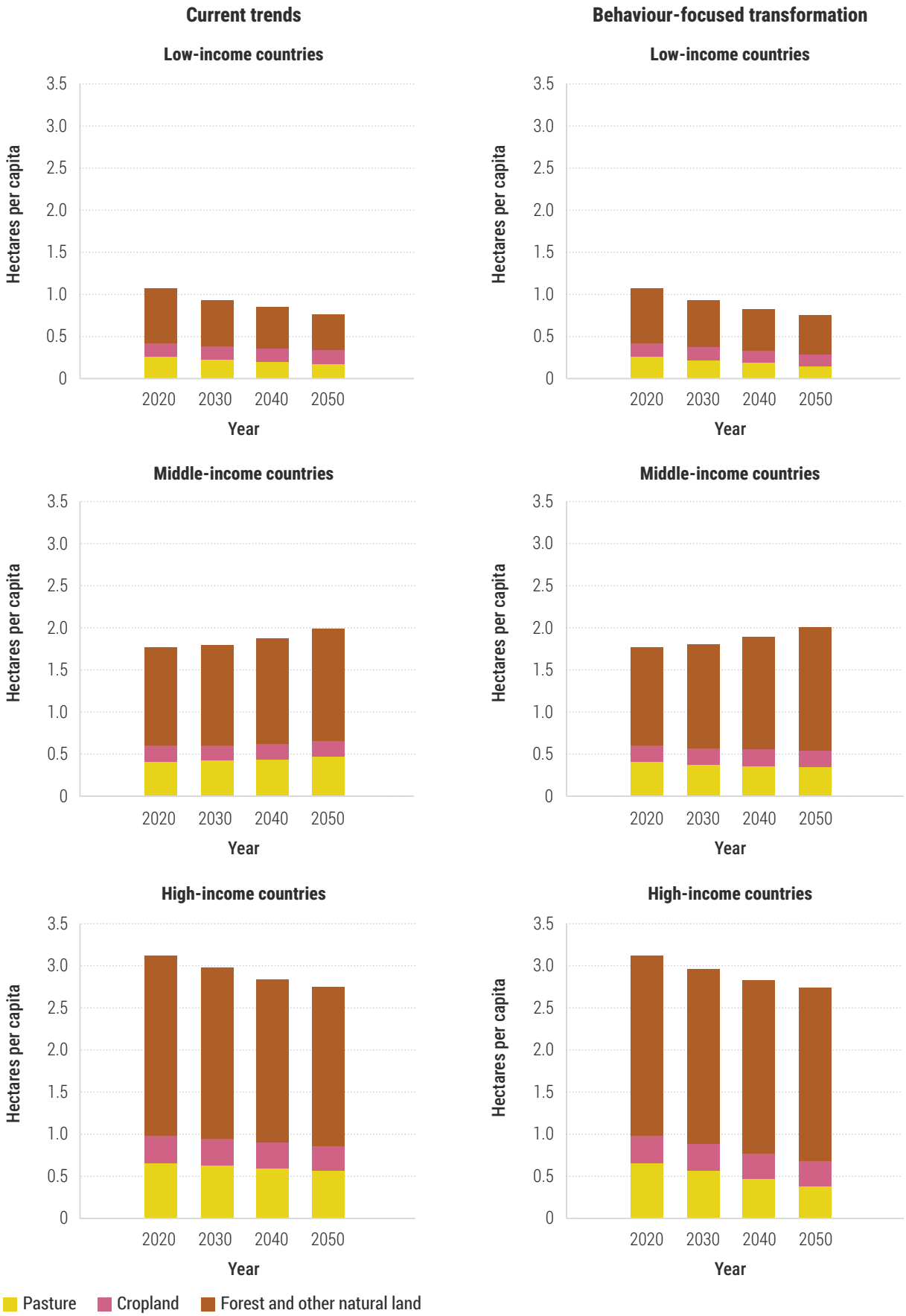
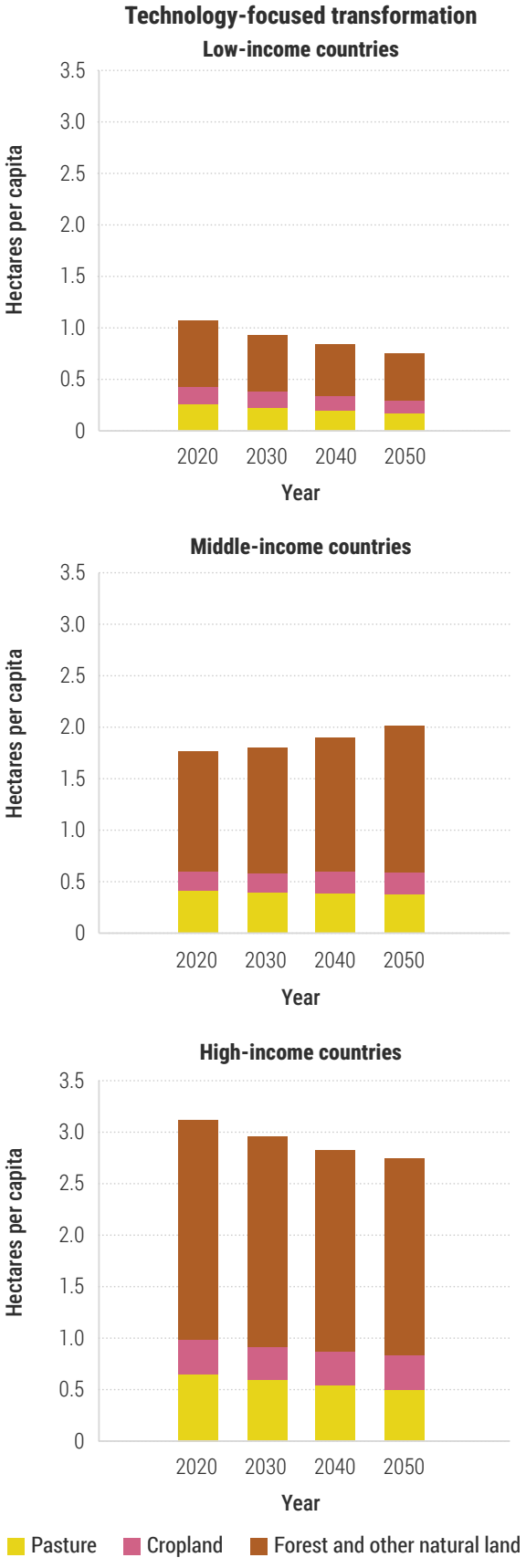


Figure 19.7: Land availability of cropland, pasture, and forest and other natural lands for the current trends, technology-focused and behavioural-focused scenarios from 2020 to 2050



focused scenario, cropland per person increases from 0.3 ha in 2020 to 0.34 ha in 2050. Meanwhile, the development scenario focused on behaviour change is projected to preserve the most forest and natural land, at 2.06 ha per person.

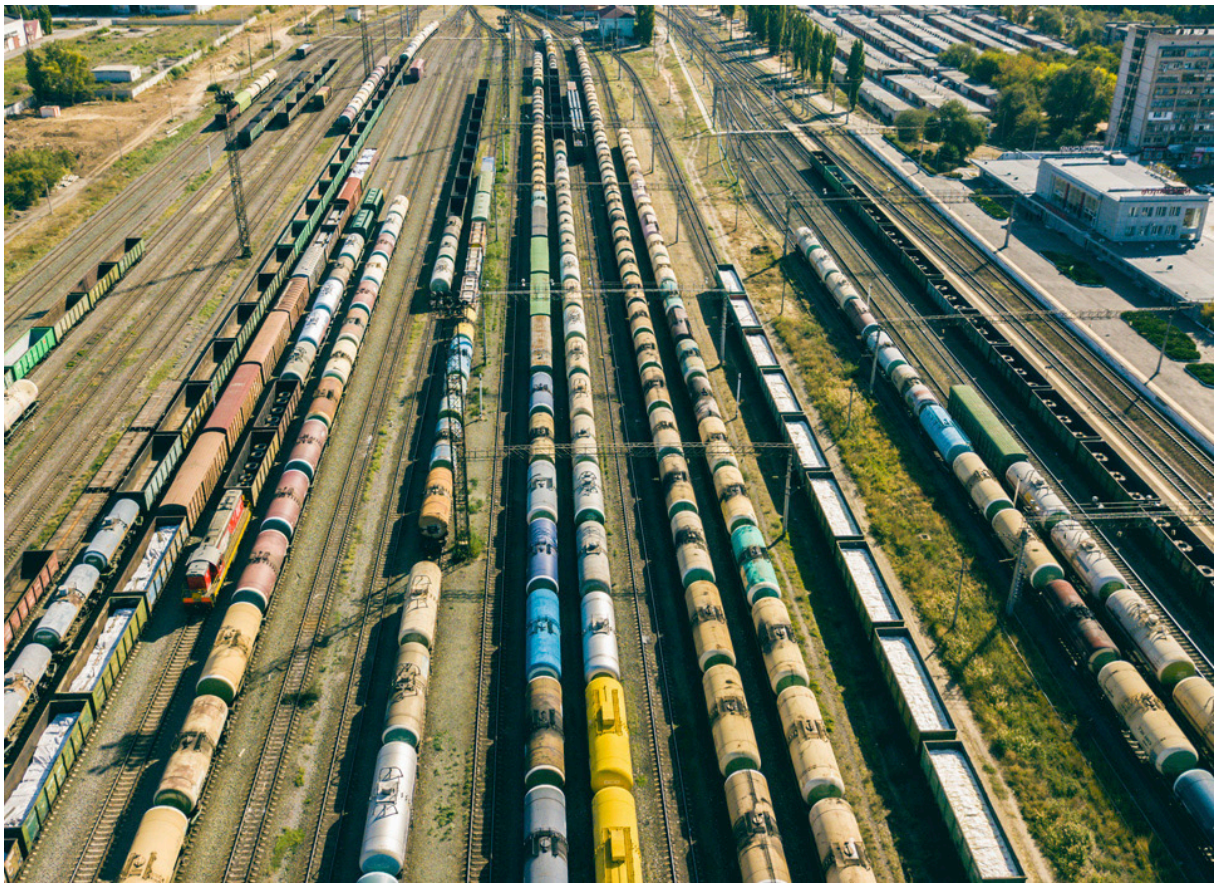
From 2020 to 2050, middle-income countries are expected to have 0.19 ha of land per person in the reference scenario. This increases slightly to 0.22 ha in the Technology-focused scenario. In the Behaviour-focused Scenario, pasture land becomes more limited, but there is more forest and natural land.

According to the projections of the reference scenario in low-income countries, the amount of land per capita is expected to be 0.16 ha but drops to 0.13 ha in the Technology-focused Scenario and to 0.14 ha in the Behaviour-focused Scenario. In countries of this income group, people have similar amounts of cropland and pasture land, but pasture is lowest in the Behaviour-focused Scenario, which preserves the highest amount of forest and natural land, at 0.47 hectares per capita. These patterns are shaped by a significant population growth, from 3.1 billion to 4.4 billion people.

The extremely high land pressure in low-income countries likely affects food security and biodiversity loss. While growth in absolute forest and natural land across the three economic groups in both transformation scenarios, compared to the reference scenario, may help prevent biodiversity loss, it also reduces food production, export potential, and overall food security.

19.7 Transformation of environmental Systems

Humanity has breached six of the nine planetary boundaries crucial for maintaining a safe and equitable operating space (Richardson et al. 2023; Ross 2020), and is considerably behind in meeting the SDGs by 2030. To stay within planetary boundaries and achieve the SDGs, a holistic transition that reduces greenhouse gas emissions, limits pollution, and prevents biodiversity loss is necessary. Environmental challenges and opportunities vary across countries, shaped by demographics, economic conditions, gender, and vulnerabilities to climate change. Achieving sustainability requires tailored strategies that address these differences.



Credit: MikeShots/Envato

19.7.1 High-income countries' environmental responsibilities extend beyond their own borders

Environmental challenges in HICs are well-documented, including issues like excessive consumption and waste (Wiedmann et al. 2020; Garcia et al. 2021; Hickel et al. 2022), biodiversity loss driven by urbanization (McDonald et al. 2019) and industrial agriculture (Tilman et al. 2017; Hallmann et al. 2017), as well as pollution from outdated water treatmentfacilities (Khan et al. 2021; Wear et al. 2021), among other concerns.

A more concealed challenge for HICs is emissions outsourcing, mainly to lower-income countries. Emissions outsourcing here refers to the transfer of emissions (e.g., greenhouse gases, $PM_{2.5}$, SO_2) by shifting polluting industries to nations with weaker emission rules (Abbasi and Bouman 2020). Generally, HICs tend to have stricter regulations on GHGs and pollution compared to middle- and low-income countries (OECD 2016). Emissions outsourcing is a business decision to avoid regulatory compliance costs, often as an unintended result of national emission laws. High income countries then importing goods containing "embodied emissions" (Choi and Yu 2018; Ambrose et al. 2023), which are emissions produced in the upstream supply chain before import (Baker 2017; Wang et al. 2024). This practice can retain their consumption patterns and create a misleading sense of environmental progress in HICs while potentially increasing emissions overall (Baumert et al. 2019; Dar et al. 2022).

Globalized supply chains and the shift of extractive industries to middle- and lower-income countries also have other environmental impacts. For example, food imports to HICs lead to deforestation and biodiversity loss abroad (Searchinger et al. 2022; Wiebe and Wilcove 2025). Similarly, importing cobalt can lead to toxic run-off in producing regions (Calvão, McDonald and Bolay 2021), while exporting wastes and recycling to countries with limited treatment capacity shifts the pollution burden (Cotta 2020). See also **Box 19.5**.

Regarding GHGs, emissions outsourcing can be promoted through the production-based emissions accounting required by the Paris Agreement (Dar et al. 2022). This framework enables outsourcing nations

Box 19.5: European Green Deal initiatives for environmentally responsible sourcing

The EU is implementing responsible sourcing policies across key trade sectors as part of the European Green Deal. In October 2023, the EU introduced the Carbon Border Adjustment Mechanism (CBAM). This policy imposes carbon emission tariffs on various industrial imports. The goal is to prevent EU producers from relocating polluting activities to countries with weaker environmental standards (Bellora and Fontagné 2023). The CBAM fee is based on the difference between the EU Emission Trading System's carbon price and the price that the exporting country charges for emissions (Clausing et al. 2024). This phased-in programme will begin in 2026 (European Commission 2023). Carbon tariffs are expected to generate positive spillover effects by encouraging exporting countries to implement their own carbon pricing, thereby motivating industries to reduce emissions (Clausing et al. 2024).

The European Union Deforestation Regulation (EUDR) will impose due diligence rules on traders to guarantee deforestation-free sourcing of palm oil, cocoa, coffee, soy, rubber, cattle, timber, and related products (European Commission 2024). It is set to come into force in December 2025 (European Commission 2024).

Credit: chuyu2014/Envato

to lower their officially acknowledged carbon emissions without decreasing their consumption of products that contain embodied emissions. Carbon carbon tariffs have been suggested to address carbon emissions outsourcing (Larch and Wanner 2017; Kopp, Pizer and Rennert 2023), though none are currently fully implemented.

To soften the economic impacts of carbon tariffs on lower income countries, revenues generated from CBAM can be used to support exporting nations in acquiring the technology needed to fulfil CBAM standards (Do 2025). In the case of the EUDR, the EU is forming partnerships with exporting countries to facilitate technology transfer to prevent deforestation (European Commission 2024) (**Box 19.5**). This approach aligns both CBAM and EUDR with the Technology-focused Transformation Scenario outlined in Chapter 11.

From the Behaviour-focused Transformation Scenario of Chapter 11, eco-certification, such as

the Rainforest Alliance, provides information to assist environmentally responsible consumers in HICs in choosing sustainably produced imported products (Pinto et al. 2014). Additionally, digital carbon tracking apps can help consumers steer clear of imported goods with a high carbon footprint (Hoffmann et al. 2024).

Figure 19.8 illustrates simulated per capita GHG emissions and biodiversity loss trends from 2020 to 2050 in HICs. Although the policies mentioned earlier are not explicitly included in the scenarios, each can be seen as supporting different transformation scenarios.

In terms of per capita GHG emissions, the Behaviour-focused Scenario proves more effective than the Technology-focused one, mainly due to the assumption of strong consumer demand for more climate-conscious products.

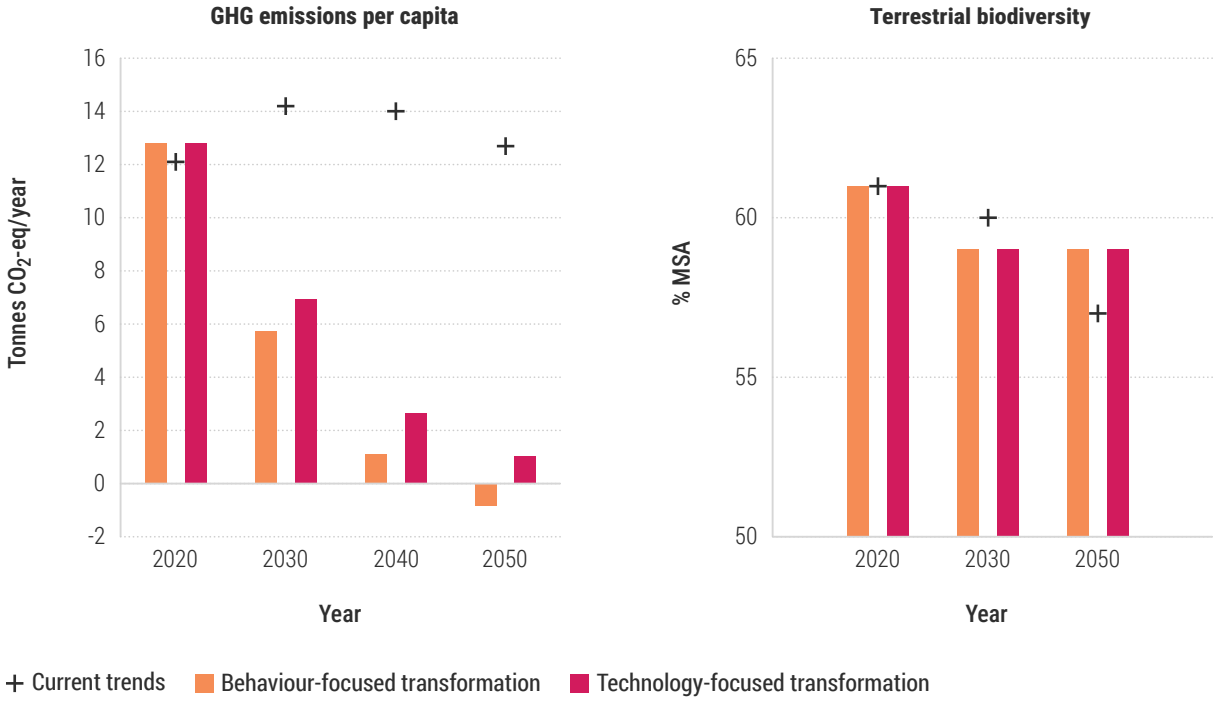
For biodiversity, both transformation scenarios offer similar benefits. Although biodiversity declines across all three scenarios, by 2050, the decline is less pronounced for the two transformation scenarios.

19.7.2 Re-setting priorities in industrializing middle-income countries

MICs face the challenge of balancing the urgent need to raise living standards with the need to ensure environmental sustainability. Governments in MICs prioritize improving living conditions through industrialization, often placing environmental quality lower on the agenda. Van Rooij and McAllister (2012) note that environmental regulation is more challenging in MICs than in HICs or LICs: "As national economies industrialize, economic interests greatly overwhelm environmental interests, undermining various forms of legal, political, and social action against polluting firms. A combination of weak enforcement and pervasive noncompliance tend to create a vicious circle that works against pollution mitigation and control."

In the initial stages, industrial development advances society by increasing incomes, employment, and delivering related benefits. However, under favourable policies and unconstrained by regulation, industry can expand quickly, leading to higher air pollution and

Figure 19.8: Simulated per capita GHG emissions and terrestrial biodiversity in percentage Mean Species Abundance (MSA) in high-income countries under current trends and behavioural-focused and technology-focused transformation pathways



Note: Model output data was not available for biodiversity for the year 2040 and for clear comparison across the years, the values of the vertical axis in the terrestrial biodiversity graph start at 50% MSA

greenhouse gas emissions (Van Rooij and McAlister 2012). The World Bank highlights that air pollution is especially widespread in developing countries undergoing industrialization (Rentschler and Leonova 2023). Notably, $PM_{2.5}$ is a leading cause of respiratory diseases and mortality. $PM_{2.5}$ has been associated not only with asthma and other respiratory diseases but also with circulatory problems and cognitive decline, which can significantly reduce productivity and, ultimately, reduce economic well-being (Aguilar-Gomez et al. 2022). Low-income, marginalized populations, and the elderly face disproportionate exposure to air pollution and are more vulnerable to respiratory illnesses (Canaday, Georas and Croft 2024). These health effects can create a feedback loop that compromises the social benefits gained from industrialization. Often, there is a delay in recognizing the impact of pollution, allowing pollution levels to rise before governments respond (Fuller et al. 2022).

Possible strategies include providing incentives for the adoption of clean technologies and fuels, eliminating fossil fuel subsidies, and offering affordable healthcare in industrial regions, as the poorest communities suffer from pollution the most. (Rentschler and Leonova 2023). Additionally, Rentschner and Leonova (2023) suggest incorporating environmental and health externalities into planning processes to protect vulnerable populations. Fuller et al. (2022) advocate for a swift, large-scale shift to renewable energy, which would decrease ambient pollution and help mitigate climate change. Van Rooij and McAllister (2012) highlight the importance of effective regulation in MICs. They argue that regulatory agencies must work together with citizens affected by industrial pollution to encourage industry compliance with regulations. Fuller et al. (2022) emphasize the importance of monitoring pollutants and public concern regarding pollution and health, stating that "the public demand for more effective action against pollution by governments can be powerfully catalytic." See **Box 19.6**.

Figure 19.9 shows simulated trends in per capita greenhouse gas emissions and biodiversity for MICs. The differences between the Behaviour-focused and Technology-focused Transformation Scenarios are minimal for both indicators. Under the current scenario, per capita GHG emissions in MICs are projected to steadily increase through 2050, whereas **Figure 19.8** shows that in HICs emissions initially rise and then decline - a trend consistent with the earlier discussion about emissions outsourcing. Despite the upward trajectory under the current scenario, both transformation scenarios in MICs offer a huge potential for reducing GHG emissions.

19.7.3 Systemic threats to the environment in low-income countries

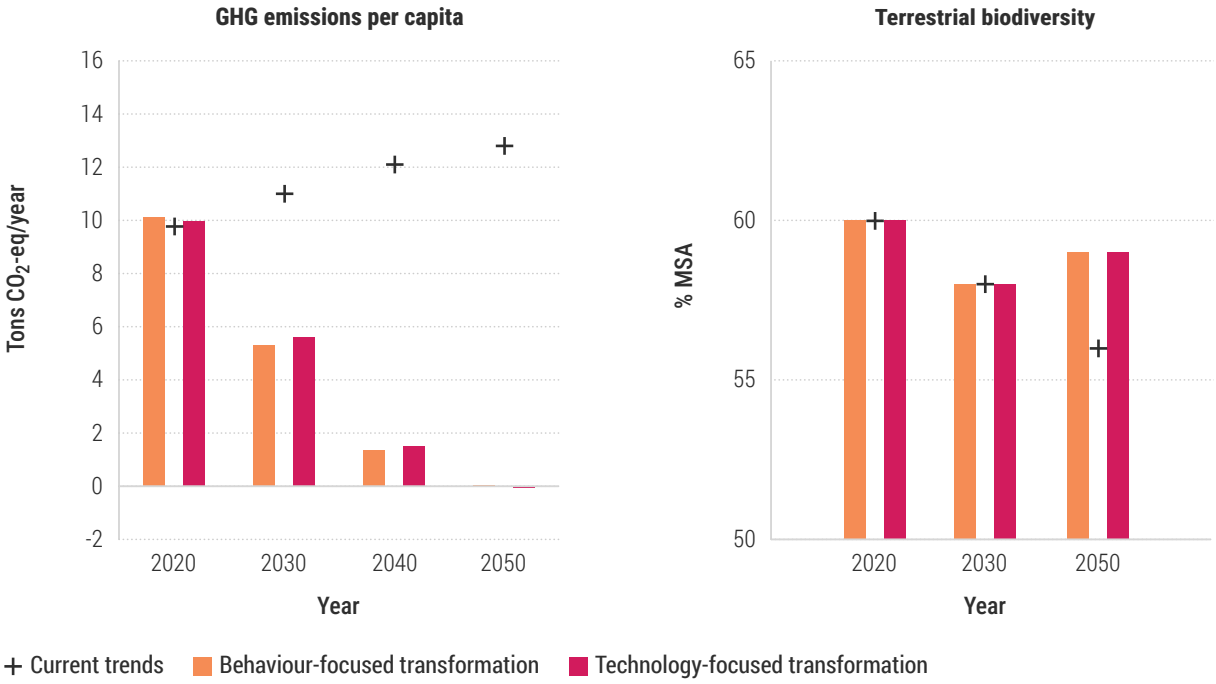
Countries with low incomes often heavily rely on their natural resources to meet their basic needs, which can create vicious cycles of resource decline and poverty (Ngonghala et al. 2014). Unsustainable agriculture practices are considered one of the most serious environmental threats in LICs (Sarkodie and Owusu 2022). As populations grow, the need for food and livelihoods drive agricultural expansion, placing pressure on forests, habitats, and biodiversity, and may result in human-wildlife conflicts (Gross et al. 2021). Intensive land use is often a response to limited arable land availability, which itself is the result of population pressure and land degradation from unsustainable land management (Sarkodie and Owusu 2022).

To mitigate ecological harm caused by agricultural expansion and unsustainable practices, the FAO promotes agroecology. It defines this approach as "the science of applying ecological concepts and principles to manage interactions between plants, animals, humans, and the environment for food security and nutrition" (FAO 2019). Agroecology reduces reliance on synthetic chemicals and relies on ecological science and Indigenous Knowledge (Utter et al. 2021; Ntamwira et al. 2023). The importance of semi-natural habitats, such as forests, for pollination and other ecosystem services in agricultural systems is also acknowledged (Ulyshen

Box 19.6: Social media voices influence on air quality improvement in China

Wang and Jia (2021) conducted a study social media can exert bottom-up pressure on air quality governance in China. Analysing data from Weibo, researchers observed that a 10 per cent increase in environmnet-related posts was associated with a 2.7 per cent reduction in $PM_{2.5}$ levels.This suggests that growing public attention online could play a role in shaping government action on air quality.

Figure 19.9: Simulated per capita GHG emissions and terrestrial biodiversity in percentage Mean Species Abundance (MSA) in middle-income countries under current trends and behavioural-focused and technology-focused transformations



Note: Model output data was not available for biodiversity for the year 2040 and for clear comparison across the years, the values of the vertical axis in the terrestrial biodiversity graph start at 50% MSA.

et al. 2023). Promoting biodiversity is essential for natural pest control and pollination.

Agroecology focuses on building and maintaining soil organic matter, which can help mitigate climate change by turning agriculture from a source of carbon emissions into a carbon sink (Leippert et al. 2020). Along with similar strategies like agroforestry, agroecology also enhances resilience to climate change by improving soil stability and moisture retention (Dittmer et al. 2023). Nonetheless, there are risks involved. It takes time to improve soils, and yields may temporarily decline after adopting these practices, which could hinder efforts to scale agroecology (Morais et al. 2021). Successfully scaling agroecology will depend on capacity building and policies that promote adoption. These might include tax incentives, subsidy programmes, certification schemes, and price premiums (Miles, DeLonge and Carlisle 2017).

As populations and agriculture expand, human-wildlife conflicts in LICs are rising, mainly affecting smallholder farmers and pastoralists (World Bank 2023b). These conflicts worsen due to increasing resource scarcity driven by climate change (Abrahms 2021). The World Bank encourages governments to establish a shared vision among stakeholders for coexistence with wildlife (World Bank 2023b). Effective policies include installing physical barriers, compensating for wildlife-related damages, and providing employment in wildlife tourism, among other measures (Gross et al. 2021) (**Box 19.7**).

LICs suffer the most from climate change impacts, despite HICs being the primary contributors to global GHG emissions (United Nations Environment Programme [UNEP] 2023a). Effects include more frequent and more severe droughts and flooding (IPCC 2021). The 2023 UNEP Emission Gap Report estimates that LICs need 10 to 18 times more funding for climate adaptation than is currently available (UNEP 2023). It emphasizes the need for increased international, domestic, and private sector financing, along with improved international cooperation and reform of the global financial system (UNEP 2023). Adaptation investments must be tailored to local circumstances.

There is also a need to develop local capacities for managing natural resources in climate adaptation

Box 19.7: Human-wildlife coexistence, Chitwan National Park, Nepal

At Chitwan National Park in Nepal, integrated buffer zone management has led to a 75 per cent decrease in livestock predation by tigers over the last decade, despite a 143 per cent increase in the tiger population from 38 in 2000 to 92 in 2018. The Nepali Government requires that 30 per cent of all park entry fees benefit nearby villages in buffer zones, supporting community development to sustain forest resources and improve human-wildlife coexistence. Additionally, a fund has been established to compensate villagers for wildlife-related losses involving species such as rhinoceroses, elephants, tigers, leopards, and bears (Gross et al. 2021).

efforts (Williams et al. 2020). Beyond securing financing, this involves integrating climate change adaptation into national policies and strengthening institutional frameworks (IPCC 2014). Nature-based solutions should take priority; examples such as wetland and mangrove restoration, along with watershed reforestation, offer cost-effective, multi-faceted benefits. These include enhancing resilience against climate change-triggered storms and floods, while also supporting biodiversity and improving water quality (World Bank 2022).

Figure 19.10 shows that the LICs' per capita GHG emissions are much lower than those of the HICs (**Figure 19.8**) and the MICs (**Figure 19.9**). The current trend is projected to steadily increase; however, the transformation scenarios have the potential to significantly reduce GHGs by 2050. Both scenarios also decrease biodiversity loss. However, biodiversity in 2050 remains lower than in 2020 under both transformation scenarios, despite an increase in forest cover shown in **Figure 19.6.** This aligns with the observation that biodiversity recovery can require lengthy time delays, spanning decades or centuries (Ackleh *et* al. 2018, Rozendaal *et* al. 2019). Assisted Natural Regeneration (ANR) (Shono et al. 2020) and species reintroduction (Seddon et al. 2014) may help overcome these challenges to biodiversity recovery.

Figure 19.10: Simulated per capita GHG emissions and terrestrial biodiversity in percentage Mean Species Abundance (MSA) in low-income countries under current trends and behavioural-focused and technology-focused transformations

Note: Model output data was not available for biodiversity for the year 2040 and for clear comparison across the years, the values of the vertical axis in the terrestrial biodiversity graph start at 50% MSA.

19.8 Implications for the three economic groups

This chapter discussed managing transitions across five system dimensions for countries in different income/economic groups. **Table 19.1** below summarizes the opportunities worth considering.

19.9 Summary and conclusions

Countries at different levels of economic development – HICs, MICs, and LICs – face distinct challenges and opportunities in their path to sustainability. Tailored strategies are necessary for each group to achieve its environmental,

Table 19.1: Summary of opportunities for different economic groups by system

System	Low-income	Middle-income	High-income
Economic system	Seek green finance, to accelerate development goals. Strengthen capacity in sustainable finance.	Reorient public funds and provide incentives for the private sector to value the environment and avoid environmental risks. Invest in resilient infrastructure for long-term economic returns.	Align multilevel and multilateral governance, macroeconomic and fiscal policy with sustainable financing. Explore "post-growth" and "degrowth" economic models.
Towards circularity	Promote and engage the informal sector in resource recovery.	Invest in resource-efficient buildings and infrastructure.	Leverage technology for resource management and waste minimization.
	Ensure effective waste management and resource recovery.		
		Transition to resource-efficient production and consumption. Develop a workforce equipped for green technologies.	
Energy system	Expand access to clean and affordable energy. Develop decentralized and off-grid energy solutions. Leverage climate financing and investment.	Scale up clean energy technologies. Improve grid infrastructure and reliability. Promote energy-efficient urbanization and industrial development.	Accelerate decarbonization of existing systems. Enhance energy efficiency and demand management. Electrify transport and heating.
	Plan for coal phase out and reform fossil fuel subsidy. Develop and promote renewable energy and storage.		
Food system	Invest in agricultural infrastructure. Promote affordable, healthy diets in poor, rural areas.	Make farming an attractive career choice. Invest in livestock productivity. Promote cultivation of neglected and underutilized species. Encourage a return to traditional diets.	Enhance food security and food system resilience through higher self-sufficiency and shorter supply chains. Promote plant-based diet.
	Promote agroecology to improve soil health and yields.	Reduce food waste through education, public awareness, financial incentives, supply chain technologies, smart product labelling, on-farm solutions.	
Environmental systems	Develop mutually beneficial coexistence with wildlife. Build local capacity for climate adaptation. Support community-led conservation programmes and nature-based solutions.	Incorporate environmental and health externalities in planning decisions. Monitor and enforce pollution control and reduction measures.	Impose carbon tariffs on imports. Use eco-certification to guide consumer behaviour.
All systems	Support international action and cooperation in science, technology and innovation, and capacity building.		

Credit: seventyfourimages/Envato

social, and economic objectives. The key themes examined in this chapter include economic growth, circular economy, energy, food, and environmental systems across these economic groups, highlighting diverse solution portfolios for each.

HICs aim to decrease their environmental impact by implementing green technologies, supporting sustainable finance, and shifting to circular economy practices. These countries face challenges including high material use, large amounts of waste, reliance on imports, and outsourced carbon emissions. To lead global sustainability efforts, HICs needs policies that enhance resource efficiency, promote low-carbon innovations, and drive behavioural change.

Countries with middle incomes are experiencing rapid urbanization and economic growth. However, they face challenges in balancing development with sustainability. To transition effectively, it is crucial for these countries to invest in renewable energy, upgrade infrastructure, and promote circular economy practices. Additionally, overcoming dependencies on fossil fuels and creating resilient urban environments are essential steps in this process.

LICs encounter significant financial challenges and are particularly vulnerable to environmental degradation and climate change. International support, including targeted financing and technology transfer, plays an important role in their development. Key strategies for sustainable progress include enhancing governance, integrating the informal economy, and investing in climate-resilient infrastructure.

In terms of energy systems, HICs can lead by advancing electrification and expanding renewable energy, MICs can benefit from reducing reliance on coal, and LICs can explore the opportunity to leapfrog to renewable solutions suited to their infrastructure limitations, like off-grid and decentralized systems.

Food systems face unique challenges: HICs need to address overconsumption, MICs must balance food security and environmental impacts, and LICs must tackle undernutrition. Transforming these systems requires changing dietary habits, minimizing waste, and investing in sustainable agricultural practices and technologies.

Environmental systems emphasize the need to align global efforts with local contexts. HICs must address the outsourcing of environmental impacts, MICs face pollution issues from industrialization, and LICs require nature-based solutions for climate adaptation.

The chapter concludes that both the Behaviour-focused and Technology-focused Transformation Scenarios offer valuable guidance for advancing sustainability. Meaningful progress depends on cooperation, multilevel governance, and global solidarity. Realizing these transformations requires institutional reforms, innovative policies, and public engagement to ensure a balanced integration of environmental, economic, and social aspects within each country's development path.

Appendix 19.1: Country Data

Table 19.2 Data was utilized to formulate the country groupings.

Countries are divided into three main groups based on income level. These classifications follow the traditional income categories of the World Bank, which are determined using GNI per capita for 2022 (World Bank 2023a). In this analysis, low-income includes the traditional low to lower-middle category ($4,465 or less), the middle class covers those earning from US$4,466 to US$13,845 (upper-middle-income countries), and the high-income group remains the traditional high-income category ($13,845 or more). Population density is defined as the number of people per km² of land area. Data on population density was obtained from the Our World in Data 2022 data set (Ritchie et al. 2023). Countries are classified as either having high or low population density, based on the median value across all countries included in the analysis (median = 8.55/km², n=197 countries). Additional data on the country's physical trade balance and status is included to inform the chapter analysis. 197 countries are included in the data set in accordance with the UN Statistics Division Standard Country or Area Codes for Statistical Use, also known as the M49 Standard.

Code	Country or area	Region	Income group	Population density	Population density class	Trade Status
AND	Andorra	Western European and Other Groups	High	169.88	High density	Importer
ARE	United Arab Emirates (the)	Asia and the Pacific	High	132.94	High density	Exporter
ATG	Antigua and Barbuda	Latin America and the Caribbean	High	213.12	High density	Importer
AUS	Australia	Western European and Other Groups	High	3.40	Low density	Exporter
AUT	Austria	Western European and Other Groups	High	108.33	High density	Importer
BEL	Belgium	Western European and Other Groups	High	384.94	High density	Importer
BHR	Bahrain	Asia and the Pacific	High	1875.46	High density	Importer
BHS	Bahamas (the)	Latin America and the Caribbean	High	40.96	Low density	Importer
BRB	Barbados	Latin America and the Caribbean	High	654.99	High density	Importer
BRN	Brunei Darussalam	Asia and the Pacific	High	85.20	Low density	Exporter
CAN	Canada	Western European and Other Groups	High	4.29	Low density	Exporter
CHE	Switzerland	Western European and Other Groups	High	221.19	High density	Importer
CHL	Chile	Latin America and the Caribbean	High	26.37	Low density	Importer
CYP	Cyprus	Asia and the Pacific	High	135.44	High density	Importer

Code	Country or area	Region	Income group	Population density	Population density class	Trade Status
CZE	Czechia	Eastern Europe	High	135.94	High density	Importer
DEU	Germany	Western European and Other Groups	High	238.62	High density	Importer
DNK	Denmark	Western European and Other Groups	High	147.06	High density	Importer
ESP	Spain	Western European and Other Groups	High	95.20	High density	Importer
EST	Estonia	Eastern Europe	High	31.02	Low density	Exporter
FIN	Finland	Western European and Other Groups	High	18.23	Low density	Exporter
FRA	France	Western European and Other Groups	High	118.03	High density	Importer
GBR	United Kingdom of Great Britain and Northern Ireland	Western European and Other Groups	High	279.04	High density	Importer
GRC	Greece	Western European and Other Groups	High	80.57	Low density	Importer
GRL	Greenland (Denmark)	Western European and Other Groups	High	0.14	Low density	Importer
GUY	Guyana	Latin America and the Caribbean	High	4.11	Low density	Exporter
HRV	Croatia	Eastern Europe	High	72.02	Low density	Importer
HUN	Hungary	Eastern Europe	High	109.22	High density	Importer
IRL	Ireland	Western European and Other Groups	High	72.91	Low density	Importer
ISL	Iceland	Western European and Other Groups	High	3.70	Low density	Importer
ISR	Israel	Western European and Other Groups	High	417.67	High density	Importer
ITA	Italy	Western European and Other Groups	High	199.64	High density	Importer
JPN	Japan	Asia and the Pacific	High	340.06	High density	Importer
KNA	Saint Kitts and Nevis	Latin America and the Caribbean	High	183.39	High density	Importer
KOR	Republic of Korea (the)	Asia and the Pacific	High	530.90	High density	Importer
KWT	Kuwait	Asia and the Pacific	High	239.56	High density	Exporter

Code	Country or area	Region	Income group	Population density	Population density class	Trade Status
LIE	Liechtenstein	Western European and Other Groups	High	245.97	High density	Importer
LTU	Lithuania	Eastern Europe	High	43.92	Low density	Exporter
LUX	Luxembourg	Western European and Other Groups	High	251.55	High density	Importer
LVA	Latvia	Eastern Europe	High	29.74	Low density	Exporter
MCO	Monaco	Western European and Other Groups	High	18002.47	High density	Importer
MLT	Malta	Western European and Other Groups	High	1666.54	High density	Importer
NIU	Niue	Asia and the Pacific	High	7.51	Low density	Importer
NLD	Netherlands (Kingdom of the)	Western European and Other Groups	High	521.65	High density	Importer
NOR	Norway	Western European and Other Groups	High	14.92	Low density	Exporter
NRU	Nauru	Asia and the Pacific	High	634.55	High density	Importer
NZL	New Zealand	Western European and Other Groups	High	19.69	Low density	Exporter
OMN	Oman	Asia and the Pacific	High	14.79	Low density	Exporter
PAN	Panama	Latin America and the Caribbean	High	59.43	Low density	Importer
POL	Poland	Eastern Europe	High	130.20	High density	Importer
PRT	Portugal	Western European and Other Groups	High	112.12	High density	Importer
QAT	Qatar	Asia and the Pacific	High	234.56	High density	Exporter
ROU	Romania	Eastern Europe	High	85.45	Low density	Importer
SAU	Saudi Arabia	Asia and the Pacific	High	16.94	Low density	Exporter
SGP	Singapore	Asia and the Pacific	High	8322.69	High density	Importer
SMR	San Marino	Western European and Other Groups	High	561.50	High density	Importer
SVK	Slovakia	Eastern Europe	High	117.38	High density	Importer

Code	Country or area	Region	Income group	Population density	Population density class	Trade Status
SVN	Slovenia	Eastern Europe	High	105.27	High density	Importer
SWE	Sweden	Western European and Other Groups	High	25.90	Low density	Exporter
SYC	Seychelles	Africa	High	232.90	High density	Importer
TTO	Trinidad and Tobago	Latin America and the Caribbean	High	298.45	High density	Exporter
URY	Uruguay	Latin America and the Caribbean	High	19.56	Low density	Exporter
USA	United States of America (the)	Western European and Other Groups	High	36.98	Low density	Exporter
ALB	Albania	Eastern Europe	Middle	103.73	High density	Importer
ARG	Argentina	Latin America and the Caribbean	Middle	16.63	Low density	Exporter
ARM	Armenia	Eastern Europe	Middle	97.66	High density	Importer
AZE	Azerbaijan	Eastern Europe	Middle	125.33	High density	Exporter
BGR	Bulgaria	Eastern Europe	Middle	62.47	Low density	Exporter
BIH	Bosnia and Herzegovina	Eastern Europe	Middle	63.15	Low density	Importer
BLR	Belarus	Eastern Europe	Middle	46.97	Low density	Exporter
BLZ	Belize	Latin America and the Caribbean	Middle	17.77	Low density	Importer
BRA	Brazil	Latin America and the Caribbean	Middle	25.76	Low density	Exporter
BWA	Botswana	Africa	Middle	4.64	Low density	Importer
CHN	China	Asia and the Pacific	Middle	151.88	High density	Importer
COK	Cook Islands	Asia and the Pacific	Middle	70.97	Low density	Importer
COL	Colombia	Latin America and the Caribbean	Middle	46.75	Low density	Exporter
CRI	Costa Rica	Latin America and the Caribbean	Middle	101.47	High density	Importer
CUB	Cuba	Latin America and the Caribbean	Middle	108.02	High density	Importer

Code	Country or area	Region	Income group	Population density	Population density class	Trade Status
DMA	Dominica	Latin America and the Caribbean	Middle	97.01	High density	Importer
DOM	Dominican Republic (the)	Latin America and the Caribbean	Middle	232.43	High density	Importer
ECU	Ecuador	Latin America and the Caribbean	Middle	72.48	Low density	Exporter
FJI	Fiji	Asia and the Pacific	Middle	50.89	Low density	Importer
GAB	Gabon	Africa	Middle	9.27	Low density	Exporter
GEO	Georgia	Eastern Europe	Middle	53.88	Low density	Importer
GNQ	Equatorial Guinea	Africa	Middle	59.71	Low density	Exporter
GRD	Grenada	Latin America and the Caribbean	Middle	369.00	High density	Importer
GTM	Guatemala	Latin America and the Caribbean	Middle	166.52	High density	Importer
IDN	Indonesia	Asia and the Pacific	Middle	146.74	High density	Exporter
IRQ	Iraq	Asia and the Pacific	Middle	102.50	High density	Exporter
JAM	Jamaica	Latin America and the Caribbean	Middle	261.07	High density	Importer
KAZ	Kazakhstan	Asia and the Pacific	Middle	7.19	Low density	Exporter
LBY	Libya	Africa	Middle	3.87	Low density	Exporter
LCA	Saint Lucia	Latin America and the Caribbean	Middle	294.87	High density	Importer
MDA	Republic of Moldova (the)	Eastern Europe	Middle	99.53	High density	Importer
MDV	Maldives	Asia and the Pacific	Middle	1745.99	High density	Importer
MEX	Mexico	Latin America and the Caribbean	Middle	65.59	Low density	Importer
MHL	Marshall Islands (the)	Asia and the Pacific	Middle	231.07	High density	Importer
MKD	North Macedonia	Eastern Europe	Middle	83.01	Low density	Importer
MNE	Montenegro	Eastern Europe	Middle	46.62	Low density	Importer

Code	Country or area	Region	Income group	Population density	Population density class	Trade Status
MUS	Mauritius	Africa	Middle	640.14	High density	Importer
MYS	Malaysia	Asia and the Pacific	Middle	103.30	High density	Exporter
NAM	Namibia	Africa	Middle	3.12	Low density	Importer
PER	Peru	Latin America and the Caribbean	Middle	26.60	Low density	Exporter
PLW	Palau	Asia and the Pacific	Middle	39.31	Low density	Importer
PRY	Paraguay	Latin America and the Caribbean	Middle	17.07	Low density	Exporter
PSE	State of Palestine (the)	Asia and the Pacific	Middle	872.11	High density	Importer
RUS	Russian Federation (the)	Eastern Europe	Middle	8.84	Low density	Exporter
SLV	El Salvador	Latin America and the Caribbean	Middle	305.81	High density	Importer
SRB	Serbia	Eastern Europe	Middle	82.57	Low density	Importer
SUR	Suriname	Latin America and the Caribbean	Middle	3.96	Low density	Importer
THA	Thailand	Asia and the Pacific	Middle	140.34	High density	Importer
TKM	Turkmenistan	Asia and the Pacific	Middle	13.68	Low density	Exporter
TON	Tonga	Asia and the Pacific	Middle	148.43	High density	Importer
TUR	Türkiye	Western European and Other Groups	Middle	110.89	High density	Importer
TUV	Tuvalu	Asia and the Pacific	Middle	377.83	High density	Exporter
VCT	Saint Vincent and the Grenadines	Latin America and the Caribbean	Middle	266.56	High density	Importer
VEN	Venezuela (Bolivarian Republic of)	Latin America and the Caribbean	Middle	32.09	Low density	Exporter
ZAF	South Africa	Africa	Middle	49.37	Low density	Exporter
AFG	Afghanistan	Asia and the Pacific	Low	63.06	Low density	Importer
AGO	Angola	Africa	Low	28.55	Low density	Exporter

Code	Country or area	Region	Income group	Population density	Population density class	Trade Status
AGO	Angola	Africa	Low	28.55	Low density	Exporter
BDI	Burundi	Africa	Low	501.93	High density	Importer
BEN	Benin	Africa	Low	118.42	High density	Importer
BFA	Burkina Faso	Africa	Low	82.87	Low density	Importer
BGD	Bangladesh	Asia and the Pacific	Low	1315.10	High density	Importer
BOL	Bolivia (Plurinational State of)	Latin America and the Caribbean	Low	11.28	Low density	Exporter
BTN	Bhutan	Asia and the Pacific	Low	20.52	Low density	Exporter
CAF	Central African Republic (the)	Africa	Low	8.96	Low density	Importer
CIV	Côte d'Ivoire	Africa	Low	88.56	Low density	Importer
CMR	Cameroon	Africa	Low	59.05	Low density	Importer
COD	Democratic Republic of Congo	Africa	Low	43.67	Low density	Importer
COG	Congo (the)	Africa	Low	17.48	Low density	Exporter
COM	Comoros (the)	Africa	Low	449.64	High density	Importer
CPV	Cabo Verde	Africa	Low	147.19	High density	Importer
DJI	Djibouti	Africa	Low	48.35	Low density	Importer
DZA	Algeria	Africa	Low	18.85	Low density	Exporter
EGY	Egypt	Africa	Low	111.50	High density	Importer
ERI	Eritrea	Africa	Low	30.44	Low density	Importer
ETH	Ethiopia	Africa	Low	109.32	High density	Importer
FSM	Micronesia (Federal States of)	Asia and the Pacific	Low	163.11	High density	Importer
GHA	Ghana	Africa	Low	147.13	High density	Importer

Code	Country or area	Region	Income group	Population density	Population density class	Trade Status
GIN	Guinea	Africa	Low	56.40	Low density	Exporter
GMB	Gambia (the)	Africa	Low	267.39	High density	Importer
GNB	Guinea-Bissau	Africa	Low	74.88	Low density	Importer
HND	Honduras	Latin America and the Caribbean	Low	93.24	High density	Importer
HTI	Haiti	Latin America and the Caribbean	Low	420.36	High density	Importer
IND	India	Asia and the Pacific	Low	476.65	High density	Importer
IRN	Iran (Islamic Republic of)	Asia and the Pacific	Low	54.58	Low density	Exporter
JOR	Jordan	Asia and the Pacific	Low	127.10	High density	Importer
KEN	Kenya	Africa	Low	94.93	High density	Importer
KGZ	Kyrgyzstan	Asia and the Pacific	Low	34.57	Low density	Importer
KHM	Cambodia	Asia and the Pacific	Low	94.99	High density	Importer
KIR	Kiribati	Asia and the Pacific	Low	162.02	High density	Exporter
LAO	Lao People's Democratic Republic (the)	Asia and the Pacific	Low	32.62	Low density	Exporter
LBN	Lebanon	Asia and the Pacific	Low	536.63	High density	Importer
LBR	Liberia	Africa	Low	55.05	Low density	Importer
LKA	Sri Lanka	Asia and the Pacific	Low	352.93	High density	Importer
LSO	Lesotho	Africa	Low	75.95	Low density	Importer
MAR	Morocco	Africa	Low	83.93	Low density	Importer
MDG	Madagascar	Africa	Low	50.90	Low density	Importer
MLI	Mali	Africa	Low	18.52	Low density	Importer
MMR	Myanmar	Asia and the Pacific	Low	83.01	Low density	Exporter

Code	Country or area	Region	Income group	Population density	Population density class	Trade Status
MNG	Mongolia	Asia and the Pacific	Low	2.18	Low density	Exporter
MOZ	Mozambique	Africa	Low	41.93	Low density	Exporter
MRT	Mauritania	Africa	Low	4.60	Low density	Exporter
MWI	Malawi	Africa	Low	216.43	High density	Importer
NER	Niger (the)	Africa	Low	20.69	Low density	Importer
NGA	Nigeria	Africa	Low	239.95	High density	Exporter
NIC	Nicaragua	Latin America and the Caribbean	Low	57.74	Low density	Importer
NPL	Nepal	Asia and the Pacific	Low	213.10	High density	Importer
PAK	Pakistan	Asia and the Pacific	Low	305.92	High density	Importer
PHL	Philippines (the)	Asia and the Pacific	Low	387.56	High density	Importer
PNG	Papua New Guinea	Asia and the Pacific	Low	22.40	Low density	Exporter
PRK	Democratic People's Republic of Korea	Asia and the Pacific	Low	216.51	High density	Exporter
RWA	Rwanda	Africa	Low	558.44	High density	Importer
SDN	Sudan (the)	Africa	Low	25.09	Low density	Importer
SEN	Senegal	Africa	Low	89.94	High density	Importer
SLB	Solomon Islands	Asia and the Pacific	Low	25.88	Low density	Exporter
SLE	Sierra Leone	Africa	Low	119.23	High density	Importer
SOM	Somalia	Africa	Low	28.05	Low density	Importer
SSD	South Sudan	Africa	Low	17.27	Low density	Exporter
STP	Sao Tome and Principe	Africa	Low	236.87	High density	Importer
SWZ	Eswatini	Africa	Low	69.87	Low density	Exporter

Code	Country or area	Region	Income group	Population density	Population density class	Trade Status
SYR	Syrian Arab Republic (the)	Asia and the Pacific	Low	120.49	High density	Importer
TCD	Chad	Africa	Low	14.08	Low density	Exporter
TGO	Togo	Africa	Low	162.69	High density	Exporter
TJK	Tajikistan	Asia and the Pacific	Low	71.71	Low density	Importer
TLS	Timor-Leste	Asia and the Pacific	Low	90.20	High density	Exporter
TUN	Tunisia	Africa	Low	79.53	Low density	Importer
TZA	United Republic of Tanzania	Africa	Low	73.94	Low density	Importer
UGA	Uganda	Africa	Low	235.64	High density	Importer
UKR	Ukraine	Eastern Europe	Low	68.52	Low density	Exporter
UZB	Uzbekistan	Asia and the Pacific	Low	78.58	Low density	Importer
VNM	Viet Nam	Asia and the Pacific	Low	313.27	High density	Importer
VUT	Vanuatu	Asia and the Pacific	Low	26.80	Low density	Importer
WSM	Samoa	Asia and the Pacific	Low	80.00	Low density	Importer
YEM	Yemen	Asia and the Pacific	Low	63.82	Low density	Importer
ZMB	Zambia	Africa	Low	26.93	Low density	Importer
ZWE	Zimbabwe	Africa	Low	42.19	Low density	Importer

Appendix 19.2: Renewable energy use by region

Table 19.3 This table presents data from the World Energy Outlook 2023, focusing on the Stated Policies Scenario across various regions of the world.

The table presents information for 2022, including renewable energy supply in exajoules (EJ), total energy supply in EJ, the share of renewable energy supply relative to total energy supply, renewable energy generation in terawatt-hours (TWh), total energy generation in TWh, and the percentage of electricity generated from renewable sources compared to total electricity generation. The regions included are Africa, Asia and the Pacific, Brazil, Central and South America, China, the European Union, India, Japan, the Middle East, and North America. Russian Federation, Southeast Asia, the United States of America, and the World. These regions are based on the published data by IEA 2023a. Note that population density and income levels closely match, but not exactly, those in Annex I above, due to disparities in data aggregation. The regional categorization of the World Energy Outlook differs from the one of GEO-7.

REGION	Year	Population Density	Income Level	Renewable Supply (EJ)	Total Supply (EJ)	Renewables Share of Total Supply (%)	Renewables Generation (TWh)	Total Generation (TWh) Supply (EJ)	Renewables Share of Total Generation (%)
Africa	2022	Low	Low	5.765	36.422	15.8%	210.45	890.08	23.6%
Asia Pacific 2022 Low	2022	Low	High	30.486	281.025	10.8%	3932.02	14482.81	27.1%
Brazil	2022	Low	Middle	7.006	13.953	50.2%	593.71	677.17	87.7%
Central and South America	2022	Low	Middle	10.015	29.053	34.5%	1018.34	1388.83	73.3%
China	2022	High	Middle	14.875	159.7	9.3%	2681.36	8911.84	30.1%
Eurasia	2022	Low	Middle	1.303	41.575	3.1%	276.62	1476.08	18.7%
Europe	2022	High	High	14.869	78.164	19.0%	1619.63	3995.57	40.5%
European Union	2022	High	High	11.081	56.179	19.7%	1085.25	2795.4	38.8%
India	2022	High	Low	6.224	41.969	14.8%	398.87	1765.82	22.6%
Japan	2022	High	High	1.38	16.637	8.3%	224.83	1061.55	21.2%
Middle East	2022	High	Low	0.268	36.379	0.7%	44.93	1275.76	3.5%
North America	2022	Low	High	12.76	114.46	11.1%	1496.66	5524.04	21.1%
Russia	2022	Low	Middle	1.021	33.997	3.0%	204.54	1169.64	17.5%
Southeast Asia	2022	High	Middle	5.838	30.26	19.3%	340.05	1219.72	27.9%
United States	2022	Low	High	10.103	93.803	10.8%	972.9	4491.21	21.7%
World	2022	World	World	75.48	631.978	11.9%	8598.65	29033.19	29.6%

Appendix 19.3: Disaggregation of model data by country grouping

The grouping of countries in the modelling results differs from those in Chapter 19 because of how geographical regions are defined in the respective modelling tools. A more detailed explanation of these groupings can be found in Chapter 9 (9.5).

For the analysis, data from the IMAGE and IFs models, covering indicators such as primary energy, final energy, electricity generation, GHG emissions, biodiversity loss, water scarcity, pollution, and well-being, were available for the following countries:

High-Income: Canada, Japan, the United States of America, Western Europe, Oceania;
Middle-Income: Mexico, South Africa, Türkiye, Brazil, China, Indonesia, Russian Federation;
Low-Income: India, Rest of Southern Africa, Eastern Africa, Northern Africa, Rest of South Asia, Western Africa.

Whereas some regions, such as the "Rest of Latin America" and the "Middle East," are excluded from these income-density groupings because they include countries across different income categories, which would complicate the analysis. Additionally, the "Rest of Southern Africa" region is not included in the mapping for materials demand, waste and recycling, or economic data, which introduces discrepancies that should be noted when interpreting results.

For indicators from the AIMS model, data for the following countries within the respective income groups were available:

- High-Income: Canada, Japan, United States of America, EU, New Zealand and Australia
- Middle-Income: Türkiye, Brazil, China, Former USSR
- Low-Income: India, Northern Africa, Rest of Africa (including South Africa), Rest of Asia

System indicator (model output data)	
Economics	HDI (IFS) GDP per capita (IFS or GEM - E3 marker model) - Modelling team will provide
Food:	Water use (water withdrawal) (IMAGE & AIM*) Land-use change – links into environmental section (land cover) (IMAGE & AIM*)
Environmental:	GHG emissions (IMAGE & AIM*) Pollution related – particulate matter (pm25) (FAST – under IMAGE) Biodiversity (MSA) (IMAGE – maker model GLOBIO) (Lazlo must disaggregate and send)
Energy:	Secondary energy by source (electricity mix) (IMAGE & AIM*) Final energy demand by sector (IMAGE & AIM*)
Waste:	Material footprint (GTEM) Material productivity (also linked to economic section) (GTEM) Waste to landfill (GTEM) Circularity rate (amount of recovered material) (GTEM)

* AIM provides the model output data for the REF scenario & IMAGE provides the model output data for the Technology-focused and Behaviour-focused Transformation Scenarios.

References

Abbasi Golnoush, B.E.A. (2020). Emissions outsourcing in the EU: A review of potential effects on industrial pollution. Eionet Report–ETC/ATNI. https://nilu.com/publication/1800515/

Abdulwakil, M., A.S, A.R., Chindo, S., Alsaleh, M. and Bah, M. (2022). Energy Subsidies and Environmental Quality: Evidence from Low- and Middle-Income Countries. IOP Conference Series: Earth and Environmental Science 1102, 012039. https://doi.org/10.1088/1755-1315/1102/1/012039

Abrahms, B. (2021). Human-wildlife conflict under climate change. Science 373(6554), 484-485. https://doi.org/10.1126/science.abj4216

Ackleh, A., Caswell, H., Chiquet, R., Tang, T. and Veprauskas, A. (2018). Sensitivity analysis of the recovery time for a population under the impact of an environmental disturbance. Natural Resource Modeling 32, e12166. https://doi.org/10.1111/nrm.12166

Adun, H., Ishaku, H.P. and Ogungbemi, A.T. (2022). Towards Renewable energy targets for the Middle East and North African region: A decarbonization assessment of energy-water nexus. Journal of Cleaner Production 374, 133944. https://doi.org/10.1016/j.jclepro.2022.133944

Aguilar-Gomez, S., Dwyer, H., Graff Zivin, J. and Neidell, M. (2022). This Is Air: The "Nonhealth" Effects of Air Pollution. Annual Review of Resource Economics 14(1), 403-425. https://doi.org/10.1146/annurev-resource-111820-021816

Agyemang, P., Kwofie, E.M. and A, F. (2022). Integrating framework analysis, scenario design, and decision support system for sustainable healthy food system analysis. Journal of Cleaner Production 372, 133661. https://doi.org/10.1016/j.jclepro.2022.133661

Ahmad, S., Tang, L., Shahzad, R., Mawia, A.M., Rao, G.S., Jamil, S. et al. (2021). CRISPR-Based Crop Improvements: A Way Forward to Achieve Zero Hunger. Journal of Agricultural and Food Chemistry 69(30), 8307-8323. https://doi.org/10.1021/acs.jafc.1c02653

Ahmed, Z., Mahmud, S. and Acet, H. (2022). Circular economy model for developing countries: evidence from Bangladesh. Heliyon 8. https://doi.org/10.1016/j.heliyon.2022.e09530

Ahsan, M.N., Islam, M., Halim, S.F., Khatun, F., Alam, M., Maria, S. et al. (2024). Examining Farmers' Behavioral Drivers to Adopt Floating Farming: A Study in the Wetlands of Southwestern Coastal Bangladesh. Earth Systems and Environment (9)1, 215-239. https://doi.org/10.1007/s41748-024-00433-w

Aleluia, J. and Ferrão, P. (2016). Characterization of urban waste management practices in developing Asian countries: A new analytical framework based on waste characteristics and urban dimension. Waste Management 58, 415-429. https://doi.org/10.1016/j.wasman.2016.05.008

Ambrose, A., Rafalowicz-Campbell, M., Castano Garcia, A., Hawkins, A. and Parkes, S. (2023). High consumption in the UK: an exploration of secondary data. Sheffield Hallam University, Center for Regional Economic and Social Research. . https://www.shu.ac.uk/centre-regional-economic-social-research/publications/high-consumption-in-the-uk

Azarpour, A., Mohammadzadeh, O., Rezaei, N. and Zendehboudi, S. (2022). Current status and future prospects of renewable and sustainable energy in North America: Progress and challenges. Energy Conversion and Management 269, 115945. https://doi.org/10.1016/j.enconman.2022.115945

Azhgaliyeva, D. and Mishra, R. (2022). Feed-in tariffs for financing renewable energy in Southeast Asia. WIREs Energy and Environment 11(3), e425. https://doi.org/10.1002/wene.425

Backhouse, M. and Lehmann, R. (2020). New 'renewable' frontiers: contested palm oil plantations and wind energy projects in Brazil and Mexico. Journal of Land Use Science 15(2-3), 373-388. https://doi.org/10.1080/1747423X.2019.1648577

Baker, L. (2017). Of embodied emissions and inequality: Rethinking energy consumption. Energy Research & Social Science 36. https://doi.org/10.1016/j.erss.2017.09.027

Basnet, S., Wood, A., Röös, E., Jansson, T., Fetzer, I. and Gordon, L. (2023). Organic agriculture in a low-emission world: exploring combined measures to deliver sustainable food system in Sweden. Sustainability Science 18, 1-19. https://doi.org/10.1007/s11625-022-01279-9

Baumert, N., Kander, A., Jiborn, M., Kulionis, V. and Nielsen, T. (2019). Global outsourcing of carbon emissions 1995–2009: A reassessment. Environmental Science & Policy 92, 228-236. https://doi.org/10.1016/j.envsci.2018.10.010

Bellora, C. and Fontagné, L. (2023). EU in search of a Carbon Border Adjustment Mechanism. Energy Economics 123, 106673. https://doi.org/10.1016/j.eneco.2023.106673

Bhattacharyya, S.C. (2017). Industrial energy use in Asia. In Routledge Handbook of Energy in Asia, 62-80. Routledge. https://www.routledge.com/Routledge-Handbook-of-Energy-in-Asia/Bhattacharyya/p/book/9780367660017

Rother, B., Sosa, S., Kim, D., Kohler, L.P., Pierre, G., Kato. N et al. (2022). Tackling the Global Food Crisis: Impact, Policy Response, and the Role of the IMF. IMF Notes No 2022/004IMF. https://www.imf.org/en/Publications/IMF-Notes/Issues/2022/09/27/Tackling-the-Global-Food-Crisis-Impact-Policy-Response-and-the-Role-of-the-IMF-523919

Blondeel, M., Van de Graaf, T. and Haesebrouck, T. (2020). Moving beyond coal: Exploring and explaining the Powering Past Coal Alliance. Energy Research & Social Science 59, 101304. https://doi.org/10.1016/j.erss.2019.101304

Buyukyazici, D. and Quatraro, F. (2025). The skill requirements of the circular economy. Ecological Economics 232, 108559. https://doi.org/10.1016/j.ecolecon.2025.108559

Calvão, F., McDonald, C.E.A. and Bolay, M. (2021). Cobalt mining and the corporate outsourcing of responsibility in the Democratic Republic of Congo. The Extractive Industries and Society 8(4), 100884. https://doi.org/10.1016/j.exis.2021.02.004

Canaday, F., Georas, S. and Croft, D. (2024). Examining the impact of air pollution, climate change, and social determinants of health on asthma and environmental justice. Current opinion in pulmonary medicine 30(3), 276-280. https://doi.org/10.1097/MCP.0000000000001065

Ceesay, E.K. and Ben Omar Ndiaye, M. (2022). Climate change, food security and economic growth nexus in the Gambia: Evidence from an econometrics analysis. Research in Globalization 5, 100089. https://doi.org/10.1016/j.resglo.2022.100089

Childs, J. (2020). Extraction in Four Dimensions: Time, Space and the Emerging Geo(-)politics of Deep-Sea Mining. Geopolitics 25(1), 189-213. https://doi.org/10.1080/14650045.2018.1465041

Cho, S.J. (2022). Food Security Challenges in Developing Countries During COVID-19 Pandemic. KIEP Research Paper, KIEP Opinions 237. http://dx.doi.org/10.2139/ssrn.4122493

Choi, J.Y., Yu, E.S.H. (2018). International outsourcing, environmental costs, and welfare ADBI Working Paper. Tokyo: Asian Development Bank Institute. https://www.adb.org/publications/international-outsourcing-environmental-costs-and-welfare

Clarkero, L., Wei, Y.-M., De La Vega Navarro, A., Garg, A., Hahmann, A.N., Khennas, S. et al. (2022). Energy Systems (Chapter 6). In: IPCC 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Eds. Shukla, A.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum. et al. 613-746 Cambridge, UK and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157926.008

Clausing, K., Elkerbout. M., Nehrkorn, K., Wolfram, C. (2024). How Carbon Border Adjustments Might Drive Global Climate Policy Momentum. Resources for the Future. https://www.rff.org/publications/reports/how-carbon-border-adjustments-might-drive-global-climate-policy-momentum/

Cotta, B. (2020). What goes around, comes around? Access and allocation problems in Global North–South waste trade. International Environmental Agreements: Politics, Law and Economics 20(2), 255-269. https://doi.org/10.1007/s10784-020-09479-3

Crespo-Rosas, N. and Franco-García, L. (2023). Improving Gender Equality with Social Entrepreneurship and Circular Economy: A Mexican Case. In The Social Dimensions of the Circular Economy. de Souza Campos, L.M. and Vázquez-Brust, D.A. (eds.). Cham: Springer International Publishing. 241-263. https://doi.org/10.1007/978-3-031-25436-9_11

Cumming, G.S. and von Cramon-Taubadel, S. (2018). Linking economic growth pathways and environmental sustainability by understanding development as alternate social–ecological regimes. Proceedings of the National Academy of Sciences 115(38), 9533-9538. https://doi.org/10.1073/pnas.1807026115.

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH (2021). Just Transition to a Green Economy: Employment, Economic, and Social Consequences of the Transition to an Ecologically Sustainable Economy in Developing Countries. https://mia.giz.de/qlinkdb/cat/ID=248698000

Dalei, N.N. and Joshi, J.M. (2023). Analysis of the market for renewable energy sources in the Asia and the Pacific region. Technology Audit and Production Reserves 1(4(69), 25-29. https://doi.org/10.15587/2706-5448.2023.274273

Dar, R., Duan, R., Liang, H., Ng, L. (2022). Do US companies outsource their carbon footprints to overseas suppliers to maintain competitiveness? PRI: Principles for Responsible Investment. https://www.unpri.org/pri-blog/do-us-companies-outsource-their-carbon-footprints-to-overseas-suppliers-to-maintain-competitiveness/9363.article. Accessed January 10 2024

DeAngelo, J., Azevedo, I., Bistline, J., Clarke, L., Luderer, G., Byers, E. et al. (2021). Energy systems in scenarios at net-zero CO_2 emissions. Nature Communications 12(1), 6096. https://doi.org/10.1038/s41467-021-26356-y

Denny, D.M.T. (2020). Competitive renewables as the key to energy transition—RenovaBio: the Brazilian biofuel regulation. In The regulation and policy of latin American energy transitions. 223-242. Elsevier. https://www.sciencedirect.com/science/article/pii/B9780128195215000139

Diluiso, F., Walk, P., Manych, N., Cerutti, N., Chipiga, V., Workman, A. et al. (2021). Coal transitions—part 1: a systematic map and review of case study learnings from regional, national, and local coal phase-out experiences. Environmental Research Letters 16(11), 113003. https://doi.org/10.1088/1748-9326/ac1b58

Dittmer, K.M., Rose, S., Snapp, S.S., Kebede, Y., Brickman, S., Shelton, S. et al. (2023). Agroecology Can Promote Climate Change Adaptation Outcomes Without Compromising Yield In Smallholder Systems. Environmental Management 72(2), 333-342. https://doi.org/10.1007/s00267-023-01816-x

Do, T.N. (2025). Reimagining carbon border adjustment mechanisms: A path to climate and development synergy. Global Transitions 7, 144-147. https://doi.org/10.1016/j.glt.2025.03.003

European Commission (2023). Carbon Border Adjustment Mechanism. https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en. Accessed: 10 January 2024

European Commission (2024). EUDR Cooperation and Partnerships: Country Benchmarking. https://green-business.ec.europa.eu/deforestation-regulation-implementation/eudr-cooperation-and-partnerships_en?. Accessed 17 March 2025

European Parliamentary Research Service (2023). From growth to 'beyond growth': Concepts and Challenges. https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/747107/EPRS_BRI(2023)747107_EN.pdf

Feng, Y., Song, F. and Chen, P. (2023). Evaluating the cost impacts to meet China's renewable electricity portfolio standard target in 2030. International Journal of Green Energy 20(13), 1434-1450. https://doi.org/10.1080/15435075.2022.2155969

Food and Agriculture Organization of the United Nations, FAO (2019). Globally Important Agricultural Heritage Systems (GIAHS): Combining Agricultural Biodiversity, Resilient Ecosystems, Traditional Farming Practices and Cultural Identity. FAO: Rome, Italy. http://www.fao.org/documents/card/fr/c/I9187EN

Food and Agriculture Organization of the United Nations, FAO (2021). The State of Food and Agriculture: Making agrifood systems more resilient to shocks and stresses: FAO: Rome, Italy. https://doi.org/10.4060/cb7351en

Frongillo, E., Nguyen, P., Sanghvi, T., Mahmud, Z., Aktar, B., Alayon, S. et al. (2019). Nutrition Interventions Integrated into an Existing Maternal, Neonatal, and Child Health Program Reduce Food Insecurity Among Recently Delivered and Pregnant Women in Bangladesh. The Journal of Nutrition 149, 159-166. https://doi.org/10.1093/jn/nxy249

Frongillo, E., Nguyen, H., Smith, M., Coleman-Jensen, A., et al. (2019) Food Insecurity Is More Strongly Associated with Poor Subjective Well-Being in More-Developed Countries than in Less-Developed Countries. The Journal of Nutrition 149,330-335.https://doi.org/10.1093/jn/nxy261

Fuller, R., Landrigan, P.J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M. et al. (2022). Pollution and health: a progress update. Lancet Planet Health 6(6), e535-e547. https://doi.org/10.1016/s2542-5196(22)00090-0

Garcia, A., Ambrose, A., Hawkins, A. and Parkes, S. (2021). High consumption, an unsustainable habit that needs more attention. Energy Research & Social Science 80, 102241. https://doi.org/10.1016/j.erss.2021.102241

Geissdoerfer, M., Morioka, S.N., de Carvalho, M.M. and Evans, S. (2018). Business models and supply chains for the circular economy. Journal of Cleaner Production 190, 712-721. https://doi.org/10.1016/j.jclepro.2018.04.159

Geissdoerfer, M., Savaget, P., Bocken, N.M.P. and Hultink, E.J. (2017). The Circular Economy – A new sustainability paradigm? Journal of Cleaner Production 143, 757-768. https://doi.org/10.1016/j.jclepro.2016.12.048

Gerst, M.D., Raskin, P.D. and Rockström, J. (2014). Contours of a Resilient Global Future. Sustainability 6(1), 123-135. https://doi.org/10.3390/su6010123

Global Commission on Adaptation (2019). Adapt now: A Global Call for Leadership on Climate Resilience https://gca.org/reports/adapt-now-a-global-call-for-leadership-on-climate-resilience

Global Sustainable Finance Working Group (2022). 2022 G20 Sustainable Finance Report: Indonesia https://g20sfwg.org/wp-content/uploads/2022/10/2022-G20-Sustainable-Finance-Report-2.pdf

Godrich, S.L., Doe, J., Goodwin, S., Alston, L. and Kent, K. (2023). A scoping review of the impact of Food Policy Groups on local food systems in high-income countries. Nutrition Research Reviews, 1-24. https://doi.org/10.1017/S0954422423000173

Gross E, J.N., Brooks A., Polet G., Wadhwa R. and Hilderink-Koopmans F. (2021). A Future for All: The Need for Human-Wildlife Coexistence. WWF, Gland, Switzerland. https://wwfint.awsassets.panda.org/downloads/a_future_for_all___the_need_for_human_willdife_coexistence.pdf

Haas, W., Krausmann, F., Wiedenhofer, D. and Heinz, M. (2015). How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. Journal of Industrial Ecology 19(5), 765-777. https://doi.org/10.1111/jiec.12244

Hallmann, C., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H. et al. (2017). More than 75 percent decline over 27 years in total flying insect biomass in protected areas. PLOS ONE 12, 1-21. https://doi.org/10.1371/journal.pone.0185809

Ritchie, H., Rodés-Guirao. L., Mathieu, E., Gerber, M., Ortiz-Ospina, E., Hasell, J. and Roser, M. (2023). "Population Growth". Our World in Data. https://ourworldindata.org/grapher/population-density

Hansen, U.E., Nygaard, I., Romijn, H., Wieczorek, A., Kamp, L.M. and Klerkx, L. (2018). Sustainability transitions in developing countries: Stocktaking, new contributions and a research agenda. Environmental Science & Policy 84, 198-203. https://doi.org/10.1016/j.envsci.2017.11.009

Hatfield-Dodds, S., Schandl, H., Newth, D., Obersteiner, M., Cai, Y., Baynes, T. et al. (2017). Assessing global resource use and greenhouse emissions to 2050, with ambitious resource efficiency and climate mitigation policies.

Journal of Cleaner Production 144, 403-414. https://doi.org/10.1016/j.jclepro.2016.12.170

Hausman, C. (2012). Biofuels and Land Use Change: Sugarcane and Soybean Acreage Response in Brazil. Environmental and Resource Economics 51(2), 163-187. https://doi.org/10.1007/s10640-011-9493-7

Hebb, T. (2019). Investing in Sustainable Infrastructure. In: Arvidsson, S. (eds) Challenges in Managing Sustainable Business. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-319-93266-8_11

Hickel, J. (2021). What does degrowth mean? A few points of clarification. Globalizations 18(7), 1105-1111. https://doi.org/10.1080/14747731.2020.1812222

Hickel, J., O'Neill, D., Fanning, A. and Zoomkawala, H. (2022). National responsibility for ecological breakdown: a fair-shares assessment of resource use, 1970–2017. The Lancet Planetary Health 6, e342-e349. https://doi.org/10.1016/S2542-5196(22)00044-4

Hoey, L., Khoury, C.K., Osiemo, J., Shires, A., Binge, B., Duong, T.T. et al. (2021). Challenges to Operationalizing Sustainable Diets: Perspectives From Kenya and Vietnam. Frontiers in Sustainable Food Systems 5, 690028. https://doi.org/10.3389/fsufs.2021.690028

Hoffmann, S., Lasarov, W., Reimers, H. and Trabandt, M. (2024). Carbon footprint tracking apps. Does feedback help reduce carbon emissions? Journal of Cleaner Production 434, 139981. https://doi.org/10.1016/j.jclepro.2023.139981

Hristescu, C. (2022). Analysis on the sustainability of different low CO_2 emission Hydrogen production technologies for transition towards a 'zero emission' economy. Proceedings of the International Conference on Business Excellence 16(1), 1159-1167. https://doi.org/10.2478/picbe-2022-0106

International Energy Agency (2023a). World Energy Outlook. IEA Publications. https://iea.blob.core.windows.net/assets/86ede39e-4436-42d7-ba2a-edf61467e070/WorldEnergyOutlook2023.pdf

International Energy Agency (2023b). The world's top 1% of emitters produce over 1000 times more CO_2 than the bottom 1%. https://www.iea.org/commentaries/the-world-s-top-1-of-emitters-produce-over-1000-times-more-co2-than-the-bottom-1. Accessed: 24 January 2024

International Panel on Climate Change, IPCC. (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, R.K. Pachauri and L.A. Meyer (ed.). Geneva, Switzerland: IPCC. https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf

International Panel on Climate Change, IPCC. (2021). The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391. https://doi.org/10.1017/9781009157896

International Renewable Energy Agency (2020). Power sector planning in Arab countries: Incorporating variable renewables. International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jan/IRENA_Arab_VRE_planning_2020.pdf

International Renewable Energy Agency and the African Development Bank (2022). Renewable Energy Market Analysis: Africa and Its Regions. International Renewable Energy Agency and African Development Bank, Abu Dhabi and Abidjan. https://www.irena.org/publications/2022/Jan/Renewable-Energy-Market-Analysis-Africa

Jewell, J., Vinichenko, V., Nacke, L. and Cherp, A. (2019). Prospects for powering past coal. Nature Climate Change 9(8), 592-597. https://doi.org/10.1038/s41558-019-0509-6

Johnson, O.W., du Pont, P. and Gueguen-Teil, C. (2021). Perceptions of climate-related risk in Southeast Asia's power sector. Climate Policy 21(2), 264-276. https://doi.org/10.1080/14693062.2020.1822771.

Khan, S., Ponce, P., Yu, Z., Golpîra, H. and Mathew, M. (2021). Environmental technology and wastewater treatment: Strategies to achieve environmental sustainability. Chemosphere 286, 131532. https://doi.org/10.1016/j.chemosphere.2021.131532

Kopp Raymond J., P.W., Rennert Kevin (2023). Carbon Border Adjustments: Design Elements, Options, and Policy Decisions. Resources for the Future. https://www.rff.org/publications/reports/carbon-border-adjustments-design-elements-options-and-policy-decisions/

Kroposki, B., Johnson, B., Zhang, Y., Gevorgian, V., Denholm, P., Hodge, B.-M., & Hannegan, B. (2017). Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy. IEEE Power and Energy Magazine. https://ipu.msu.edu/wp-content/uploads/2018/01/IEEE-Achieving-a-100-Renewable-Grid-2017.pdf

Krupa, J., Poudineh, R. and Harvey, L.D.D. (2019). Renewable electricity finance in the resource-rich countries of the Middle East and North Africa: A case study on the Gulf Cooperation Council. Energy 166, 1047-1062. https://doi.org/10.1016/j.energy.2018.10.106

Lamb, W.F., Wiedmann, T., Pongratz, J., Andrew, R., Crippa, M., Olivier, J.G.J. et al. (2021). A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. Environmental Research Letters 16(7), 073005. https://doi.org/10.1088/1748-9326/abee4e

Larch, M. and Wanner, J. (2017). Carbon tariffs: An analysis of the trade, welfare, and emission effects. Journal of International Economics 109, 195-213. https://doi.org/10.1016/j.jinteco.2017.09.003

Lau, H.C., Zhang, K., Bokka, H.K. and Ramakrishna, S. (2022). A Review of the Status of Fossil and Renewable Energies in Southeast Asia and Its Implications on the Decarbonization of ASEAN. Energies 15(6), 2152. https://doi.org/10.3390/en15062152

Leippert, F., Darmaun, M., Bernoux, M., and Mpheshea, M (2020). The potential of agroecology to build climate-resilient livelihoods and food systems. FAO and Biovision, Rome. https://doi.org/10.4060/cb0438en

Li, J. and Lin, B. (2019). The sustainability of remarkable growth in emerging economies. Resources, Conservation and Recycling 145, 349-358. https://doi.org/10.1016/j.resconrec.2019.01.036

Liu, Y., Chen, J., Zhao, L. and Liao, H. (2023). Rural photovoltaic projects substantially prompt household energy transition: Evidence from China. Energy 275, 127505. https://doi.org/10.1016/j.energy.2023.127505

Liu, Y. and Zhou, Y. (2021). Reflections on China's food security and land use policy under rapid urbanization. Land Use Policy 109, 105699. https://doi.org/10.1016/j.landusepol.2021.105699

Lockwood, M., Davidson, J., Curtis, A., Stratford, E. and Griffith, R. (2010). Governance Principles for Natural Resource Management. Society & Natural Resources 23(10), 986-1001. https://doi.org/10.1080/08941920802178214

Losos, E., Pfaff, A. and Pimm, S. (2024). Tackling debt, biodiversity loss, and climate change. Science 384(6696), 618-621.. https://doi.org/10.1126/science.ado7418

Mangır, N. and Şahin, Ü.A. (2022). An environmentally extended global multi-regional input–output analysis of consumption-based and embodied import-based carbon emissions of Turkey. Environmental Science and Pollution Research 29(36), 54813-54826. https://doi.org/10.1007/s11356-022-19290-z

McDonald, R., Mansur, A., Ascensão, F., Colbert, M.I., Crossman, K., Elmqvist, T. et al. (2019). Research gaps in knowledge of the impact of urban growth on biodiversity. Nature Sustainability 3, 1-9. https://doi.org/10.1038/s41893-019-0436-6

McKinsey and Company (2022). The net-zero transition: What it will cost, what it would bring. https://www.mckinsey.com/capabilities/sustainability/our-insights/how-the-net-zero-transition-would-play-out-in-countries-and-regions

McDowall, W., Geng, Y., Huang, B., Barteková, E., Bleischwitz, R., Türkeli, S. et al. (2017). Circular Economy Policies in China and Europe. Journal of Industrial Ecology 21(3), 651-661. https://doi.org/10.1111/jiec.12597

Measham, T., Fleming-Muñoz, D. and Schandl, H. (2015). Socio-economic impacts of unconventional fossil fuel extraction: a discussion and conceptual model. http://dx.doi.org//10.1016/j.gloenvcha.2015.12.002

Mekonnen, D.A., Akerele, D., Achterbosch, T., de Lange, T. and Talsma, E.F. (2021). Affordability of Healthy and Sustainable Diets in Nigeria. Frontiers in Sustainable Food Systems 5, 726773. https://doi.org/10.3389/fsufs.2021.726773

Mi, Z., Zheng, J., Meng, J., Ou, J., Hubacek, K., Liu, Z. et al. (2020). Economic development and converging household carbon footprints in China. Nature Sustainability 3(7), 529-537. https://doi.org/10.1038/s41893-020-0504-y

Miladinov, G. (2023). Impacts of population growth and economic development on food security in low-income and middle-income countries. Frontiers in Human Dynamics 5, 1121662. https://doi.org/10.3389/fhumd.2023.1121662

Miles, A., DeLonge, M.S. and Carlisle, L. (2017). Triggering a positive research and policy feedback cycle to support a transition to agroecology and sustainable food systems. Agroecology and Sustainable Food Systems 41(7), 855-879. https://doi.org/10.1080/21683565.2017.1331179

Militao, E.M.A., Uthman, O.A., Salvador, E.M., Vinberg, S. and Macassa, G. (2023). Food Insecurity and Associated Factors among Households in Maputo City. Nutrients 15(10), 2372. https://doi.org/10.3390/nu15102372

Morais, T.G., Teixeira, R.F.M., Lauk, C., Theurl, M.C., Winiwarter, W., Mayer, A. et al. (2021). Agroecological measures and circular economy strategies to ensure sufficient nitrogen for sustainable farming. Global Environmental Change 69, 102313. https://doi.org/10.1016/j.gloenvcha.2021.102313

Navarro Garcia, J., Marcos-Martinez, R., Mosnier, A., Schmidt-Traub, G., Javalera Rincon, V., Obersteiner, M. et al. (2023). Multi-target scenario discovery to plan for sustainable food and land systems in Australia. Sustainability Science 18(1), 371-388. https://doi.org/10.1007/s11625-022-01202-2

Ngonghala, C.N., Pluciński, M.M., Murray, M.B., Farmer, P.E., Barrett, C.B., Keenan, D.C. et al. (2014). Poverty, Disease, and the Ecology of Complex Systems. PLOS Biology 12(4), e1001827. https://doi.org/10.1371/journal.pbio.1001827

Ntamwira, J., Ocimati, W., Blomme, G., Lubobo, A.K., Mwarabu Lolonga Pyame, D. and Dhed'a Djailo, B. (2023). Innovative agroecological practices can restore degraded farmlands and revive crop yields. Frontiers in Sustainable Food Systems, 7, 1017341. https://doi.org/10.3389/fsufs.2023.1017341

Nurhasan, M., Maulana, A.M., Ariesta, D.L., Usfar, A.A., Napitupulu, L., Rouw, A. et al. (2022). Toward a Sustainable Food System in West Papua, Indonesia: Exploring the Links Between Dietary Transition, Food Security, and Forests. Frontiers in Sustainable Food Systems 5, 789186. https://doi.org/10.3389/fsufs.2021.789186

Olanrele, I.A. and Fuinhas, J.A. (2022). Assessment of renewable electricity adoption in sub-Saharan Africa. Energy & Environment 35(2), 848-873. https://doi.org/10.1177/0958305X221118878

Organisation for Economic Co-operation and Development (2016). How stringent are environmental policies?. Better Policies for Better Lives OECD. Paris. https://www.oecd.org/economy/greeneco/How-stringent-are-environmental-policies.pdf

Organisation for Economic Co-operation and Development (2019). Aid in Support of Environment. Statistics based on DAC Members' reporting on the Environment Policy Marker 2016-2017. Paris

Organisation for Economic Co-operation and Development (2022). Global Outlook on Financing for Sustainable Development 2023: No Sustainability Without Equity. Paris. https://www.oecd.org/en/publications/global-outlook-on-financing-for-sustainable-development-2023_fcbe6ce9-en.html

Organisation for Economic Co-operation and Development (2024). Development Co-operation Profiles. Paris. https://www.oecd.org/en/publications/2023/06/development-co-operation-profiles_17afa013.html

Pawlak, K. and Kołodziejczak, M. (2020). The Role of Agriculture in Ensuring Food Security in Developing Countries: Considerations in the Context of the Problem of Sustainable Food Production. Sustainability 12(13), 5488. https://doi.org/10.3390/su12135488

Picchioni, F., Goulao, L.F. and Roberfroid, D. (2022). The impact of COVID-19 on diet quality, food security and nutrition in low- and middle-income countries: A systematic review of the evidence. Clinical Nutrition 41(12), 2955-2964. https://doi.org/10.1016/j.clnu.2021.08.015

Pinto, L.F., Gardner, T., McDermott, C. and Lara Ayub, K. (2014). Group certification supports an increase in the diversity of sustainable agriculture network–rainforest alliance certified coffee producers in Brazil. Ecological Economics 107, 59–64. https://doi.org/10.1016/j.ecolecon.2014.08.006

Pollard, C.M. and Booth, S. (2019). Food Insecurity and Hunger in Rich Countries-It Is Time for Action against Inequality. International journal of environmental research and public health 16(10), 1804. https://doi.org/10.3390/ijerph16101804

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E. et al. (2017). Land-use futures in the shared socio-economic pathways. Global Environmental Change 42, 331-345. https://doi.org/10.1016/j.gloenvcha.2016.10.002

Pratiwi, S. and Juerges, N. (2020). Review of the impact of renewable energy development on the environment and nature conservation in Southeast Asia. Energy, Ecology and Environment 5(4), 221-239. https://doi.org/10.1007/s40974-020-00166-2

Putra, A.S., Tong, G. and Pribadi, D.O. (2020). Food Security Challenges in Rapidly Urbanizing Developing Countries: Insight from Indonesia. Sustainability 12(22), 9550. https://doi.org/10.3390/su12229550

Rajput, A., Jiang, Y., Nayak, S. and Mostafavi, A. (2023). Mapping Inequalities in Activity-Based Carbon Footprints of Urban Dwellers Using Fine-Grained Human Trajectory Data.arXiv preprint arXi:2304.14417. Cornell University. https://arxiv.org/abs/2304.14417

Rashed, A., Yong, C.-C. and Soon, S.-V. (2022). The nexus among foreign direct investment in renewable electricity industry, renewable electricity production, and economic growth in Africa. Cogent Economics & Finance 10(1) 2001141. https://doi.org/10.1080/23322039.2021.2001141

Rehbein, J.A., Watson, J.E.M., Lane, J.L., Sonter, L.J., Venter, O., Atkinson, S.C. et al. (2020). Renewable energy development threatens many globally important biodiversity areas. Global Change Biology 26(5), 3040-3051. https://doi.org/10.1111/gcb.15067

Rentschler, J. and Leonova, N. (2023). Global air pollution exposure and poverty. Nature Communications 14(1), 4432. https://doi.org/10.1038/s41467-023-39797-4

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S., Donges, J. et al. (2023). Earth beyond six of nine planetary boundaries. Science Advances 9. https://doi.org/10.1126/sciadv.adh2458

Rodrik, D. and Stiglitz, J.E (2024). A New Growth Strategy for Developing Nations. Havard University. https://rasa-africa.org/ens/wp-content/uploads/2024/01/a_new_growth_strategy_for_developing_nations.pdf

Röös, E., Carlsson, G., Ferawati, F., Hefni, M., Stephan, A., Tidåker, P. et al. (2020). Less meat, more legumes: prospects and challenges in the transition toward sustainable diets in Sweden. Renewable Agriculture and Food Systems 35(2), 192-205. https://doi.org/10.1017/S1742170518000443

Ross, F. (2020). Kate Raworth-Doughnut economics: Seven ways to think like a 21st century economist (2017). Regional and Business Studies 11(2), 81-86. https://doi.org/10.33568/rbs.2409

Roth, A., Dukan, M., Anatolitis, V., Jimeno, M., Banasiak, J., Brückmann, R. et al. (2022). Financing conditions of renewable energy projects? results from an EU wide survey [version 2; peer review: 2 approved]. Open Research Europe 1(136). https://doi.org/10.12688/openreseurope.13969.2

Roy, D., Tarafdar, A. (2022). Solid Waste Management and Landfill in High-Income Countries. In: Pathak, P., Palani, S.G. (eds) Circular Economy in Municipal Solid Waste Landfilling: Biomining & Leachate Treatment . Radionuclides and Heavy Metals in the Environment. Springer, Cham. https://doi.org/10.1007/978-3-031-07785-2_1

Rozendaal, D., Bongers, F., Aide, T.M., Alvarez-Davila, E., Ascarrunz, N., Balvanera, P. et al. (2019). Biodiversity recovery of Neotropical secondary forests. Science Advances 5, eaau3114. https://doi.org/10.1126/sciadv.aau3114

Sarkodie, S.A. and Owusu, P.A. (2022). Global land-use intensity and anthropogenic emissions exhibit symbiotic and explosive behavior. iScience 25(8), 104741. https://doi.org/10.1016/j.isci.2022.104741

Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N. et al. (2018). Global Material Flows and Resource Productivity: Forty Years of Evidence. Journal of Industrial Ecology 22(4), 827-838. https://doi.org/10.1111/jiec.12626

Schandl, H., Hatfield-Dodds, S., Wiedmann, T., Geschke, A., Cai, Y., West, J. et al. (2016). Decoupling global environmental pressure and economic growth: scenarios for energy use, materials use and carbon emissions. Journal of Cleaner Production 132, 45-56. https://doi.org/10.1016/j.jclepro.2015.06.100

Searchinger, T., James, O., Dumas, P., Kastner, T. and Wirsenius, S. (2022). EU climate plan sacrifices carbon storage and biodiversity for bioenergy. Nature 612(7938), 27-30. https://doi.org/10.1038/d41586-022-04133-1

Seddon, P., Griffiths, C., Soorae, P. and Armstrong, D. (2014). Reversing defaunation: Restoring species in a changing world. Science 345, 406-412. https://doi.org/10.1126/science.1251818

Shono, K., Chazdon, R.L., Bodin, B., Wilson, S.E. and Durst, P.B. (2020). Assisted natural regeneration: harnessing nature for restoration. Unasylva, 252(71), 71-81. https://api.semanticscholar.org/CorpusID:226306092

Shrestha, A. and Kakinaka, M. (2023). Nexus between renewable energy certificates and electricity prices in India: Evidence from wavelet coherence analysis. Renewable Energy 204, 836-847. https://doi.org/10.1016/j.renene.2023.01.068

Siala, K., Chowdhury, A.K., Dang, T.D. and Galelli, S. (2021). Solar energy and regional coordination as a feasible alternative to large hydropower in Southeast Asia. Nature Communications 12(1), 4159. https://doi.org/10.1038/s41467-021-24437-6

Siddique, K. and Cuong, P. (2018). Rediscovering hidden treasures of neglected and underutilized species for Zero Hunger in Asia. Future Smart Food working for Zero Hunger. United Nations Food and Agriculture Organization, 181-192. https://openknowledge.fao.org/server/api/core/bitstreams/c96d9929-584c-4e8b-b1b9-b68068a8bec9/content

Simon, S., Naegler, T. and Gils, H.C. (2018). Transformation towards a Renewable Energy System in Brazil and Mexico—Technological and Structural Options for Latin America. Energies 11(4), 907. https://doi.org/10.3390/en11040907

Song, D., Jia, B. and Jiao, H. (2022). Review of Renewable Energy Subsidy System in China. Energies, 15(19), 7429. https://doi.org/10.3390/en15197429

Stamm, A. (2023). The sustainability transition requires extended and differentiated North South Cooperation for Innovation. UNCTAD Background Paper, United Nations Conference on Trade and Development, Geneva. https://unctad.org/system/files/non-official-document/tir2023_background5_en.pdf

Starr, J., Nicolson, C., Ash, M., Markowitz, E.M. and Moran, D. (2023). Income-based U.S. household carbon footprints (1990–2019) offer new insights on emissions inequality and climate finance. PLOS Climate 2(8), e0000190. https://doi.org/10.1371/journal.pclm.0000190

Sturm, V. and Banse, M. (2021). Transition paths towards a bio-based economy in Germany: A model-based analysis. Biomass and Bioenergy 148, 106002. https://doi.org/10.1016/j.biombioe.2021.106002

Sustainable Banking Finance Network, SBFN (2024). About the Sustainable Banking and Finance Network https://www.sbfnetwork.org/about-sbf-network. Accessed 1 September 2024

Teixidó-Figueras, J., Steinberger, J.K., Krausmann, F., Haberl, H., Wiedmann, T., Peters, G.P. et al. (2016). International inequality of environmental pressures: Decomposition and comparative analysis. Ecological Indicators 62, 163-173. https://doi.org/10.1016/j.ecolind.2015.11.041

Tilman, D., Clark, M., Williams, D., Kimmel, K., Polasky, S. and Packer, C. (2017). Future threats to biodiversity and pathways to their prevention. Nature 546, 73-81. https://doi.org/10.1038/nature22900

Turner, C., Kalamatianou, S., Drewnowski, A., Kulkarni, B., Kinra, S. and Kadiyala, S. (2020). Food Environment Research in Low- and Middle-Income Countries: A Systematic Scoping Review. Advances in Nutrition 11(2), 387-397. https://doi.org/10.1093/advances/nmz031

Tweneboah-Koduah, D., Arah, M. and Botchway, T. (2023). Globalization, renewable energy consumption and sustainable development. Cogent Social Sciences 9, 2223399. https://doi.org/10.1080/23311886.2023.2223399

Ulyshen, M., Urban-Mead, K., Dorey, J. and Rivers, J. (2023). Forests are critically important to global pollinator diversity and enhance pollination in adjacent crops. Biological reviews of the Cambridge Philosophical Society 98. https://doi.org/10.1111/brv.12947

United Nations (2023a). Financing for Sustainable Development Report: Financing Sustainable Transformations. Geneva, Switzerland. https://financing.desa.un.org/document/2023-financing-sustainable-development-report-financing-sustainable-transformations

United Nations (2023b). Global Sustainable Development Report. United Nations, New York https://sdgs.un.org/gsdr/gsdr2023.

United Nations Environment Programme (2019a). Global Resources Outlook 2019. International Resource Panel. Nairobi. https://www.resourcepanel.org/reports/global-resources-outlook

United Nations Environment Programme (2019b). Nigeria turns the tide on electronic waste https://www.unep.org/news-and-stories/press-release/nigeria-turns-tide-electronic-waste

United Nations Environment Programme (2024). Emissions Gap Report 2024: No more hot air ... please! With a massive gap between rhetoric and reality, countries draft new climate commitments. Nairobi. https://doi.org/10.59117/20.500. 11822/46404

United Nations Environment Programme (2024). Global Resources Outlook 2024. International Resource Panel. Nairobi. https://wedocs.unep.org/20.500.11822/44901

United States Energy Information Administration (2023). Coal Data Browser. https://www.eia.gov/beta/coal/data/browser. Accessed 7 February 2024

Utter, A., White, A., Méndez, V. and Morris, K. (2021). Co-creation of knowledge in agroecology. Elementa: Science of the Anthropocene 9(1), 00026. https://doi.org/10.1525/elementa.2021.00026

Van Rooij, B. and McAllister, L. (2012). Environmental Challenges in Middle-Income Countries: A Comparison of Enforcement in Brazil, China, Indonesia, and Mexico. Law and Development of Middle-Income Countries: Avoiding the Middle-Income Trap, 288-306. https://doi.org/10.1017/CBO9781139235730.018

van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., Doelman, J.C., van den Berg, M., Harmsen, M. et al. (2017). Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environmental Change 42, 237-250. https://doi.org/10.1016/j.gloenvcha.2016.05.008

Verhagen, J., Elzen, B., Koopmanschap, E., Reinhard, S., Verburg, C., Naranjo Barrantes, M. et al. (2022). Deltas under pressure, guidelines to facilitate transition pathways. Wageningen University & Research, The Netherlands. https://edepot.wur.nl/557946

Vicente Vicente, J., Doernberg, A., Zasada, I. and Piorr, A. (2021). A dataset of the food self-sufficiency assessment of Bristol and Vienna based on a foodshed approach. Data in Brief 38, 107434. https://doi.org/10.1016/j.dib.2021.107434

Vilaysouk, X., Schandl, H. and Murakami, S. (2019). A Comprehensive Material Flow Account for Lao PDR to Inform Environmental and Sustainability Policy. Journal of Industrial Ecology 23(3), 649-662. https://doi.org/10.1111/jiec.12764

Waha, K., Accatino, F., Godde, C., Rigolot, C., Bogard, J., Domingues, J.P. et al. (2022). The benefits and trade-offs of agricultural diversity for food security in low- and middle-income countries: A review of existing knowledge and evidence. Global Food Security 33, 100645. https://doi.org/10.1016/j.gfs.2022.100645

Wang, J., Li, C., Deng, Z., Carr, J., Stringer, L.C., Li, K. et al. (2025). Biodiversity Impacts of Land Occupation for Renewable Energy Infrastructure in a Globally Connected World. Environmental Science & Technology. https://doi.org/10.1021/acs.est.4c11453

Wang, J., Ji, C.-J., Liu, Y., Shan, Y., Hubacek, K., Wei, Y.-M. et al. (2024). Re-investigating the shared responsibility for trade-embodied carbon emissions. Ecological Economics 220, 108162. https://doi.org/10.1016/j.ecolecon.2024.108162

Wang, K., Cui, Y., Zhang, H., Shi, X., Xue, J. and Yuan, Z. (2022a). Household carbon footprints inequality in China: Drivers, components and dynamics. Energy Economics 115, 106334. https://doi.org/10.1016/j.eneco.2022.106334

Wang, F., Han, H., Liu, L. and Zhao, J. (2022b). Assessing the contribution of optimizing energy mix to China's carbon peaking. Environmental Science and Pollution Research 30(7), 18296-1831. https://doi.org/10.1007/s11356-022-23451-5

Wang, Q., Wang, L. and Li, R. (2022c). Does the energy transition alleviate environmental degradation? Evidence from the high income, upper and lower middle-income economies. Energy Strategy Reviews 44, 100966. https://doi.org/10.1016/j.esr.2022.100966

Wang, J. and Jia, Y. (2021). Social media's influence on air quality improvement: Evidence from China. Journal of Cleaner Production 298, 126769. https://doi.org/10.1016/j.jclepro.2021.126769

Wear, S., Acuña, V., McDonald, R. and Font, C. (2021). Sewage pollution, declining ecosystem health, and cross-sector collaboration. Biological Conservation 255, 109010. https://doi.org/10.1016/j.biocon.2021.109010

Wiebe, R.A. and Wilcove, D.S. (2025). Global biodiversity loss from outsourced deforestation. Nature 639(8054), 389-394. https://doi.org/10.1038/s41586-024-08569-5

Wiedenhofer, D., Guan, D., Liu, Z., Meng, J., Zhang, N. and Wei, Y.-M. (2017). Unequal household carbon footprints in China. Nature Climate Change 7(1), 75-80. https://doi.org/10.1038/nclimate3165

Wiedmann, T., Lenzen, M., Keyßer, L. and Steinberger, J. (2020). Scientists' warning on affluence. Nature Communications 11, 3107. https://doi.org/10.1038/s41467-020-16941-y

Williams, D., Celliers, L., Unverzagt, K., Videira, N., Manez Costa, M. and Giordano, R. (2020). A Method for Enhancing Capacity of Local Governance for Climate Change Adaptation. Earth's Future 8. https://doi.org/10.1029/2020EF001506

Wojtynia, N., van Dijk, J., Derks, M., Groot Koerkamp, P.W.G. and Hekkert, M.P. (2021). A new green revolution or agribusiness as usual? Uncovering alignment issues and potential transition complications in agri-food system transitions. Agronomy for Sustainable Development 41(6), 77. https://doi.org/10.1007/s13593-021-00734-8

Wolske, K.S. and Stern, P.C. (2018). Contributions of psychology to limiting climate change: Opportunities through consumer behavior. In Psychology and climate change: Human perceptions, impacts, and responses. San Diego, CA, US: Elsevier Academic Press. 127-160. https://doi.org/10.1016/B978-0-12-813130-5.00007-2

Woodhill, J., Kishore, A., Njuki, J., Jones, K. and Hasnain, S. (2022). Food systems and rural wellbeing: challenges and opportunities. Food Security 14(5), 1099-1121. https://doi.org/10.1007/s12571-021-01217-0

World Bank (2022). What you need to know about nature-based solutions to climate change. Washington DC, USA. https://www.worldbank.org/en/news/feature/2022/05/19/what-you-need-to-know-about-nature-based-solutions-to-climate-change

World Bank (2023a). World Bank Country and Lending Groups. Washington DC, USA. https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups. Accessed 25 January 2024

World Bank (2023b). Human-Wildlife Conflict: Global Policy and Perception Insights. Washington DC, USA. https://www.worldbank.org/en/programs/global-wildlife-program/brief/human-wildlife-conflict-global-policy-and-perception-insights

World Resources Institute (2019). Creating a sustainable food future. A menu of solutions to feed nearly 10 billion people by 2050. Washington DC, USA. https://www.wri.org/research/creating-sustainable-food-future

Wudil, A.H., Usman, M., Rosak-Szyrocka, J., Pilař, L. and Boye, M. (2022). Reversing Years for Global Food Security: A Review of the Food Security Situation in Sub-Saharan Africa (SSA). International Journal of Environmental Research and Public Health 19(22), 14836. https://doi.org/10.3390/ijerph192214836

Zhang, X.-P., Ou, M., Song, Y. and Li, X. (2017). Review of Middle East energy interconnection development. Journal of Modern Power Systems and Clean Energy 5(6), 917-935. https://doi.org/10.1007/s40565-017-0335-7

20 Regional Dimensions of the Transformative Solutions for the Global Environmental Crises

Overall Coordinating Lead Authors: Lindsay Beevers (The University of Edinburgh), Madhav Bahadur Karki (Centre for Green Economy Development, Nepal)

General Contributing Authors: Edward Byers (IIASA), Jianguo Liu (Michigan State University)

AFRICA AND SUBREGIONS

Coordinating Lead Authors: Monday Businge (University of Nairobi), Rachid Mrabet (National Institute of Agricultural Research, Morocco)

Lead Authors: Aliyu Salisu Barau (Bayero University Kano; Urban Climate Change Research Network), Souhila Boulouta (National Economic Social and Environmental Council), Veronica Mwangi (University of Nairobi), William Armand Mala (Department of Plant Biology, University of Yaoundé I, Cameroon)

Contributing Author: Tanya Brodie Rudolph (University of Stellenbosch)

Fellows: Jan Matuštík (University of Chemistry and Technology Prague), Sènankpon Tcheton (Global Change Institute of the University of the Witwatersrand)

ASIA AND THE PACIFIC AND SUBREGIONS

Coordinating Lead Authors: Meena Bohara (National Young Academy of Nepal, Forest Action Nepal), Gensuo Jia (Chinese Academy of Sciences)

Lead Authors: Sanchit Saran Agarwal (The Energy and Resources Institute), Kalpana Chaudhari (Shah and anchor Kutchhi engineering college, institute for sustainable development and research (ISDR) , India), Hancheng Dai (Peking University), Fangxia Shen (Beihang University), Jinlong Liu (Renmin university of China)

Contributing Authors: Shaneel Chandra (Central Queensland University), Leila Zamani (Department of Environment of Iran), Kejun Jiang (Hong Kong University of Science and Technology), Jiayi Ng (Agency for Science, Technology and Research)

Fellow: Ruijun Chen (Fuzhou University, China)

EASTERN EUROPE AND SUBREGIONS

Coordinating Lead Authors: Kateřina Černý Pixová (Czech University of Life Sciences Prague), George Florin Staicu (Academy for Economic Studies, Bucharest, Romania)

Lead Authors: Aistė Balžekienė (Kaunas University of Technology, Lithuania), Judit Oláh (John von Neumann University Doctoral School of Management and Business Administration, Hungary; Faculty of Economics and Business, University of Debrecen, Hungary), József Popp (John von Neumann University Doctoral School of Management and Business Administration, Hungary)

Fellow: Jan Matuštík (University of Chemistry and Technology Prague)

LATIN AMERICA AND THE CARIBBEAN AND SUBREGIONS

Coordinating Lead Authors: Donovan Campbell (The University of the West Indies), Gladys Cecilia Hernandez-Pedraza (Centro de Investigaciones de la Economia Mundial)

Lead Authors: Danielle Mendes Thame Denny (University of São Paulo - Research Centre for Greenhouse Gas Innovation and Centre for Carbon Research in Tropical Agriculture), Alma Mendoza-Ponce (National Autonomous University of Mexico (UNAM)), Jean Pierre Ometto (National Institute for Space Research (INPE), Brazil)

Contributing Author: Shaneica Lester (The University of West Indies)

Fellow: Emmanuelle Freitas (Centre for Mineral Technology), Shaneica Lester (The University of West Indies)

WESTERN EUROPE AND OTHERS GROUP AND SUBREGIONS

Coordinating Lead Authors: Barbara Amon (Leibniz Institute for Agricultural Engineering and Bioeconomy), Paul Sutton (University of Denver)

Lead Authors: Peter Edwards (Manaaki Whenua Group, Bioeconomy Science Institute, Wellington, New Zealand), Michele Filippo Fontefrancesco (Università Cattolica del Sacro Cuore), Joana Portugal Pereira (Coppe/ Federal University of Rio de Janeiro and IST/ULisboa), Thomas Thornton (University of Alaska)

Contributing Authors: Alan Feest (University of Bristol), Amy Molotoks (Stockholm Environment Institute, University of York)

Fellow: Amy Molotoks (Stockholm Environment Institute, University of York)

Credit: KrzysztofBubel/Envato

Chapter summary

Credit: ©UNEP

OVERALL MESSAGE: There is an urgent need for regionally specific transformative actions. It is clear from our analysis that continuing the current pathway is undesirable and unsustainable (*well established*).

Human and natural systems around the globe are connected both locally and through distant processes (tele-coupling), such as international trade, migration, foreign investment, and flows of ecosystem services (Chapter 8) {20.9} **The regionally specific transformative pathways provide ways in which transformation can happen across the five interconnected systems for the global regions. As the systems are transformed in an interconnected manner at regional and subregional scales, there is a need to reflect on the global interconnections by examining change in tele-coupling dynamics** (*well established*). {20.9, 20.9.1, 20.9.1.1} **Changing tele-coupling dynamics may reshape the geographic distribution of environment-socioeconomic impacts. To minimize trade-offs, it is crucial to enhance synergies among different regions for global sustainability** (*established but incomplete*). {20.9.1}

A. Economic and financial system transformation

A transformation of financial and economic systems in Africa can support the significant debt crisis across the region where countries are dependent on foreign aid. To accelerate much-needed financial systems reforms, Africa needs to fully unlock the continent's potential by greening and incentivizing finance systems (*established but incomplete*). Developing mechanisms by which both public and private creditors can provide debt relief to African Nations is critical; investment in the green transition is expected to reach US$190 billion and increasing private finance is essential to supplement public contribution, such as through supporting the African Union's Green Recovery Action Plan. African nations can develop partnerships that promote mutual benefit and long-term sustainability rather than resorting to aid that perpetuates a cycle of dependency undermining the goals of development assistance. African demographics show significant youth-dominated regions can become the next frontier for

investment by leveraging the demographic dividend. A strategic and multi-sectoral approach to investment in preserving ecological infrastructure and ecosystem services and the reorientation of revenue streams towards sustainability principles are essential for allocating scarce public and private resources to achieve economic and social-ecological priorities. Economically more-developed economies can be encouraged to support Africa's green investments under the principle of common but differentiated responsibility. {14.5.1; 14.3; 14.6; 20.4.2.4; 20.4.3.4}

The Asia and the Pacific (AP) region can accelerate climate and biodiversity solutions by transforming their financial systems and integrating green finance measures in national budgeting and expenditure processes (*well established*). **It is imperative that an integrated socio-ecological and economic accounting system is developed that links biophysical aspects of ecosystems with human benefits through the concept of ecosystem services. At the same time, regional finance institutions need to undergo major reform, by mainstreaming climate-resilient and nature-positive financing strategies to transform them into environmentally sound financial institutions** (*established but incomplete*). Environmentally sound financial institutions can fund projects and companies that are benefiting the environment. The Asian Development Bank and the Asian Infrastructure Investment Bank can be reformed further to invest in climate-inclusive and green initiatives. These financial institutions can scale-up concessional loans, equity investments, guarantees, capacity-building and investment-advisory services to support green projects, especially in low-income countries across the region. Enhanced Nationally Determined Contribution commitments can be achieved through increased investments in nature-based solutions to protect natural capital, including sustainable management of terrestrial, freshwater and marine ecosystems. {14.3; 14.4; 20.5.2.5; 20.5.3.4}

Financial and economic transformation in the Eastern European (EE) region is diverse and ranges across European Union (EU) candidate/member states and other countries. For EU member states, and candidate and partnership countries, reforms aligning with EU directives and green transition policies can deliver transformations (*established but incomplete*). **Green innovation-based finance and carbon tax measures can boost investments and consumption towards sustainability. Meanwhile, non-EU related countries can implement distinct strategies** (*well established*). Eastern Europe needs targeted policies to unlock green finance and ensure effective deployment across urban and rural systems. Policy innovation should integrate water-smart strategies – such as household metering, pricing signals, and drought-resilient infrastructure – to minimize water demand, especially in agriculture and peri-urban areas. Green infrastructure investments, including blue-green corridors that link wetlands, parks, and stormwater systems, require long-term capital flows and risk-sharing frameworks. To accelerate uptake, financial tools such as green municipal bonds, concessional lending, and EU-aligned sustainability taxonomies must be tailored to local contexts. Equally important are behavioural communication strategies that shift public norms and business practices. Community engagement and transparent governance will be critical in scaling nature-positive infrastructure and achieving a region-wide transition to circular, low-emission economies. {14.5; 20.6.2.2; 20.6.3.2}

Transformative economic and financial reforms are essential for Latin America and the Caribbean (LAC) to avert climate-induced economic losses, currently projected to reach 100 per cent of GDP by 2050, and build a resilient, inclusive future (*well established*). Targeted investments in resilient infrastructure, fiscal realignment, and green finance are critical to mitigating climate risks that disproportionately affect the region, with estimated losses and damages at 83 per cent of regional GDP – far above the global average. Effective market interventions and stronger institutional capacities are vital for equitable economic transitions. Financial resilience requires scaling up instruments such as green bonds, climate risk insurance, community-led green investments, and debt-for-nature swaps. Carbon pricing, green taxation, and emissions trading can incentivize low-carbon development and finance of adaptation initiatives. Public-private partnerships and innovative models, such as sustainability-linked bonds, can mobilize private capital. Sovereign risk pooling and catastrophe bonds are crucial for buffering economic shocks and stabilizing growth. {14.4; 14.5; 20.7.2.4; 20.7.3.4} bonds, climate risk insurance, community-led green investments, and debt-for-nature swaps. Carbon pricing, green taxation, and emissions trading can incentivize low-carbon development and finance of

adaptation initiatives. Public-private partnerships and innovative models, such as sustainability-linked bonds, can mobilize private capital. Sovereign risk pooling and catastrophe bonds are crucial for buffering economic shocks and stabilizing growth. {14.4; 14.5; 20.7.2.4; 20.7.3.4}

Transforming the energy, material, food and environmental systems is impossible without transforming the financial system in the Western European and Others Group (WEOG) region and throughout the world (*well established*). **The WEOG countries represent roughly 10 per cent of the world's population while they own almost 60 per cent of the world's wealth and enjoy more than half of the world's annual income. Consequently, WEOG countries have a responsibility to demonstrate the desired transitions at home and abroad** (*established but incomplete*). Possible solutions include internalizing externalities or getting-prices-right, reducing risks associated with foreign direct investment in the developing world, debt cancellation, and the development and expansion of existing financial tools used for redistribution and investment, such as EU Green Bonds. These can be complemented by green finance or getting-incentives-right. Examples of this include introducing carbon taxes, green taxes and incentivizing the private sector for innovative financing of circular economic measures such as waste-to-energy. Further possibilities include strengthening the role of Government to use subsidies and revenue from taxes as disincentives for certain non-sustainable economic activities, internalization of external costs, and incentives for labelling, certification, and carbon neutrality. {14.3; 14.4; 14.6; 20.8.2.5; 20.8.3.4}).

B. Transformation towards circularity

Africa can simultaneously invest in circular economy infrastructure and technologies and integrate sustainable consumption and waste management practices utilizing the continent's excellent capacity to outpace linear development. Transitioning to responsible and sustainable material consumption, linearity to circularity, for industrial and urban systems requires substantial financial commitments in Africa (*well established*). **Africa's low industrialization and rapid urbanization offer a unique opportunity to leapfrog to circularity by designing out waste and embracing sustainable construction, resource-efficient manufacturing, and material efficiency technologies alongside honouring the 2018 African Ministerial Conference on the Environment pledge to establish concomitant harmonized regional environmental policies** (*established but incomplete*).

Africa generates 180 million tons of waste a year, of which 70 per cent is openly dumped or burned. Sustainable material production and consumption transformations are essential to conserve Africa's finite resources, with demand projected to rise by 150 per cent by 2050. The shift requires considerable investment and policy reforms. States can access multilateral and blended finance by creating conducive regulatory environments. Public awareness drives and education geared at reducing conspicuous consumption can complement technological advancements in material recycling towards circularity. The resulting economic growth, job creation, cost savings, improved efficiency, new market opportunities, and increased resilience are expected to far outweigh the initial challenges. Africa has a special opportunity to implement "extended producer responsibility" and develop this policy approach further towards "ultimate producer responsibility". Ultimate producer responsibility has the potential to be a game-changing policy instrument given the continent's rising consumption, its position as a consumer of used goods from throughout the world, and its aspirations for green industrialization. {15.2.3; 20.4.2.2; 20.4.3.3}

Five out of the ten countries with the highest plastic waste volumes and six out of the ten highest polluted countries in the world are in the AP region. This legacy pollution, high populations, high emissions and low air quality are distributed differentially across the region. Transformation towards circularity is possible with the key requirements of enforceable regulatory frameworks and citizen's participation to manage waste across sectors (*well established*). There is a need for leadership in packaging with innovation, easier recycling, creative solutions, and better garbage collection and landfill management policies. Enabling legal and policy frameworks, alongside financial and accounting frameworks can help eliminate problems such as single use plastic bags. A mix of regulatory measures, good-practice-based advocacy, knowledge and awareness building for behavioural change can help make a substantial shift in personal and organizational actions. The progress under transformation pathways will be slow initially but is projected to increase by 2030 supported by reducing material demand. {15.2; 20.5.2.4; 20.5.3.3}

By transitioning from managing waste to designing out waste and designing in circularity, the EE region can move towards a circularity transformation and address legacy pollution challenges arising from mining and the ongoing war in Ukraine (*established but incomplete*). This will require binding targets on waste reduction and material recycling, which currently only exist in the sector covering municipal waste and construction and demolition waste, but will be introduced in other sectors as currently material circularity rates are lower than most other European countries (well established). Policy measures may focus on preventing e-waste and stimulate the related e-waste collection and recycling rate and on promoting sustainable production and consumption, coupled with lifestyle change to reduce overconsumption, thus lowering material footprints. These efforts should include reversing the decline of traditional repair shops – such as watch repair, cobbler services, electronics, and home appliance repairs – coupled with the new societal practices of circular lifestyle choices. {15.2.5; 20.6.2.3; 20.6.3.3}

A transformative shift towards circularity in LAC by 2050 requires targeted actions that drive resource efficiency, waste reduction, and sustainable growth, particularly in addressing marine pollution and plastics (*well established*). Strengthening regulatory frameworks and market-based incentives can accelerate circular practices across industries, including biogas generation through anaerobic digestion, regenerative agriculture, and closed-loop manufacturing. Deploying smart waste management systems, such as real-time tracking and automated sorting, can optimize resource flows and minimize leakage into the environment. Modernizing municipal waste systems through public-private partnerships and sustainability financing can improve collection and recycling in underserved areas. Expanding circular business models and building skilled workforces through reskilling programs are crucial for sustainable economic growth and resilient supply chains. {15.3; 20.7.2.3; 20.7.3.3}.

The WEOG countries can address transforming material and waste management systems to circularity through the reallocation of existing resources. The three primary levers of control for transformation in WEOG are implementation of circularity principles, eliminating planned outdatedness, and increasing eco-taxation (*well established*). The shift towards green consumerism through prioritizing sustainable eco-friendly products and services can be supported by digital tools such as community platforms and by new regulatory oversight of advertising messages and emerging market reforms to support the sharing economy. Similarly, behaviour change can be achieved with financial incentives such as eco-taxation to support a shift towards sustainable lifestyles that prioritize quality over quantity, As well, sharing and reductions in material consumption should be supported. {15.2.2; 20.8.2.3}

C. Energy system transformation

By taking a holistic, integrated and Africa-led approach to addressing both the supply and demand sides of energy, the continent can achieve universal energy access, drive sustainable economic growth, and play a global leadership role in the clean and just energy transition. Africa can transform the primary energy system while simultaneously increasing access to energy at the household level, through rural electrification drives, connecting households to national and decentralized grids and increasing the overall share of renewables enhancing the existing hydropower provision and embracing solar, wind and geothermal technologies (*well established*). With 13 per cent of the world's hydropower potential, Africa can use its available water resources, such as the Congo River Basin, to realize its hydropower potential and scale-up clean-energy provision. To address inequitable energy access in Africa, aggressive rural electrification and decentralized grids can be delivered through new wind and solar technology, alongside a just transition to modern clean cooking fuels at the household level. Financial incentives through repurposed subsidies can support this transition alongside raising awareness, aligning with evolving pro-environmental consumer values,, providing sustainable mobility choices such as mass rapid transit systems, and enforcing responsibility through taxation, underpinned by sound governance. {16.2.1; 16.2.2; 16.3.3; 16.4.2; 20.4.2.1; 20.4.3.1}

Regionally diverse and with the largest energy use, driven by increased consumption especially from emerging economies, Asia and the Pacific region is expected to increase its share of the global energy demand by 2050. The region can achieve a transformation to meet universal electricity access

by 2050, with financial system support, through regionally appropriate renewable energy deployment, increased energy access, rural electrification and decentralized grids, and electrification of transport systems (*well established*). Most AP countries can embrace solar and wind technologies, increasing the market to 38 per cent by 2050 (**Figure 20.6**). The Pacific Island countries can promote floating solar off-grid solutions, while there is high potential for wind and solar energy production in West Asia. Grid infrastructure strengthening with associated policy reform is necessary to support hydrogen and biofuel energy in emerging economies. Electrification of the transport system, especially in large urban conurbations, alongside financial incentives through taxation of large vehicles. Private sector involvement in financial policies and regulation is required, alongside demand side measures driven by lifestyle changes and market reforms. {16.2.1.; 16.3.2; 16.3.3; 20.5.2.1; 20.5.3.1}

Eastern Europe depends heavily on fossil fuels, however by 2050 a low-emission, green economy is possible through following similar pathways as pursued by the EU. This entails embracing renewable energy through repurposing financial subsidies, developing a cross-border carbon adjustment mechanism, breaking monopolies, and enforcing stronger regulation of energy markets (*well established*). To improve the environment and public health, particularly air quality, and to reduce energy poverty, EE can increase the renewable share through policy incentives such as decentralized green energy production and support civic energy to break state monopolies through establishing energy communities. As well, repurposing subsidies, such as EU Social Climate Fund and ETS revenues, can lower energy bills, promote clean transport, and invest in energy-efficient housing. These changes can be supported by awareness-raising about lower energy lifestyles, mechanisms to finance renewable and efficient energy infrastructure at the household level, and sustainable mobility options. {16.3.2; 16.2.3; 16.3.3; 20.6.2.4; 20.6.3.4}

Resilient decarbonization through smart electrification and microgrids is essential for sustainable energy transformation in LAC by 2050 (*well established*). Electricity demand is expected to increase significantly under both behaviour and technology-focused pathways, highlighting the need for decentralized energy systems that enhance disaster resilience, expand rural access, and support renewable integration. Abundant wind, solar, and bioenergy resources can complement existing hydropower, reducing water stress. Regional cooperation is crucial to fund clean energy projects like offshore floating photovoltaics and wind installations, minimizing land-use changes. In the Caribbean, transitioning to wind and solar could cut fuel imports by 70 per cent and reduce fossil fuel dependence by 60 per cent by 2050. Community-shared energy facilities – such as micro hydro, solar home systems, and off-grid mini-grids – could electrify 20 million underserved rural residents. {16.2.1; 16.2.3; 20.7.3.1}

The WEOG countries have a long legacy of mineral and fossil fuel extraction, therefore, they can achieve rapid decarbonization through transitioning to renewable energy, enhancing energy efficiency, reducing energy consumption, and supporting electricity-based transportation. As well, WEOG countries can refine and demonstrate carbon dioxide removal strategies. Three primary actions for transformation are ending fossil fuel subsidies, large-scale implementation of smart grids and efficiency gains in both consumption and production of energy (*well established*). Carbon capture and storage and bioenergy with carbon capture and storage technology are projected to rise by 2050. However, this projection is based on currently unachieved scientific and technological innovations. Reductions in energy use can be supported through low-energy consumption principles at both industry and household level, alongside a move to collective community action adopting domestic energy production by 2050. {16.2.2; 16.2.3; 16.3.3; 20.8.2.1; 20.8.3.1}

D. Transformation of food systems

To address food security and undernourishment, with 286 million undernourished population in 2020, Africa can transform the food systems taking a holistic approach that prioritizes sustainability, equity and the integration of Indigenous Knowledge and Local Knowledge processes with modern technologies (*well established*). In other terms, by systematically addressing interconnected dimensions of food security, environment sustainability and social harmony, Africa can build resilient, equitable, and sustainable food systems that not only feed

its population but also nurture its environment and foster lasting peace. Dietary change in Africa can be achieved through leveraging indigenous cultivar and culinary diversity and commercially producing protein-rich food sources and encouraging using all part of a plant to reduce waste, which can improve food security in low-income communities. By strategically integrating transhumance and stable livestock farming, Africa can transform its livestock sector into a more productive, resilient, and environmentally sustainable system, contributing significantly to food security and rural development, particularly in the Sahel and East Africa. Inclusive governance, conservation-based agriculture intensification, and agroecological innovation can deliver stable and quality food production while strengthening energy, food, and nutrition security and reducing poverty, thereby improving the resilience and health security of vulnerable communities. {17.2.1; 17.2.3; 17.2.4; 20.4.3.2}.

To address food security and nutritional food demand, food system transformation in the Asia and the Pacific region is critical due to increasing demand and supply gap, unsustainable production practices, rapid population growth and urban expansion. Transformation can be achieved through a shift to sustainable diets, including Indigenous and local food systems and production of novel foods. An important component is countering the rise in meat and dairy consumption among AP's growing middle class, by rearing regionally appropriate livestock on pasture, supporting the growing vegetarian and vegan movement and connecting small-scale farmers with supermarkets through government support or private finance (*established but incomplete*). Reducing food loss and reusing food waste for nutrient recovery through backyard composting in rural towns can reduce pressure on land degradation. Specific to AP is the potential for aquaculture to remain a global strength, with 92 per cent of the global market in farmed fish. Sustainable aquaculture must be supported through governance reform to curb overfishing and promote responsible intensification by redirecting subsidies into upgrading the value chain. {17.2.5; 17.2.3; 20.5.2.2; 20.5.3.2}

Eastern Europe is a crucial contributor to global food security, currently producing 22 per cent of the world's wheat. Achieving food system transformation must address land degradation and rural depopulation. Transformation can occur through shifting to a sustainable diet of plant-based food, improving health outcomes. This shift will drive an 11 per cent increase in demand for food crops by 2050, supported by a 41 per cent increase in agricultural productivity by 2050 if precision farming and waste reduction strategies are embraced (*well established*). Eastern Europe's agricultural sector is poised to remain a cornerstone of regional GDP, offering both economic stability and a safety net through resilient small-scale farming. Empowering these producers with access to land, finance, and markets can safeguard food sovereignty and rural livelihoods. Dietary shifts away from livestock-based diets – potentially reducing crop demand for feed by up to 49 per cent – can lower land-use intensity and soil degradation. This transition must be supported by policies that promote nutrient-rich, plant-based diets and encourage food literacy through schools and community programmes. Eastern Europe can leverage its long-standing tradition of community-based food systems – such as cooperative farming, local markets, and household gardens – to advance circularity, nutrition security, and climate-smart agriculture. Integrated policy support linking agroecology, sustainable consumption, and low-impact production will be essential to address environmental pressures while ensuring inclusive economic opportunities across urban and rural communities. {17.2.1; 17.2.5; 20.6.2.5; 20.6.3.5}

Achieving a just and resilient food system transformation in LAC by 2050 requires targeted support for smallholders and Indigenous communities, alongside climate-adaptive agricultural practices that restore ecosystems and enhance food security (*well established*). Prioritizing agroecology, secure land tenure, and healthy diets can drive forest recovery and biodiversity gains. The behaviour-focused pathway envisions a 46 per cent reduction in agricultural land by 2050, while the technology-focused pathway anticipates a 50 per cent increase in livestock and cropland, risking ecological harm. Sustainable food production strategies include urban agriculture in the Caribbean, precision farming in Central America, and no-deforestation supply chains in South America. These shifts can reduce water demand by 12 per cent, nutrient run-off by 20 per cent, and malnutrition by 98 per cent, while improving calorie distribution by 58 per cent. Financial mechanisms, regional cooperation, and inclusive policies that consider

gender, rural and low-income populations, are essential for equitable and sustainable food systems. {17.2.2; 17.2.3; 20.7.2.2; 20.7.3.2}.

The WEOG region currently produces 30 per cent of the global food supply. The transformation to sustainable food production – threatened by climate-induced heat, flooding and drought – is possible by shifting to more plant-based diets potentially supplemented by new products and markets (*well established*)**.** The three primary actions for transforming the food system in WEOG are promoting sustainable agricultural practices and food production systems, including Indigenous practices that support food sovereignty, circular economies, and well-being; optimizing logistics for food value chains to reduce food waste; and shifting towards plant-dominated diets (well established). To support a just transition, the promotion of ecologically sound agriculture intensification and customized technological interventions should be prioritized to achieve sustainable farming practices. These efforts can be bolstered by advancements in precision farming and developments in plant and livestock breeding. Reducing food waste is essential. {17.2.4; 17.2.5; 20.8.2.2; 20.8.3.2}

E. Environmental System Transformation

Environmental sustainability in Africa is crucial, given the continent's immense biodiversity, vulnerability to climate change, reliance on natural resources for livelihoods, and rapid population growth and urbanization. Transformative nature-positive and climate-adaptive actions can slow down the 1.4 million km^2 of land degraded and reverse deforestation trends, such as the 20 per cent decrease in vegetation cover experienced in the East African Highlands (*well established*). Africa's diverse ecosystems offer significant opportunities for sustainable conservation, ecosystem-based adaptation and carbon sequestration. To maximize this potential, initiatives like REDD+ that support green value chains, payment for ecosystem services, and community-based forest management can promote sustainable land use and forest conservation. These efforts, supported by funding from the Green Climate Fund and other financial institutions, can capture the carbon value of well-managed forests and agricultural lands. Promoting carbon-neutral energy, climate-resilient agriculture, and nature-positive investments can help policymakers reduce greenhouse gas emissions and address land-use damages like nutrient depletion, salinity and erosion, with high-emitting countries providing the requisite financial support, technology transfer, and capacity-building assistance through multilateral financial institutions. Integrating Indigenous Knowledge with scientific practices can further enhance sustainable land management, reduce deforestation, and strengthen climate resilience. Africa can genuinely transform its financial system to become a potent force for biodiversity preservation and climate action – unleashing its vast natural wealth for sustainable development – by concurrently bringing capital into the system and guaranteeing a strong pipeline of investable green projects. {18.2.1; 18.2.4; 20.4.2.3; 20.4.3.5}.

Strengthening regional cooperation in the AP region is vital to achieve transformative solutions through knowledge-sharing, technology transfer, and international partnership (*well established*). Adopting green innovation with integrated technology alongside lifestyle change can support environmental transformation. Regional and transboundary cooperation can lead to sustainable conservation, strengthening synergies between climate and biodiversity actions at landscape and seascape levels. Prioritizing technological innovation and energy efficiency emerge as key strategies tightly connected to emission reduction and playing vital roles in ecological management. Growing numbers of nature-based solutions pilot cases offer insights for potential adoption in the Pacific Small Island States. Ecosystem-based adaptation is widely recognized in the AP regions as sustainable approaches to climate change adaptation. Integrating climate-resilient agroforestry, sustainable forest management, and conservation agriculture practices using Indigenous and local knowledge can improve ecological integrity of both agriculture and forest ecosystems. {18.2.1; 18.2.3; 20.5.2.3; 20.5.3.5}

Although numerous sites in EE have legacy pollution issues and require revitalization, a transformation towards a resilient environmental system is possible. A shift towards sustainable diets promoted by a food system transformation will drive the adoption of precision farming, regenerative agriculture, organic farming and sustainable forestry, leading to improved soil health and reduced chemical inputs and promoting a healthier ecosystem (*well established*). Nature-based infrastructure and sustainable

production techniques can drive transformative environmental outcomes in Eastern Europe. Although the region hosts many protected areas, most suffer from poor management, weak enforcement, and fragmented ecological networks – undermining their effectiveness as biodiversity and climate buffers. Addressing land degradation will require investing in connectivity across green corridors, riparian zones, and rewilded landscapes, alongside integrated watershed management to enhance ecosystem services and water security. Nature-based solutions, such as wetland restoration, agroforestry buffers, and reforestation, must be embedded in spatial planning and regional investment strategies. However, weak environmental activism at both individual and community levels hinders behavioural transformation. {18.2.1;18.2.2; 20.6.2.6; 20.6.3.6}

Transforming environmental systems and reversing biodiversity loss by 2050 in LAC requires large-scale nature-based solutions supported by green finance and regional cooperation (*well established*). Achieving net-negative emissions through a 50 per cent reduction in CO_2, a 16 per cent expansion in forest cover, and a five gigaton gain in carbon stocks demands large-scale reforestation, regenerative agriculture, and afforestation over 190-296 million hectares. Restoring mangroves, seagrasses, and coral reefs can enhance blue carbon storage and protect coastlines. Indigenous-led stewardship, backed by policy frameworks that secure land rights and fund ecological knowledge, is crucial. Green urban infrastructure, satellite monitoring, and circular economy strategies in agriculture and construction can minimize waste and pollution. Financing mechanisms like green bonds and carbon credit markets, alongside regional cooperation in transboundary ecosystems, are essential for scaling nature-based solutions and enhancing community resilience across LAC. {18.2.1; 18.2.2; 20.7.2.5; 20.7.3.5}.

Nature-based solutions including nature-positive climate actions are imperative to address complex and interactive environmental effects in the WEOG region (*well established*). **Improvement in environmental stewardship can be achieved through establishing global monitoring of ecosystem function, developing integrated economic and environmental accounting, and enhancing natural and technical carbon sequestration** (*well established*). Countries of the WEOG, by transforming their financial systems, can lead by example, inspiring other regions to adopt similar practices. The positive examples in high-income countries can enhance international cooperation on climate initiatives, technology transfer, and sustainable development goals, creating a more robust collective global response to environmental challenges. Shifting to nature-positive diets, reducing food waste, and minimizing postharvest loss can decrease the land required for intensive agricultural production and support biodiversity. By reducing consumption and waste, material system changes decrease resource demand and environmental degradation as demonstrated by Indigenous Peoples' traditional circularity practices {18.2.3; 18.2.4; 20.8.2.4; 20.8.3.5} can enhance international cooperation on climate initiatives, technology transfer, and sustainable development goals, creating a more robust collective global response to environmental challenges. Shifting to nature-positive diets, reducing food waste and minimizing postharvest loss can decrease the area needed for agriculture, reducing biodiversity loss. By reducing consumption and waste, material system changes decrease resource demand and environmental degradation as demonstrated by Indigenous Peoples' traditional circularity practices {18.2.3; 18.2.4; 20.8.2.4; 20.8.3.5}.

20.1 Introduction

This chapter presents plausible and potential future outlooks for the five United Nations regions in the face of three global environmental crises that are formally defined as the crisis of climate change, the crisis of biodiversity loss, land degradation and desertification, and the crisis of pollution and waste. The future outlooks for the United Nations regions are assuming the effective implementation of transformative pathways (Chapters 9-11). This chapter focuses on responding to the policy questions below and discusses how the transformations of five systems – economic and financial, energy, food, materials, and environmental – can happen:

1. How does policy development and implementation in one region affect other regions or other countries, and what is needed to maximize positive and minimize negative effects?

2. How could the interrelationships of the environmental issues and the energy, food, materials/waste systems change in the future, and what pathways and scenarios could lead to environmentally sustainable futures, building on synergies, while minimizing unintended consequences?

3. Can the internationally agreed environmental goals be met? How are the socioeconomic impacts of the system transformation distributed differently across countries at different socioeconomic development trajectories and climate vulnerability?

4. How can countries address uneven or skewed effects of these socioeconomic impacts?

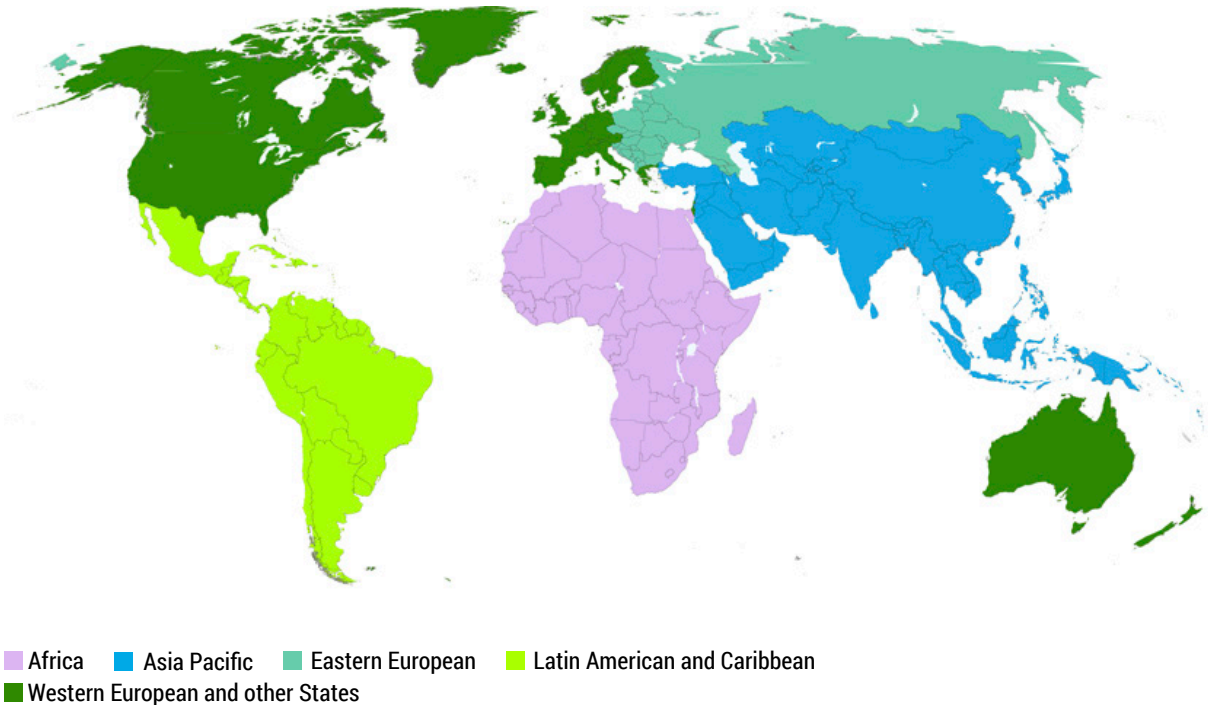
The Chapter responds to the above policy questions in a consolidated manner covering all the five United Nations regions by disaggregating the global modelling results from the previous chapters and explores regionally differentiated transformation pathways. The chapter outlines potential trajectories in which the transformation can occur.

20.2 Approach

Chapter 20 presents the regional outlooks across five United Nations-defined regions (**Figure 20.1**):

- Africa
- Asia and the Pacific [AP]
- Eastern Europe [EE]
- Latin America and the Caribbean [LAC]
- Western Europe and Other Group [WEOG]

Figure 20.1: Regional groups of UN Member States



It takes as its starting point the environmental priorities highlighted in Chapter 8 (**Table 20.1**) and focuses on analysing regional similarities and differences in the implications of two different pathways. Available literature evidence (IEA 2023; UNEP 2023; UNECS 2024a), makes it clear that developed and developing countries will follow different pathways to tackle the global environmental crises (Desai 2022). These pathways represent a spectrum of future possibilities through which transformation can happen.

Two different transformation scenarios have been designed: the *GEO-7 Behaviour-focused Transformation Scenario and the GEO-7 Technology-focused Transformation Scenario* (Chapter 11) that yield the various transformation pathways explored. The disaggregated modelling outputs are used in conjunction with the region-specific actions identified in the solution pathway chapters (Chapters 14-18) and in combination with peer-reviewed literature, including Indigenous Knowledge and Local Knowledge perspectives, to provide contextual narratives on regional trajectories and subregional differences, as well as interlinkages.

Finally, the chapter synthesizes findings across the systems and future pathways, using the types of policy and regulatory solutions identified as effective in earlier chapters (Chapters 14-18) to draw conclusions on potential future transformation. Synergies and trade-offs between regions are then explored, reflecting the tele-coupled socioeconomic and environmental interactions over distances, as presented in Chapter 8 (**Figure 20.1**).

20.3 The GEO-7 Current Trends Scenario is not a Future Option

Results from the Intergovernmental Panel on Climate Change (IPCC) AR6 indicate that the climate implications of continuing along the current path have significant adverse environmental consequences (IPCC 2023). There are notable regional differences in the impacts of climate change, which are unequally distributed across the United Nations regions, resulting in each region having a distinct future trajectory.

Exploring the regional implications of maintaining current policies and practices across all regions suggests that there are significant drawbacks to staying on this path, as reflected by the regional disaggregation of Chapter 10 findings. This *GEO-7 Current Trends Scenario* is used to assess the environmental and socioeconomic implications if global environmental crises are not addressed.

The African region is expected to face severe and widespread consequences from climate change, including extreme weather events such as droughts and intense heatwaves. West and Sub-Saharan subregions are expected to face extreme food and water insecurity due to climate change (IPCC 2023). This insecurity will have catastrophic effects on the agriculture and livestock sectors due to severe flood events as well as the expected droughts (IPCC 2023). Land degradation and desertification are expected to accelerate in North Africa and the Sahel, resulting

Table 20.1: Regional environmental priorities identified in Chapter 8

Region	Priorities
Africa	Unsustainable resource exploitation and use Ecosystem degradation and ecological vulnerability Climate change vulnerability with escalating extreme events
Asia and the Pacific (AP)	Climate change impacts on development and cultural heritage Land-use change impacts on ecosystems Pollution and waste impacts on ecosystems and human health
Eastern Europe (EE)	Loss of ecosystem services due to unsustainable agriculture Unsustainable energy system effects on climate and health Biodiversity loss due to weak management frameworks
Latin America and Caribbean (LAC)	Changes in land-cover dynamics Changes in freshwater quality and availability Degradation of coastal and marine resources
Western Europe and Others Group (WEOG)	Biodiversity loss and ecosystem change Climate extreme events Pollution and waste

in a reduction of arable land and exacerbating food insecurity. The loss of livelihood resources leads to increased vulnerability, characterized by widespread poverty, governance challenges, and a lack of social safety nets, suggesting displaced communities will emerge and there will be an increase in cross-border migration. Loss of biodiversity and worsening air, water, and land pollution are expected to further increase food and water scarcity, as well as spur diseases like malaria. Biodiversity loss, particularly of wildlife, and ecosystem collapse will threaten livelihoods and lead to further food and resource scarcity. Fishing industries in West and East Africa are expected to collapse due to coral bleaching and the degradation of coastal ecosystems. The consequences of uncontrolled industrialization and urbanization on air, water and land pollution will be significant (World Bank 2024).

For the Asia and the Pacific region, staying on the current trend threatens any chance of achieving the sustainable development goals (SDGs). Continued global warming will increase the frequency and intensity of heatwaves, floods, droughts, and cyclones, impeding food production in South and Southeast Asia. Sea level rise is expected to endanger many of the region's island states and coastal cities by 2050 (IPCC 2023). Coastal fisheries and ecotourism businesses are expected to suffer severe losses. Approximately 2 billion people are expected to face significant water shortages due to the rapid and unseasonable melting of Himalayan glaciers (IPCC 2023). Repercussions for human health due to the combined effects of climate extremes and rising pollution are expected to be severe. Vector-borne diseases, including malaria and dengue, are expected to rise. The current model of industrialization, urbanization and resource exploitation will further erode biodiversity and nature's resilience in the region (UNDP 2022).

For the Eastern European region, the results from the *GEO-7 Current Trends Scenario* show increasing pressures from climate change on environmental systems. These pressures threaten biologically valuable areas that currently lack any protection status. Significant increases are expected in the frequency and intensity of extreme precipitation events, and with this increase comes an associated increase in natural hazards such as flooding and landslides.

In Latin America and the Caribbean, the Current Trends pathway will have significant implications for human and natural systems. Consequences for biodiversity and human systems are expected to escalate due to an increase in the frequency and intensity of extreme heatwaves and droughts. Those effects, exacerbated by extreme flood events, will put heightened stress on water resources, with serious consequences for fisheries and agriculture.

Across the non-contiguous region of Western Europe and Other Groups, continuing on the Current Trends pathway has significant implications for both environmental and human systems. The cost of no transformation will lead to significant biodiversity loss across large parts of North America, continental northern Europe and parts of Australia. Water resources are likely to be significantly altered, with North America and Northern Europe experiencing increased precipitation frequency and intensity. At the same time, Australia and southern Europe are expected to face an increase in the severity of droughts and heatwaves. Socioeconomic problems are anticipated to result from environmental deterioration in the WEOG region.

20.4 Africa Region

20.4.1 Introduction

This section outlines policy and development options to reverse Africa's key environmental challenges highlighted in Chapter 8:

- Ecosystem degradation and biological vulnerability
- Unsustainable exploitation and use of natural resources
- Climate change vulnerability and extreme events

Addressing these environmental priorities is crucial for sustainable resource management, climate resilience, disaster preparedness, and positioning Africa as a leader in environmental sustainability, thereby promoting public health and strengthening social equity, livelihood and economic growth.. This section considers

the practicality and implications of addressing the above priorities by implementing intrinsically interdependent Technology-focused and Behaviour-focused transformations in Africa's energy, food, materials/waste, economic and financial/environmental systems to make them more sustainable and resilient with co-benefits from improved human health and well-being. Transformation of the energy system would enhance energy access, quality and security (IEA 2022) through an increased uptake of renewable energies such as solar photovoltaic, hydro, wind, geothermal and green hydrogen, an adoption of decentralized smart grids, and a shift to sustainable consumption behaviours. Transforming the food system through ecological intensification and technological advancements would enhance food security, food sovereignty and ecosystem health, while promoting culinary diversity and incorporating protein-rich, overlooked, indigenous foods. Entrenching circularity in the materials and waste system would help address pollution and overconsumption of the region's natural resources (FAO 2019; FAO 2023). Transforming the economic and financial systems would shift resources to sustainable businesses. Restructuring the environmental system through stringent regulations and the adoption of renewable energy, for example, can halt and reverse biodiversity loss and ecosystem destruction, as well as reduce emissions. Incorporating the perspectives offered by Indigenous Knowledge and Local Knowledge into the design of policy and strategy for all five systems, as well as their implementation and monitoring, will better ensure cultural relevance and acceptability, environmental sustainability, resilience, cost-effectiveness, and social justice and equity (UN 2023).

Although the desired outcomes are admittedly ambitious, they can be unlocked by integrating public participation, implementing governance reforms and streamlining financial systems. These can be promoted on a regional level by leveraging the flagship projects of the African Union Agenda 2063 – such as the formulation of a regional sustainable trading strategy, the strengthening of continental financial institutions and the implementation of the African Continental Free Trade Area (AfCFTA) – to develop and harmonize common regulatory frameworks that minimize negative environmental externalities and promote sustainable environmental practices across the member states (AUC 2018; Quartey 2023).

20.4.2 Technology-focused Transformation Pathway

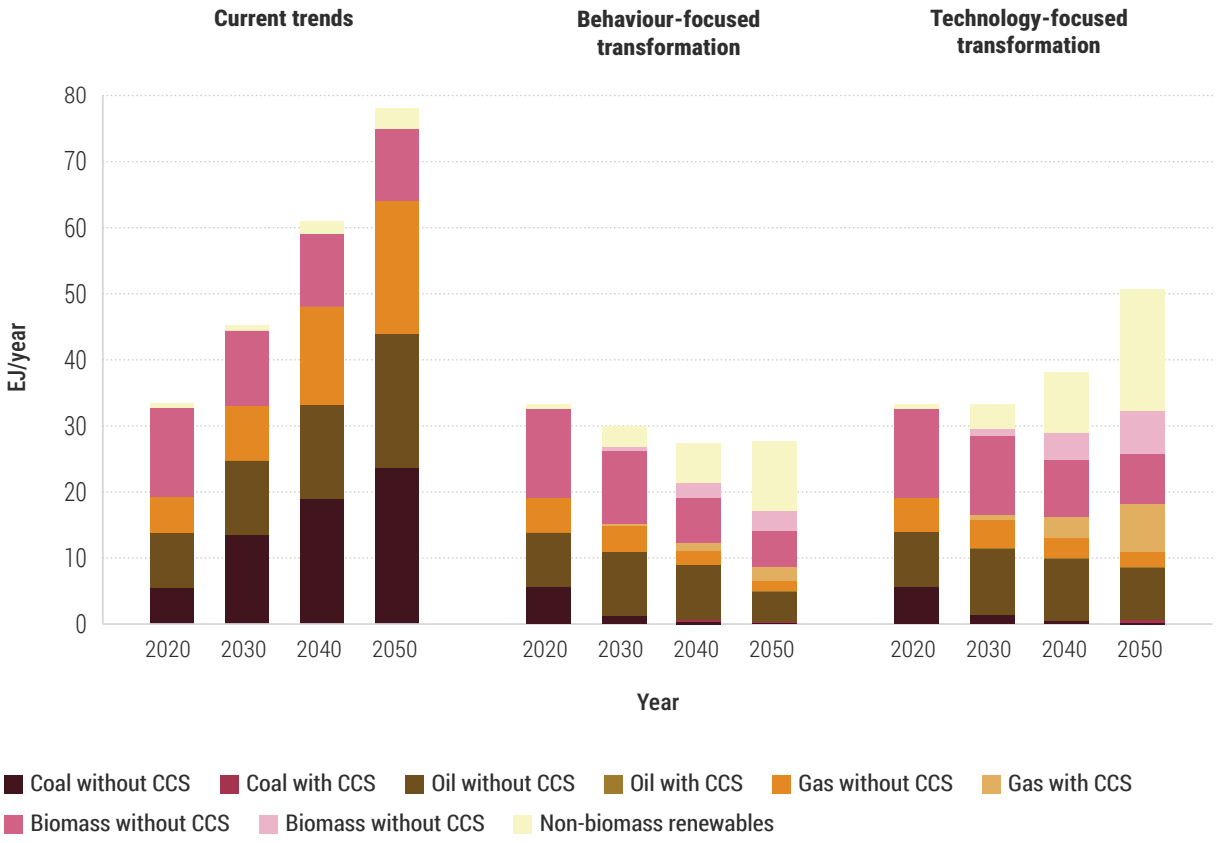
This pathway emphasizes regionally tailored, technology-driven solutions to drive systemic change across energy, agriculture, and materials sectors through transformative, integrative, and cross-sector approaches.

20.4.2.1 Transition to renewable energy

Africa has substantial opportunities to leverage the global net-zero transition (Ngondieb et al. 2020; Mutezo and Mulopo 2021; Blimpo et al. 2024) to significantly stimulate green growth and enhance public health (Maupin 2017). The Congo River basin management, for example, can mitigate the loss of arable lands and forests, thereby reducing food insecurity (Olson and Omoyajowo 2025). Integrated management of the Congo River basin can make Africa a leader in clean energy production (IEA 2020). However, addressing the increasing flood and drought scenarios in the basin will be a challenge.

Aggressive large-scale rural electrification drives that connect rural households to national or decentralized grids incentivize the adoption of energy efficiency and the transition to renewable energy. This can play a crucial role in socioeconomic development of Africa, as it can improve living standards (Deutch 2020; Cotterman et al. 2021) and achieve energy self-sufficiency (Acheampong et al. 2019; Hafner et al. 2021; Manjong et al. 2021) and security (Kouton 2021). While the region can achieve SDG 7 by 2030 (International Renewable Energy Agency [IRENA] 2021), meeting this and the Paris Agreement aspirations will require profound energy and land-use policy shifts. These shifts will encourage the integration and adoption of renewable energies, the development of necessary infrastructure for hydro, solar, geothermal and wind mini-grids, and the sustainable utilization of reserves of cobalt, lithium, manganese, and platinum that are essential inputs to renewable technologies. The deployment of solar photovoltaic, wind power, and clean-cooking solutions will tap into the region's vast renewable energy potential and protect forest ecosystems (Renewable Accelerator for Innovative and Sustainable Energy in Africa [RES4Africa] 2023) and reduce air pollution, thereby improving public health and the overall quality of life.

Figure 20.2: Increased uptake of renewable energies



The share of renewables in the primary energy mix will gradually increase to become the dominant energy source by 2050 (**Figure 20.2**). Total energy demand is projected to surpass 3100 terawatt-hours by 2040 (Nel and de Kock 2021), with installed capacity increasing by 700 gigawatts. Long-term sustainability will depend on ensuring a just energy transition that benefits the historically marginalized (Nwokolo et al. 2023) and is underpinned by sound governance (IRENA 2021). Looking towards 2040, Africa could focus on diversifying its renewable energy mix by investing in high-capacity energy storage technologies such as batteries and pumped-storage hydropower.

According to Peters et al. (2024), 76 per cent (1,225 TWh) of the estimated 1,614 terawatt-hours of electricity needs for 2040 could be met by renewable energy sources if all current wind, solar, and hydropower plants run at full capacity and all proposed plants are put into operation (82 per cent hydropower, 11 per cent solar power, and seven per cent wind power). Although hydropower has been the primary renewable energy resource up to this point, solar photovoltaic and wind turbines have the potential to lead sustainable renewable energy pathways in the future while simultaneously safeguarding freshwater ecosystems due to their 90 per cent and 60 per cent decrease in costs, respectively, since 2009 and 2010.

Incentivizing the adoption of electric vehicles including bicycles and motorcycles and establishing robust charging infrastructure will reduce Africa's reliance on fossil fuels in the transportation sector, aligning with global decarbonization goals (IEA 2022) (**Figure 20.02**).

Africa could enhance energy security and economic cooperation by establishing regional power interconnections and cross-border power trading to optimize renewable energy use, creating a resilient and integrated energy system (Africa Development Bank [AfDB] 2021). Developing a skilled workforce (UNEP 2022) and integrating renewables with agriculture, water and sanitation, and health care can create synergies to address the interconnected challenges of the global environmental crises which are interlinked with human issues (i.e. hunger and health).

As the global demand for green hydrogen is rising, Africa could benefit from the lack of legacy technologies to harness its estimated 1,590,000 terawatt-hours per year potential (European University Institute 2020). Green hydrogen can help with decarbonization of the energy sector while its amenability to be transported over long distances primes it as the next generation export which can accelerate the attainment of several SDGs particularly in the Northern and Southern Africa subregions which have significant untapped solar photovoltaic and concentrated solar power and wind energy. **Box 20.1** sets out the role of green hydrogen in development, using Namibia as a microcosm for the endowed subregions {16.2.1-16.4.2}.

20.4.2.2 Circular economy, and pollution control and prevention

Africa's low industrialization offers a unique opportunity to leapfrog to circularity through sustainable construction, resource-efficient manufacturing, and material efficiency technologies (ECA 2020). Rapid urbanization generates substantial waste, which can be repurposed for energy recovery in the form of electricity, heat, or fuel and soil nutrient recovery. With chemical and cement production projected to rise until 2050, integrating digital technologies, data analytics, and smart urban planning can help address urban challenges (Mamphiswana and Bekele 2020). Africa's regional economic communities can emulate the 2011 polythene ban by the East African Legislative Assembly. Following the publication of the 2018 Africa Waste Management Outlook, the African Ministerial Conference on the Environment pledged to establish concomitant harmonized regional environmental policies. Although the shift requires considerable investment and policy reforms, states can access multilateral and blended finance by creating conducive regulatory environments. The resulting economic growth, job creation, cost savings, improved efficiency, new market opportunities, and increased resilience are expected to far outweigh the initial challenges {15.2.3}.

20.4.2.3 Conservation and Restoration of Nature are crucial for sustainable and resilient food systems

Africa's diverse ecosystems offer significant opportunities for sustainable conservation, ecosystem-based adaptation, and carbon sequestration, with African forests projected to maintain a higher net carbon sink than Amazon forests from 1990 to 2040 (Hubau et al. 2020). To maximize this potential, initiatives like Green Value Chains, REDD+, Payment for Ecosystem Services, and community-based forest management can promote sustainable land use and forest conservation. These efforts, supported by funding from the Green Climate Fund and other financial institutions, can capture the carbon value of well-managed forests and agricultural lands. Additionally, the Taskforce on Nature-related Financial Disclosures provides guidelines for businesses to assess and manage nature-related risks, aligning financial flows with the Kunming-Montreal Global Biodiversity Framework. Integrating Indigenous Knowledge with scientific practices can further enhance sustainable land management, reduce deforestation, and strengthen climate resilience (Nkuba et al. 2020; Nkuba et al. 2023).

Promoting carbon-neutral energy, climate-resilient agriculture, and nature-positive investments can help policymakers reduce GHG emissions and mitigate land-use impacts like salinity and erosion, supporting attainment of Paris Agreement and Kunming-Montreal Global Biodiversity Framework commitments. The IPCC AR6 scenarios for limiting warming to 1.5°C include substantial carbon capture estimates of 2.3 peta-grams annually by 2050. This includes planting over 700 million hectares of forest land (Forster et al. 2018). Armani et al. (2022) stress the urgency of conserving carbon-rich ecosystems by adopting sustainable agriculture and implementing land-based carbon dioxide removal strategies. This can stabilize the climate and assure community livelihoods and regional development. Historically high-emitting countries can provide the requisite financial support, technology transfer, and capacity-building assistance through multilateral financial institutions {18.2.1; 18.2.4}.

20.4.2.4 Economic and Financial System reforms

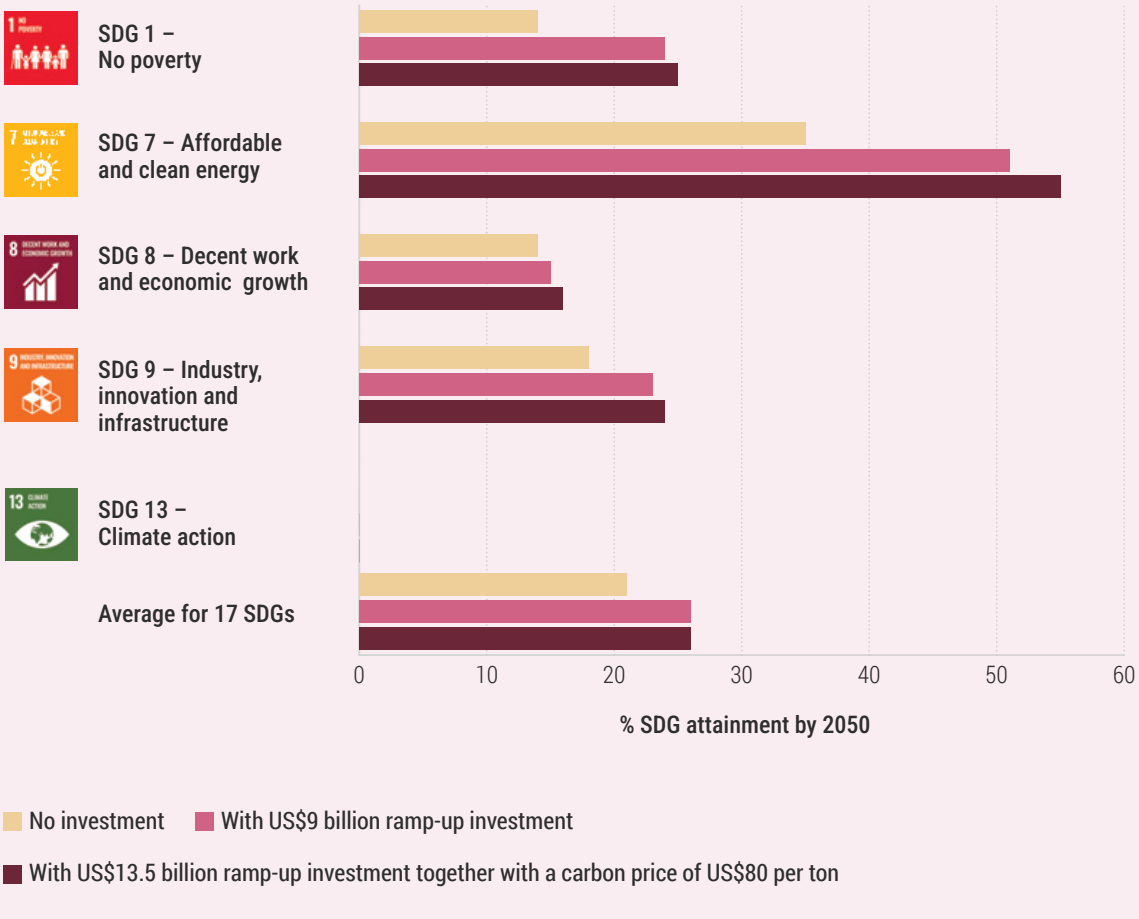
To meet the basic needs of water, food, energy, and finance, Africa needs robust climate change adaptation and net-zero plans with clear targets supported by enabling policies, regulatory frameworks and good governance mechanisms. Effective governance is essential for reducing emissions, fostering businesses, creating jobs,

Box 20.1: The green hydrogen economy in regional development. The case of Namibia

Green hydrogen (GH2), produced via renewable-powered water electrolysis, is a carbon-neutral energy carrier that can reduce emissions in hard-to-abate sectors like shipping and aviation. While currently costlier than fossil fuels, GH2 and its derivatives, such as green ammonia, methanol, and kerosene, are projected to become cost-competitive within two decades.

Namibia, leveraging its solar, wind, and coastal resources, has attracted over US$9 billion in foreign investment. The country aims to export GH2 products, create jobs, and support decarbonization. Societal impacts on SDGs 7, 8, 9, 13, and 1 to 2050 have been modeled (**Figure 20.3**)

Figure 20.3: Simulated SDG attainment at year 2050 with and without investment



The simulations explore three scenarios. The government requires that GH2 development ensure net gains in electricity, water, and biodiversity protection. GH2 investments drive GDP growth, enabling government spending on education, health, and infrastructure, related to SDGs 1, 7, 8, and 9. SDG 13 shows little progress because GH2 primarily reduces emissions without addressing adaptation. The simulations indicate that GH2 can provide social benefits if coupled with policies for environmental protection, job creation, and access to water and electricity. Global decarbonization commitments and uptake, like Maersk's green methanol vessels and the EU's sustainable aviation fuel mandate, are crucial to drive GH2 demand and prevent stranded assets.

and ensuring prosperity,while adequate financial resources are needed to implement national climate and biodiversity plans to fulfil global commitments (UNEP 2023; UNEP 2024). Africa's investment in green transition is expected to reach US$190 billion annually between 2026 and 2030, significantly lower than the US$1.6 trillion required annually to meet the region's sustainable development needs by 2030 (OECD 2023). Sub-Saharan Africa will need US$835 billion in capital investment by 2040 to meet rising electricity demand (Amir and Khan 2022). Increasing private finance is essential to supplement limited public resources for climate action and green growth. Diversifying into non-traditional exports like carbon credits can unlock funding. With banks holding over 90 per cent of financial assets (ECA 2020) and financing tools lagging behind other regions (Fintech 2022; CPI 2024), sector reforms can provide businesses with cheaper finance, enhance competitiveness, and drive reinvestment, creating a virtuous cycle (Obiwulu et al. 2022). Africa can enhance access to international finance from multilateral financial institutions such as the Green Climate Fund, Global Environment Facility, and Adaptation Fund, by reforming the global climate and nature funding architecture, diversifying financing instruments, and strengthening national capacity and coordination (CPI 2024) {14.3, 14.4;14.4}.

20.4.2.5 Implications of the transformations

20.4.2.5.1 Socioeconomic system

Implementing technology-focused transformation can exacerbate existing insecurities in Africa. Prioritizing advanced technologies may deepen climate and energy inequalities, marginalize Indigenous and local practices in agriculture and fisheries, worsen food insecurity, and drive displacement through land grabbing, exacerbating the marginalization of vulnerable communities (AfDB 2016; IPCC 2021).

Meeting the Paris Agreement target could prevent over 15 per cent of Africa's projected mid-century GDP loss, highlighting its growth potential. With vast human and natural resources, Africa is well-positioned to develop its agriculture, renewable energy, manufacturing, and agricultural sectors (Saba et al. 2023). Although this will require significant infrastructural and human investment, leveraging technology such as precision agriculture in farming, smart grids in energy, and digital manufacturing in industry can amplify these opportunities through robust data systems. In addition, the need for context-relevant climate information and developing robust climate services and forecasts are vital for Africa's ability to adapt to climate change, bridge the gap between scientific data and practical action and build a sustainable future (Vogel et al. 2019; Nkuba et al. 2019). Africa's expanding tech industry and renewable energy potential can drive job creation, economic growth, and climate resilience. Decentralized energy systems can transform rural areas, improving healthcare and green job opportunities, especially for women, while agricultural innovations empower smallholders and youth, and early warning systems enhance adaptation and disaster risk reduction. However, Africa's transformation must be guided by the imperative of aligning with SDGs to ensure the well-being of its population. This alignment, which prioritizes poverty reduction, food security, and inequality, is crucial (Zhang 2024). Tenaciously implementing enhanced nationally determined contributions (NDCs) is a key step in reducing future economic losses.

20.4.2.5.2 Unintended environmental consequences

Climate extremes are introducing significant uncertainty and volatility to Africa's energy and food sectors. This underscores the need for Africa to diversify its energy mix, exploring other renewable energy sources such as green hydrogen, solar and wind while transitioning to more regenerative, inclusive and resilient food systems. Addressing these challenges requires a holistic approach that considers the interconnectedness of these sectors, acknowledging that there may be unintended consequences or unforeseen feedback loops across different horizons.

While technology adoption can drive progress, the increased demand for devices and manufacturing facilities may lead to overconsumption of resources, increased carbon emissions, biodiversity loss, and land degradation (Pindiriri and Kwaramba 2024). Unequal access to technology could widen the digital divide, exacerbating multidimensional vulnerabilities. Additionally, the demand for critical energy transition minerals may cause deforestation, habitat destruction, and soil erosion. Intensive use of agrochemicals in advanced technologies could further degrade soil fertility.

Box 20.2: A carbon footprint integrating all ecosystem elements: application to Indigenous Knowledge systems of pastoral livestock production in the Sahel

In the Sahel, pastoral livestock farming exploits an extreme environment and is often accused of emitting too many greenhouse gases per kilogram of milk or meat produced. Research in Senegal showed that pastoral livestock farming, grounded in Indigenous Knowledge of landscape ecosystems, biodiversity, and ecosystem service dynamics, can achieve a neutral carbon footprint. In other terms, animal emissions are offset by carbon sequestration in soils and vegetation. The study, conducted i n northern Senegal, found that the ecosystem method used takes into account the entire ecological functioning of a territory, focusing on specific processes like animal consumption of fodder on the stalk and used an original method to estimate the indigenous practices of feeding behavior of ruminants and the emission of methane from their digestion, called "enteric methane." The study proposes new standards for daily ingestion, such as 18g/kg for cattle and 34g/kg for small ruminants. The carbon footprint was calculated by assessing all greenhouse gas emissions and carbon sequestered, converting these flows into carbon equivalents.

The new daily intake standards are adjustable (+12%) depending on the territory's resources, livestock practices, and seasons. Despite this, they have consequences for estimating enteric methane emissions: for Sahelian cattle, current official estimates are believed to be twice the actual level. These standards could contribute to revising those used i n the guidelines of the IPCC. The work showed that the territory's carbon footprint is balanced, even if it varies depending on the location and the season. In the area studied, one hectare of pastoral ecosystem emits 0.71 tonnes of carbon equivalent per year and sequesters 0.75 tonnes; in other words, it stores the difference, or 40 ± 6 kilograms of carbon equivalent.

In the Sahel, storage in trees, shrubs, and soils offsets greenhouse gas emissions from animals linked to their diet and the deposit of their droppings. More precisely, the annual carbon footprint varies from one location to another, and this variation is linked to livestock farming practices. Grassy, shrubby, and wooded rangelands, where animals move to graze, are places where sequestration prevails. Conversely, rest areas near camps and the areas around watering points, which receive a lot of droppings, are places that emit the most carbon.

Promoting Indigenous Knowledge Systems of pastoral livestock management covering nearly 1.3 million hectares on the international carbon market is an opportunity for Africa, representing significant potential for carbon sequestration. Green funds and carbon credits could also be mobilized for the benefit of pastoral livestock farming in sub-Saharan countries.

The carbon footprint per hectare offers a valuable additional indicator for assessing the performance of extensive grass-based livestock systems in tropical regions. Hence, by advancing the debate on pastoral livestock farming, this metric aligns closely with the objectives of the Koronivia Joint Work on Agriculture, adopted at the 23rd Conference of the Parties to the UNFCCC (COP 23, 2017).

Source: Adapted from IPBES (2018) and Imarc Group

20.4.3 Behaviour-focused Transformation Pathway

Behaviour-focused transformation can drive local and individual actions by changing behaviours, social norms, and collective efforts through nature-positive activities and renewable energy solutions.

20.4.3.1 Implications of energy system transformation

By addressing both the supply and demand sides of the energy equation with a holistic, integrated, and Africa-led approach, the continent can achieve universal energy access, drive sustainable economic growth, and become

a global leader in the clean energy transition. Countries can promote sustainable consumption and production by using financial incentives and raising awareness about nature's true value (Khanna et al. 2021), encouraging the adoption of renewable energy (Global Wind Energy Council [GWEC] 2019; IEA 2019), reducing waste, and fostering environmentally responsible behaviours. These would concomitantly conserve the region's forests and biodiversity due to reduced solid biomass burning. The renewables would complement the installed hydropower capacity (Cáceres 2022) whose scalability is impeded by its capital-intensive nature (McMillan and Zeufack 2022)and frequent outage (Ateba and Prinsloo 2018) as well as increasing frequency of floods and droughts the solution for which is building of climate-resilient hydropower infrastructure (IEA 2020).

As Africa ascends the energy ladder, the focus could shift to educating households to purchase energy-efficient appliances and to ingrain electricity-saving practices such as keeping building doors and windows closed when using heating, ventilation, and air-conditioning (HVAC) systems (Mutumbi et al. 2022), and embracing green architecture and sustainable building codes and building with sustainable construction materials. Access to affordable capital would enable industrial and mining sectors to invest in more energy-efficient machinery and processes (Apeaning and Thollander 2013; Du Plessis 2015). Africa's transport sector can be nudged to adopt more energy-efficient vehicles through economic instruments (such as punitive taxation) that ensure the internalization of externalities, alongside investments in mass rapid transit systems and provisions for non-motorized travel through smart spatial planning and design (Agyekum et al. 2023; Lefèvre & Mainbuy 2009) (Lefèvre and Mainbuy 2009; Agyekum et al. 2023) {16.2.1-16.4.2}.

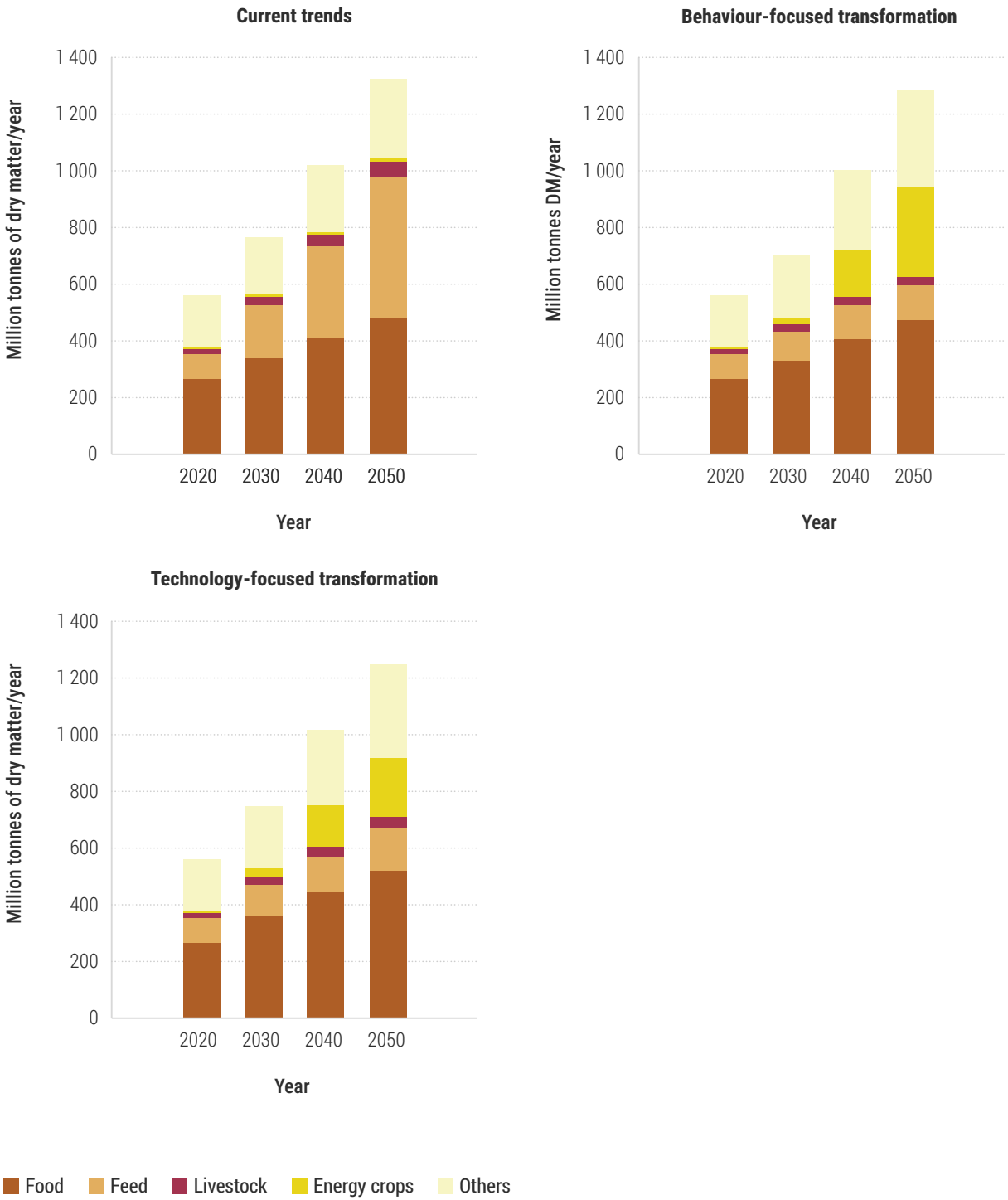
20.4.3.2 Implications of food system transformation

Africa's food systems can be transformed to meet four policy priorities: accessibility, affordability, availability and inclusivity (Global Panel on Agriculture and Food Systems for Nutrition [GPAFSN] 2020). Governance reforms that dismantle conceptual and institutional silos around agriculture, biodiversity, forests and land, and entrench integrated practices such as conservation-based intensification and agroecology can markedly increase and stabilize yields, assure energy, food and nutritional security, reduce poverty (Islam et al. 2019; Mrabet and Moussadek 2022), and enhance the provision of ecosystem services (DeClerck et al. 2023). At the international level, there is need for coordination among multilateral environmental agreements to ensure that cross-cutting issues are addressed collectively. At national level, leveraging Indigenous Knowledge for cultivar and culinary diversity by incorporating commercially producing protein-rich edible insects in select communities and practising specialized farming systems can provide good health benefits with strong safety and quality regulations (Kelemu etal. 2015; Van Huis 2015; Matandirotya et al. 2022). Underutilized crops such as finger and pearl millet, sorghum, tubers, and legumes (Popoola et al. 2023) can be promoted by encouraging the consumption of the leaves, flowers, fruits, stalks, bark, and roots (UNEP 2023). Nutritious and well-adapted African super foods, promoted through advertisements and product placement (WFA 2021; Herrero et al. 2023), can enhance flavour and reduce waste. This can bolster impoverished communities' food security and food sovereignty (Van Huis 2015; Smith et al. 2021). Postharvest loss and waste can be addressed across the value chain through adoption of preservation technologies and building consumer awareness (Cattaneo et al. 2021).

As depicted in **Figure 20.4**, the period 2025-2050 witnesses a marked increase in energy crops in behaviour-focused transformation with a sharp inflexion in 2037, mainly at the expense of feed crops, emphasizing the role of behavioural spurs in driving the shift from animal to plant-based, lower carbon-emission diets. The anticipated rise in demand for energy crops under the behaviour-focused transformation is considerably higher than that projected under the technology-focused transformation, pointing to the role of raising consumers' environmental consciousness in driving demand for cleaner energies such as biofuels. Nevertheless, a degree of technological innovation anticipated under the technology-focused transformation will be needed to boost demand for sustainable energy crops, as they optimize energy extraction (Toromade et al. 2024; Ezeh & Agu 2025; Akinbobola et al. 2025).

Promoting a combination of transhumant and stable livestock farming is crucial for improving the carbon efficiency of food production. While ranches in the low-rainfall areas (less than 500 mm/year)

Figure 20.4: Shift towards a plant-based diet from 2020 to 2050



of Australia and the United States produce 0.3 to 0.5 kg of animal protein per hectare per year, the transhumant Fulani herds in the comparable Sahel of Mali produce markedly more meat of 0.6 to 3.2 kg per hectare per year. Similar productivity trends are observed among transhumant herders in East Africa, highlighting the benefits of traditional pastoralism over ranching {17.2.1-17.2.4}.

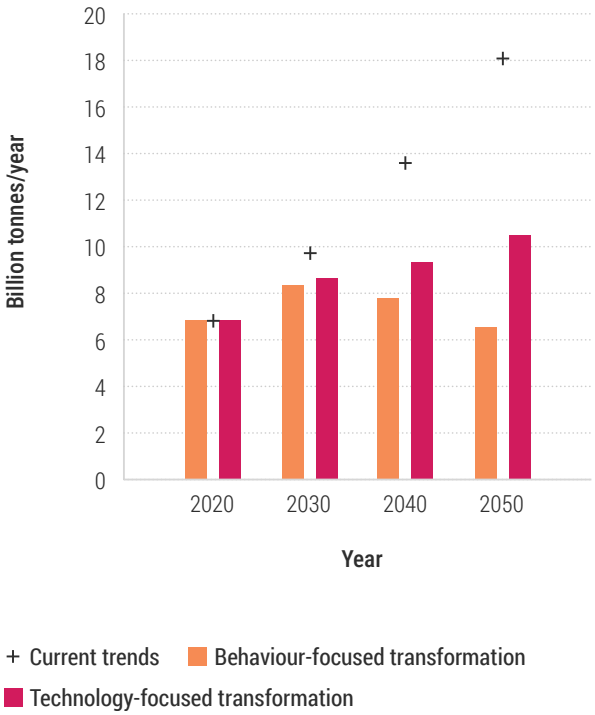
20.4.3.3 Implications of materials/ waste system transformation

Sustainable material production and consumption transformations are essential to conserve Africa's finite resources, whose demand under the Current Trends Scenario is projected to rise by 150 per cent to 17,800 MT/yr by 2050. Although simultaneously

implementing Technology and Behaviour-focused Transformation Pathways produces the best results, behaviour-focused transformation pathway promotes a noticeable behavioural shift from linearity to circularity, conserving resources and minimizing adverse environmental impacts. Public awareness drives geared at reducing conspicuous consumption can complement technological advancements in material recycling, as shown in **Figure 20.5.**

Africa's material and waste management systems can only be transformed if resource-efficient technological innovations are complemented with behavioural shifts towards sustainable consumption and waste generation. Key shifts include integrating resource-efficient manufacturing technologies and processes (UNEP 2019), circularity models that prioritize sustainable product design, extended product lifespans, and products that are reusable, repairable, and recyclable (UNEP 2022). Embedding these practices into corporate culture and aligning them with individual, departmental and organizational performance metrics are essential for long-term success. In addition, widespread adoption of B2B and B2C e-commerce platforms can help reduce the carbon footprint associated with traditional intermediation (Nwokolo et al. 2023). Digital platforms, such as block-chain-based apps, offer further potential as enable

Figure 20.5: Total materials demand as a function of transformation pathways



material traceability, improve demand management, and match suppliers with buyers in real-time (IEA 2020; UNEP 2023), thereby streamlining the value chain through disintermediation. Moreover, investing in and scaling waste-to-energy technologies, waste-to-soil enhancers, and digital waste management infrastructure can mitigate the environmental impact of Africa's rapid urbanization, which is expected to continue beyond 2050 (World Economic Forum [WEF] 2022; UNEP 2023){15.2.3}.

20.4.3.4 Implications of finance and economic system transformation

Overhauling Africa's finance system to make it more climate and biodiversity inclusive will necessitate both supply and demand side interventions. The sustainable funding per capita from international public sources such as multilateral financial institutions, bilateral cooperation and private global private sources in the form of lending and blended finance as well as domestic public and private sources (Ludwig 2021; Atteridge et al. 2022; Brears 2022) needs to be substantially increased and made more affordable. This will bridge the annual financing gap for nature-based solutions estimated to total US$230 billion by 2025 and US$674 billion by 2050 while that for climate resilience and adaptation will exceed US$127.2 billion per year by 2030 (AfDB 2023). Through compliance and voluntary carbon markets, Africa can leverage its untapped CO_2 potential estimated at 2,400 metric tons ($MtCO_2e$) per annum, 400 $MtCO_2e$ of which can be technically harnessed by 2030, unlocking US$7 billion annually (Africa Carbon Markets Initiative [ACMI] 2022). Development and commercial banks can educate staff to green their loan portfolio by attracting sustainable projects particularly to meet national priorities and to capitalize on the anticipated demographic dividend. Integration of climate risk management considerations into financial operations and lending practices should ensure transparency and accountability in their monitoring and evaluation systems, and incorporate environmental, social, and governance factors into annual reporting (UNEP 2023). Implementing national, economic bloc-wide and region-wide projects under the auspices of the AfCFTA can create synergies and level trading playing field. Beyond Extended Producer Responsibility schemes, Africa could develop and adopt Ultimate Producer Responsibility, which establishes a fair funds transfer mechanism for imports of used goods. Ultimate

Producer Responsibility ensures that producers bear fair costs when their responsibilities for end-of-life management of goods shift across national borders and with government and private sector support, provides opportunities to transition to more circularity and sustainability (Peng et.al. 2023). In addition to tackling the continent's waste management issues, Ultimate Producer Responsibility would radically alter global supply chains, encourage the creation of genuinely sustainable products everywhere, and guarantee a fairer and just shift to a circular economy on a global scale. If Africa can invest the money it currently spends in fossil fuel subsidies in circular-economy-related technology adoption and infrastructure development, there can be positive changes in the materials, agrifood, energy and environmental systems (UNEP 2024). Although initial economic costs will be higher, the health, environment and biodiversity benefits will outweigh costs in the long-run Accordingly, Africa's position as a global leader in sustainable development would be cemented by this {14.3-14.6}.

20.4.3.5 Implications of Environmental system transformation

Under the behaviour-focused pathway implementation, the accelerated destruction of Africa's biodiversity and mean species abundance projected by the Current Trends Scenario can be reversed for all species, although this may not lead to distinct improvement possible under the technology-focused pathway. Moreover, emissions of black carbon, organic carbon, and sulfur dioxide can exhibit a general downward trend following implementation of stringent regulations while those of ammonia emissions grow nominally owing to its widespread reuse. However, emissions of volatile organic compounds peak in 2025 at 43Mt, bottom out in 2038 at 31Mt before steadily rising to 38Mt by mid-century, driven by both rising energy consumption and legacy inefficiencies. Water withdrawals for electricity use can decrease rapidly before 2040 if there is a switch from fossil-fueled thermal power plants to renewables. The potential of irrigation water, particularly in sub-Saharan Africa, would nevertheless largely remain untapped, impeded by limited access to technology, technical know-how and finance (Bjornlund et al. 2020; Bedasa 2023; Galbert and Olinga 2023), policy and institutional constraints (Mohammedshum 2023) and cultural and social norms, including on traditional gender roles (Fredriksson and Gupta 2023){18.2.1; 18.2.4}.

20.4.3.6 Implications of the transformation under Behaviour-focused Transformation Pathways

20.4.3.6.1 Socioeconomic system impacts

Africa's growing population could demand more sustainable food production, which could raise food prices beyond the reach of the groups living below the poverty line, exacerbating rather than alleviating hunger and malnutrition (Mehra et al. 2024). The anticipated shift towards renewable energies and carbon-resilient development will create considerable job opportunities for the region's growing population. Further, the adoption of renewable energies has the potential to foster universal access to clean energy, contribute to health and well-being, mitigate inequalities, empower women, promote decent work, and stimulate economic growth (Balgehshiri and Zohuri 2023).

To address the spike in climate change impacts due to both extreme and slow-onset events especially on the health systems, Africa needs to invest in the physical infrastructure and a skilled workforce development making them resilient to climate-related risks, shocks and stressors and other emergencies (AfDB 2023).

Behavioural shifts towards responsible environmental stewardship can mitigate conflicts over land and its varying tenure systems and resources, subsequently reducing the prevalence of inter-community and gender-based violence and discrimination. Moreover, training and providing financial resources can empower women, youth and marginalized groups to participate in natural resources management, the economy and society and encourage them to adopt sustainable consumption practices. Therefore, the benefits of behavioural transformations transcend the environmental space, promoting overarching sustainability, equality, education, health care, financial inclusion and overall societal well-being in Africa.

20.4.3.6.2 Unintended consequences for the environmental system

Policies encouraging eco-friendly behaviours – such as incentives for afforestation, renewable energy adoption, or sustainable food system – need to support ecosystem restoration considering local environmental dynamics and social complexities. Large-scale tree-planting initiatives, for example,

should not lead to monoculture plantations that deplete soil nutrients, biodiversity and water resources. Similarly, promoting biofuels or alternative materials should be based sustainable land management to prevent deforestation, habitat loss, and increased carbon emissions. Overreliance on behavioural nudges, such as consumer-driven recycling initiatives, may also shift responsibility away from systemic solutions like improved waste management infrastructure or stronger environmental regulations. Furthermore, policies that impose new environmental costs, such as taxing single-use plastic without providing affordable alternatives, can push communities towards unintended substitutes that may be more harmful. Behavioural interventions therefore need to be holistic and context specific.

20.4.4 What does that mean for the regional priorities?

20.4.4.1 Implication of combined technology-focused and behaviour-focused transformations on regional priorities

The technology and behaviour-focused transformations are interdependent and should complement each other to address the environmental priorities detailed in Chapter 8 and highlighted at the beginning of this section. While technological innovations provide physical and digital tools to help solve hitherto intractable problems, and optimize efficiency and productivity, unlocking their full potential necessitates corresponding shifts in behaviour (**Table 20.2**).

Table 20.2: Drivers and actions for each transformation pathway

Systems	Technology-focused Transformation		Behaviour-focused Transformation	
	Drivers	Actions	Drivers	Actions
Economic and finance {14.3-14.6}	Reforming economic and financial systems for sustainable and green growth, poverty reduction, and resilience to global shocks.	• Macroeconomic stability • Development and reform of finance sector • Increasing private and international finance • Diversifying financing instruments • Enhancing creditworthiness and risk mitigation	Ensuring financial flows actively support environmental sustainability and human development.	• Develop and adopt the Ultimate Producer Responsibility • Developing green financial products and instruments • Strengthening financial institutions' capacity • Fostering compliance and voluntary carbon markets • Mixing or blending various financial mechanisms
Material and waste {15.2.1}	Leapfrogging to circularity and integrating zero-waste policies into its development.	• Sustainable construction • Resource-efficient manufacturing • Smart urban planning • Material efficiency technologies • Capacity-building and awareness • Responsible management for abundant resources	The indispensability of behavioural shifts to conserve Africa's finite resources while foster inclusive economic growth.	• Integrate sustainable consumption and waste generation practices • Resource-Efficient Production and manufacturing • Investing in and scaling waste-to-energy technologies, waste-to-soil enhancers, and digital waste management infrastructure

Systems	Technology-focused Transformation		Behaviour-focused Transformation	
	Drivers	Actions	Drivers	Actions
Energy {16.2-16.4}	Accelerate rural development and share of renewables dominant energy source by 2050 and aligning with global decarbonization goals.	• Increasing access to electricity • Incentivizing energy efficiency programmes • Strong commitment to renewable energy including green hydrogen	Sustainable Energy production and consumption.	• Leveraging Africa's abundant renewables • Bundling efficiency and behavioural change
Food {17.2.1-17.2.5}	Integration of conservation and restoration of nature with ecologically intensive food systems.	• Technology integration for sustainable and resilient food systems (agroforestry, conservation agriculture, forest landscape restoration etc.) • Sustainable water management and wetland regeneration and restoration • Nature-positive investments for protecting invaluable natural heritage • Capacity-building and awareness	Achieving triple-win" approach: food security, environment and social harmony.	• Diversified Farming Systems including combining transhumant and stable livestock farming • Dietary change through leveraging indigenous cultivar and breads and culinary diversity • Conservation-based intensification and agroecology • Investing in Human Capital
Environment {18.2.1; 18.2.4}	A holistic approach to environmental sustainability: transform environmental challenges into opportunities.	• Interconnectedness among drivers and Nexus thinking • Technology-focused, resilient, equitable, and sustainable development • Ecosystem-based management and Nature-based Solutions • Advancing science, fostering research, and strengthening institutional capacity	Going beyond incremental improvements to a truly transformative path of ecosystems with behavioural shifts and development.	• Promoting people-centric and inclusive development. • Prioritize policies that actively encourage eco-friendly behaviours through a mix of incentives. • Guaranteeing a strong pipeline of investable green projects.

In reversing ecosystem degradation and vulnerability, tempering depletion pressures and enhancing disaster risk reduction, the technological pathway could offer solutions which optimize resource utilization and entrench sustainable land management practices such as precision agriculture; safe, affordable, inclusive and low-carbon food system and shorter agrifood value chains. The corresponding behavioural transformation would promote shifts towards sustainable consumption patterns and land-use practices, further supporting ecosystem restoration and conservation. To bolster climate change adaptation, technology-focused transformation offers renewable energies and climate-smart agriculture. These can be complemented by behavioural changes that promote energy efficiency and conservation mind-sets.

Overall, while the technology-focused transformation provides the innovations or the "hardware" to urgently address the three regional priorities, the behaviour-focused transformation pathway offers the critical "software" part of the equation, reinforcing sustainable production and consumption patterns which in turn create demand for successively more sustainable innovations and practices, fostering synergies and creating a virtuous cycle and ultimately driving Africa's sustainable development.

20.4.4.2 Reflections: Synergies

20.4.4.2.1 Synergy by strengthening Interlinkages

The five systems are interdependent and achievements in one have co-benefits for other systems, the environment and human well-being. Equally, the Technology and Behaviour-focused Transformation Pathways can complement each other in several ways. First, the development and implementation of new technologies can influence consumers' behaviours including purchase decisions. For example, the availability of affordable, efficient renewable energies can encourage consumers to reduce their reliance on fossil fuels. Second, the behaviour-focused transformation pathway can drive demand for new technologies. As people become more aware of the scale of the global environmental crises and the concomitant need for environmentally sustainable practices, they may demand incrementally innovative technologies or quantum leaps. This demand can lead to the development and adoption of new technologies, further promoting sustainable practices. Third, technological innovations may lead to behavioural shifts, which may in turn lead consumers to demand even more environmentally sustainable products, chaining off a perpetually reinforcing virtuous cycle.

20.4.4.2.1 Balancing synergies and trade-offs

In the African context, the synergies of adopting both the complementary Technology-focused and Behaviour-focused pathways can help reinforce lasting, holistic and sustainable transformation for the five systems – energy, food, materials and waste, economic and financial and environmental – and yield co-benefits for inclusive human well-being for the region's population.

The trade-offs between the two pathways require careful balancing, so that environmental, social, and economic objectives are aligned rather than placed in conflict. Organizations should weigh initial capital investments against long-term sustainability and resource efficiency gains. Managing the complexity of technology adoption while integrating behavioural changes across diverse developmental, environmental, cultural and resilience-related national contexts calls for transformative strategies. Another critical consideration is navigating technological dependency while empowering local, Indigenous and marginalized communities to build self-reliant, inclusive and resilient practices.

20.4.5 Policy implications

The policy implications of the above analysis revolve around integrating natural resources management, good governance, overhauling economic and finance systems and embedding circularity principles across entire value chains. Regional and national policymakers could leverage some of the flagship projects of the African Union's Agenda 2063 to ensure unified regulatory frameworks that address externalities and foster sustainable environmental practices across the continent. Possibilities include development of the Grand Inga Hydropower Project, the creation of a regional trading strategy, the establishment of continental financial institutions, and the implementation of the AfCFTA. Integrating environmental management would entail multi-sector and multi-stakeholder governance among entities sharing similar mandates such as those which are responsible for the environment, energy, forests, agriculture, economic development and finance. An important first step in this direction could be establishing national interministerial councils for addressing climate, agriculture and forest and other land uses.

Effective funding governance is key to addressing environmental crises by ensuring resources are allocated efficiently and equitably. Clear guidelines can prioritize climate-resilient projects that benefit marginalized communities while supporting sustainable development. Strong governance also enables monitoring and evaluation, ensuring accountability and transparency, which builds public trust and participation. Transforming financial systems by greening loan portfolios of public financial institutions and incentivizing private sector can redirect resources towards green initiatives such as circular economy,

Credit: ©UNEP

renewable energy, climate-resilient agriculture and infrastructure blue/green economy etc.

International coordination among multilateral environmental agreements is essential for identifying synergies, preventing policy conflicts, and promoting a holistic approach to environmental management. While multilateral environmental agreements often address specific issues like climate change or biodiversity, greater cooperation can foster integrated solutions that consider land-sea connections, biodiversity-climate links, and the balance of conservation, restoration, and sustainable use of ecosystems.

The African Union Agenda 2063's flagship projects, including the AfCFTA, offer significant opportunities to address regional priorities by establishing a unified regulatory framework across member countries. This framework could enforce standards for emissions control, energy efficiency, and waste management, promoting sustainable environmental practices. AfCFTA can also facilitate the trade in products that are made with sustainably sourced raw materials and environmentally sound manufacturing methods, incentivize conservation efforts, and support biodiversity protection. Furthermore, it can accelerate the continent's clean energy transition by promoting cross-border exchange of renewable energy, production thus, reducing reliance on fossil fuels. Additionally, AfCFTA could introduce mechanisms for carbon trading and emissions reduction commitments, encouraging member countries to lower their carbon footprints and enhance climate resilience (Lokotola et al. 2023).

20.4.6 Conclusion

African countries can make significant progress towards achieving sustainable development and net-zero goals by 2050, despite challenges of poverty, capacity gaps, and infrastructure limitations (Royo et al. 2022). Through ecosystem restoration, promoting sustainable resource use, and building resilience to climate change and extreme weather events, they can unlock new growth opportunities. Progress will vary across subregions, with more advanced economies benefiting from greater technological and financial resources. With enhanced investment, international cooperation, technology transfer, innovation, sensitization, education and transformative policy reforms, Africa can drive its energy transition, strengthen climate adaptation, and advance low-carbon growth in line with its development goals.

20.5 Asia and the Pacific Region

20.5.1 Introduction

The Asia and the Pacific (AP) region is bio-culturally and geographically diverse in its state of environment and development, facing numerous challenges and opportunities (UN 2024). The key priorities of the region are climate change adaptation and resilience building against extreme events, land-use change and land degradation, and increasing waste and pollution (Chapter 8). Increasingly severe climate-induced disasters destroy lives and livelihoods in many Asian countries (IPCC 2023). Significant gaps persist in reducing GHG emissions to limit warming, as presented by the Paris Agreement (IPCC 2023).

While many countries in the region have undertaken effective measures for ecosystem restoration, biodiversity conservation and climate change adaptation (United Nations Economic and Social Commission for Asia and the Pacific [UNESCAP] 2023), further efforts are needed to ensure a sustained flow of ecosystem goods and services to achieve the SDGs by 2030. Overall, conserving biodiversity and sustainably managing natural capital can be a basis for enabling the region's economic growth and social welfare.

Asia and the Pacific countries have achieved only 17 per cent progress in the 17 SDGs – slightly above the global level. However, at the current rate, the AP region will fail to achieve 90 per cent of the 118 SDG targets by 2030 (UNESCAP 2024). Although 39 Asia and the Pacific countries have pledged to reach carbon neutrality and net-zero targets by the 2050-2070 period, few countries have developed enabling frameworks to implement NDCs to meet their net-zero pledges. The region can achieve global goals and targets only if it raises ambition in their NDCs to reduce GHG emissions and meet Paris Agreement goals (UN 2022c). The region's countries can accelerate progress through building resilience and leveraging synergies between climate and development (UN 2024).

AP countries need major transformation in energy, food, water, and material systems while simultaneously transforming their and finance systems to avoid continuing with Current Trends practices that are detrimental to all.

Chapter 11 presented transformative pathways that, if adopted either individually or in combination, can fast-track integrated and holistic solutions for these systems through simultaneous transformation of economic and finance and environmental systems to address global environmental crises. The pathways for system-wide transformation are described below.

20.5.2 Technology-focused Transformation Pathway

This pathway calls for transitioning away from fossil fuels and towards green fuels and renewable energy sources. However, technology-focused pathways depend upon reforming regulatory frameworks, finance, respecting Indigenous Peoples' aspirations, infrastructure development and enhancing energy efficiency. Tailored transformation-based solutions for the region are described below.

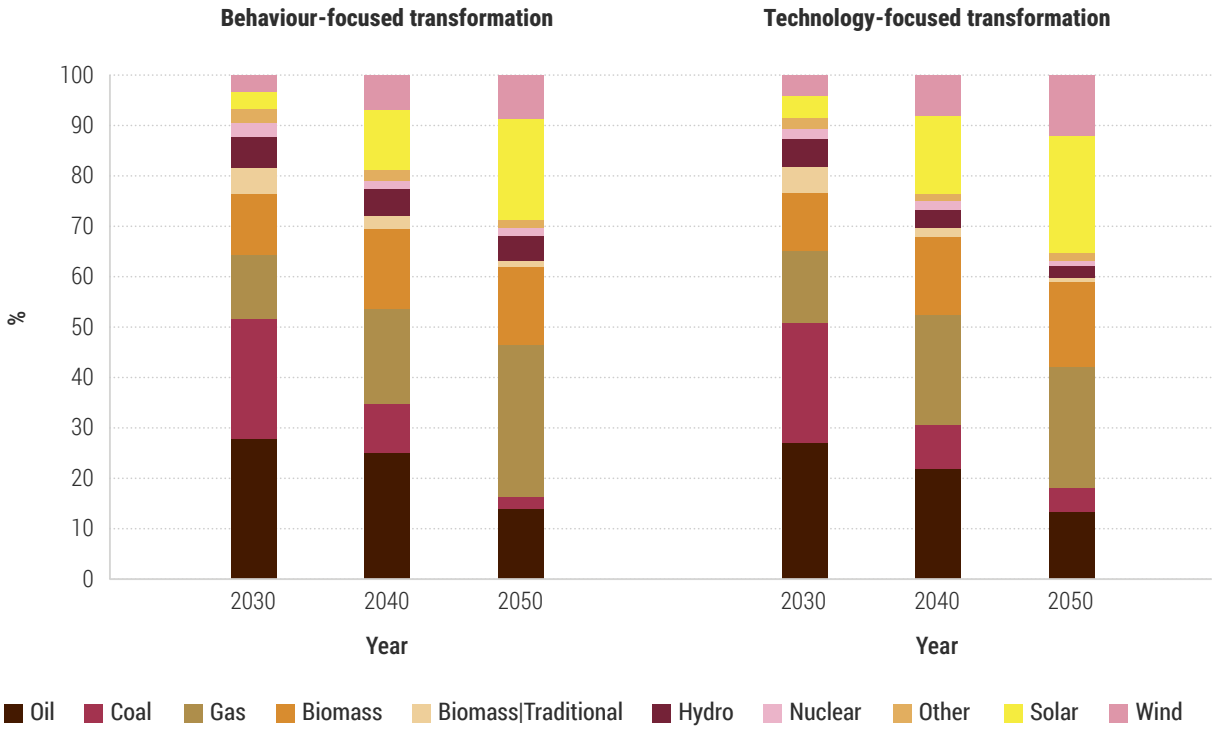
20.5.2.1 Transition to green energy

The AP region is projected to have the highest demand and supply of clean energy power by 2050 (UNDP 2022a). Renewable energy resources and low-carbon technologies are expected to penetrate multiple sectors in different proportions across the region. In the primary energy mix (6), the renewable energy penetration is projected to increase about 11 times, between 2020-2050, with 38 per cent of non-biomass renewables share by 2050. In the case of fossils, new plants could be developed with carbon capture and storage. (Chapter 11)

The primary energy is expected to decline in the short term (2020-2040), due to transition towards best-available-technologies resulting in significant efficiency improvement while it increases post 2040, due to growing in energy demand (**Figure 20.6**). (11.3.1)

Renewable energy and penetration of green fuels such as green hydrogen and biofuels into the energy system requires enhancing and strengthening of grid infrastructure (Pandey and Asif 2022; Asif et al. 2024), securing additional land, innovative financing (IRENA 2023; Skalamera 2024), phasing out fossil fuels subsidies, holistic policies and regulations (Hamelin and Bhatti 2023; IRENA 2023). It also calls for private sector involvement (Azhgaliyeva et al. 2019; IRENA 2023; Asif et al. 2024), fast-tracked planning, manpower training (IEA 2023),

Figure 20.6: Percentage share of primary energy mix in Asia and the Pacific region



policy and technology adoption from best practices, data repositories, and regional grid development. Additionally, electricity storage technologies, such as batteries and pump storage are crucial for supporting renewable penetration by maintaining grid stability (Chapter 16). Among subregions, Central and South Asia has great potential for solar and hydropower, which could be harnessed through individual and hybrid power plants (Azimov and Avezova 2022; Zakeri et al. 2022). The Pacific islands have significant solar potential (Malik 2021; Taylor and Taylor 2022; Prasad and Prasad 2023) and could also explore marine renewable energy (Malik 2021; Kazimierczuk et al. 2023) to utilize their geographical advantage, provided commensurate technological and economic challenges are addressed.

West Asia has potential to invest in hydrogen, solar and offshore wind energy solutions along with climate capture and storage (Bianco 2021; United Nations Economic and Social Commission for West Asia [UNESCWA] 2022; UNEP 2022b).

Asia may see marginal improvements in the use of non-solid cooking fuel by 2030 (IEA 2022b). Adoption of cleaner cooking fuels could be driven by affordability, efficient service, and e-payment options. The final energy consumption as compared to REF-pathway is projected to reduce by 34 per cent in 2050 (Chapter 11). Technological advancements and increased use of electricity-based technologies such as electric vehicles, electric cooking, increased electrification of industrial processes are expected to improve energy system (Pandey and Asif 2022; IRENA 2023; Asif et al. 2024), however the overall energy demand would continue to rise due to increase in population and economic growth {16.2-16.4}.

20.5.2.2 Sustainable agriculture and food system

Food system transformation is critical to the AP region due to increased food demand, production expansion, and increased pressure on arable land, driven by rapid urbanization, climate change impacts, population growth, and income rise. Additionally, environmental challenges such as increased climate extremes and land degradation further strain agricultural productivity by reducing arable land quality. The transformations are possible by adopting both technology-based and behaviour change pathways (Asia Development Bank [ADB] 2020).

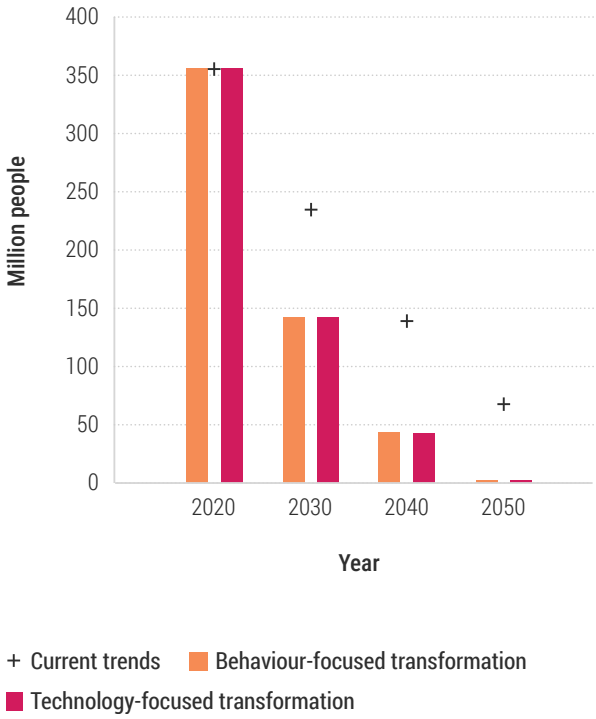
Technological advances show promising results in efficient land use, resilient food systems and low fossil-fuel-based food production throughout the supply chain (UNDP 2022). While technological applications hold great potential, it's important to

note that the region cannot achieve the SDG2 targets through the technology-focused pathway alone (**Figure 20.7**). Due to competition for arable land, projected climate-oriented technological solutions such as biofuel may lead to 225 million people at risk of hunger in 2030 and 142 million people in 2050. This is because while technology can increase food production, distribution and resilience, it cannot address socioeconomic, political and environmental causes of crises (APSDG Partnership 2024). However, combining with the behaviour-focused strategies, technology-based solutions can meet higher agricultural demand, while ensuring inclusive access to a healthy diet and addressing the undernourishment issue {17.2.1; 17.2.3; 17.2.4} (Figure **20.6**; **20.7**; **20.8**).

20.5.2.3 Conservation and restoration of nature

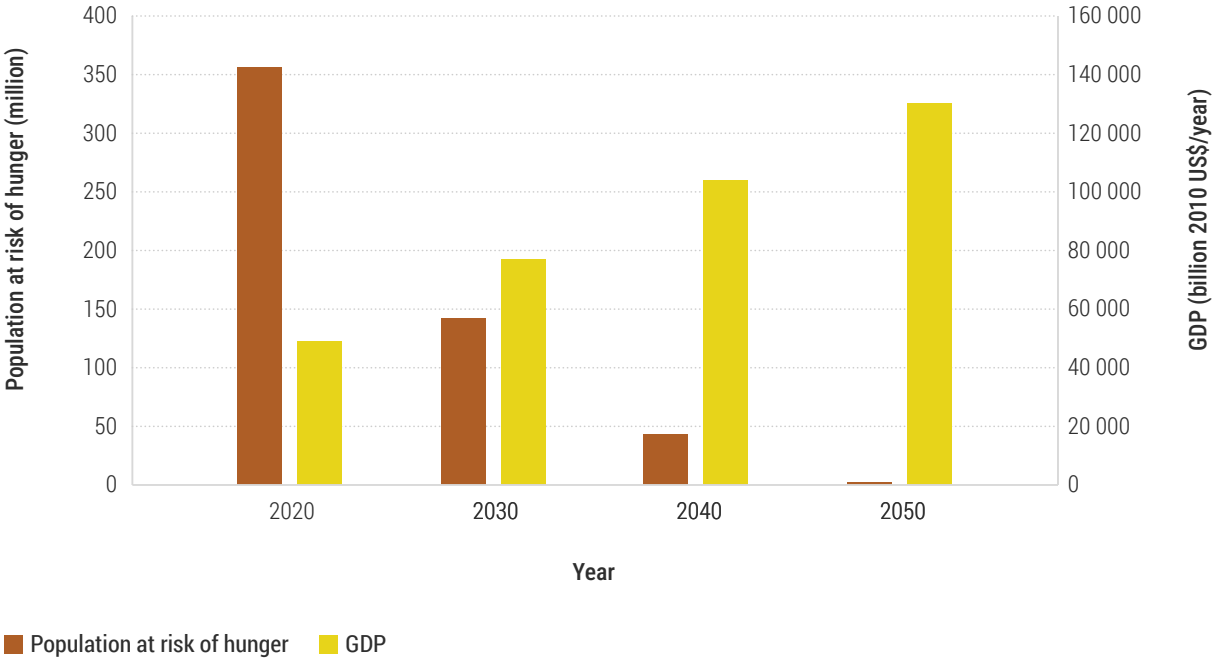
Robust environmental management is crucial to overcome industrial-driven resource exploitation that is environmentally harmful (Asian Development Bank [ASEAN] 2023). Prioritizing technological innovation

Figure 20.7: Population at risk of hunger



The Living Indus initiative aims to restore 40 per cent of the Indus basin within Pakistan by 2030. Credit: ©UNEP

Figure 20.8: Population at risk of hunger and projected GDP in Asia and the Pacific under the technology-focused transformation pathway



and energy efficiency emerges as key strategies tightly connected to emission reduction, playing vital roles in ecological management. Gradual reduction of chemical fertilizers and pesticides use in the region is possible through conservation-based system intensification, including in livestock and aquaculture subsectors improving water and air quality and contributing to sustainable land management. (Nkonya et al. 2016; Gathala. et al. 2020). Sustainable transformation of the farming system applying the principles of agrobiodiversity conservation and climate-resilient agriculture, combined with green incentive mechanisms, can promote ecological and environmentally friendly food system transformation while eliminating harmful subsidies (CIMMYT 2019; WB 2024).

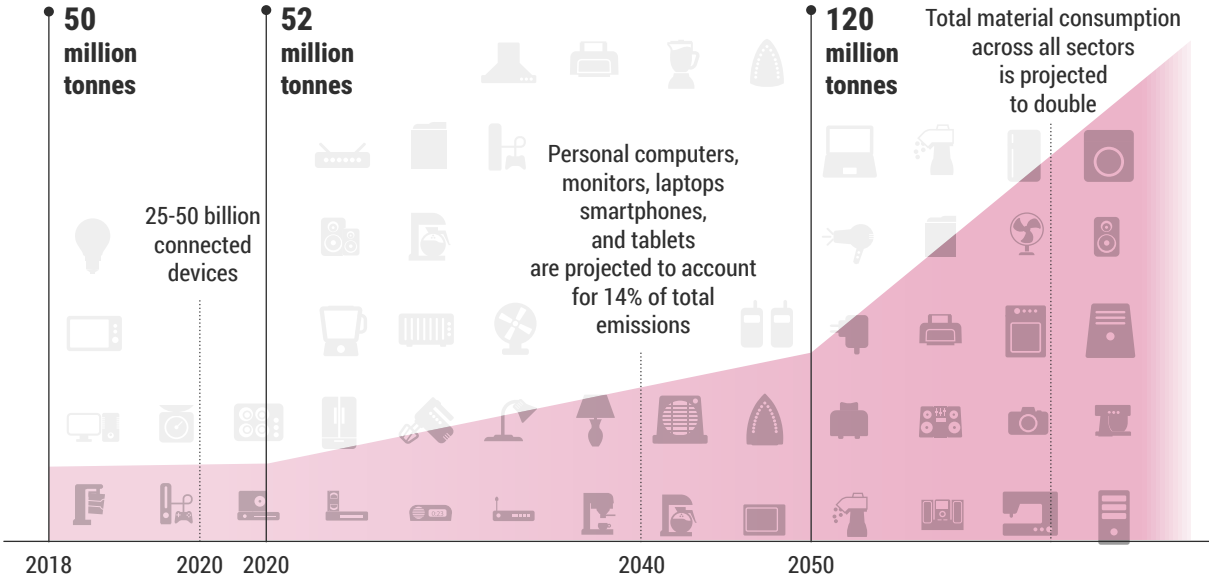
Small-scale and subsistence farming will remain an important food and income source, and a social safety net in the absence of alternative livelihood security (Giller et al. 2021). Tackling barriers such as limited access to land, education, and credit – especially for women smallholders, is critical to enabling technological solutions such as mechanizing smallholder farms. Favourable policies to promote healthy diets and Indigenous and local food systems can transform the region's food system.

20.5.2.4 Circular Economy and pollution control and prevention

The Asia and the Pacific region's top position in global waste generation, including e-waste, is expected to continue through 2050 (Herat 2021) (**Figure 20.9**). Circular economy solutions can promote sustainable waste management. In West Asia alone, circularity solutions have the potential to result in a 14 per cent reduction in e-waste generation (UNEP 2023).

Asia and the Pacific countries can adopt circular economic solutions comprising of both technology-based and behaviour change-based interventions to improve waste collection, segregation, and material recovery (Francis 2020) {15.2}. Decisions made at each stage of production and consumption – for food waste, packaging, building materials, e-waste, and plastic waste – can focus on reducing, reusing and recycling materials to minimize greenhouse gas emissions, resource consumption, and environmental consequences (Andeobu et al. 2021). The key requirement is enforceable regulatory frameworks and citizens' participation. There is a need for packaging leadership with innovation, easier recycling, creative solutions, and better garbage collection and landfill management policy. Under transformative actions,

Figure 20.9: Future of E-waste



Source: Herat (2021)

countries set ambitious goals in waste reduction, circularity and landfill management. Enabling legal and policy frameworks, can help eliminate single use plastic bags and avoidable plastic packaging. The progress under transformation pathways will be slow initially but should increase by 2030 through a reduction in materials demand. Behaviour-focused transformation pathways reduce demand for industrial round wood most significantly (**Table 20.3**).

Material demand will remain dominant in the Asia and the Pacific region for almost all materials except industrial sand and gravel. The region will be a net importer of materials, especially aluminium, copper, iron ore, and other metals and concentrations. (Chapter 11).

Countries can improve material recycling rates by using technology-focused transformations, aiming to reach 100 per cent recycling as found in the iron ore material category. Behaviour-focused transformations can increase recycling rates slightly compared to the current trends pathway while technology-focused pathways increase the recycling rate more significantly across all eight materials {15.2} (**Table 20.4**).

20.5.2.5 Economic and financial system reforms

Global and regional financial institutions need to undergo major reforms, especially by mainstreaming climate-resilient and nature-positive financing strategies that transform them into environmentally friendly institutions and green-taxonomy-based financial institutions (Song et al. 2023). Environmentally friendly institutions can fund projects and companies that are positively impacting environment and contributing to sustainability. The Asian Development Bank and the Asian Infrastructure Investment Bank can be reformed further to invest in climate inclusive and green initiatives. These financial institutions can scale-up concessional loans, equity investments, guarantees, capacity-building and investment advisory services to support green projects, especially in low-income countries across the region (Asian Infrastructure Investment Bank [AIIB] 2023). The use of public-private partnerships can attract private capital by reducing risks to their investment through public finance. Funds for responding to climate change or other crises-related loss and damage can be provided to vulnerable developing countries in addressing the adverse effects.

To meet carbon neutrality targets by 2050-2070, countries can implement innovative decarbonizing mechanisms including emissions trading systems, voluntary carbon markets, and green bonds to reduce carbon and methane emissions. Enhanced NDCs commitments can be achieved through increased investments in nature-based solutions to protect natural capital including sustainable management

Table 20.3: Annual production, demand, and extraction for different materials

Variable	Scenario	Unit	2020	2030	2024	2050
Forestry Production - Industrial Roundwood	Behaviour-Focused	Mm^3/yr	433	527	459	366
	Current Trends	Mm^3/yr	433	591	678	735
	Technology- Focused	Mm^3/yr	433	493	440	399
Material Demand - Iron Ore	Behaviour-focused	Mt/yr	2660	3090	2730	2500
	Current Trends	Mt/yr	2660	3620	4220	4730
	Technology- Focused	Mt/yr	2660	2830	2570	2600
Material Extraction - Iron Ore	Behaviour-focused	Mt/yr	1190	1380	1210	1160
	Current Trend	Mt/yr	1190	1660	1980	2270
	Technology- Focused	Mt/yr	1190	1290	1160	1190
Material Demand – Total	Behaviour-Focused	Mt/yr	61200	72100	57800	46100
	Current Trends	Mt/yr	61200	72100	96100	98800
	Technology- Focused	Mt/yr	61200	70100	62700	62000

of terrestrial, freshwater and marine ecosystems that can generate mitigation co-benefits as well as improve, protect and sustain livelihoods. However, the availability of external financing and technical support for vulnerable developing countries is required (UN 2022a) {14.3-14.6}.

Residual GHG emissions from energy and industry sectors remaining by 2050 (Chapter 12), could be offset by carbon capture and storage and sustainable land-use and management methods. This transition offers co-benefits such as safeguarding ecosystems, reducing air pollution and enhancing urban sustainability through adaptation and climate-resilient building measures (**Box 20.3**).

Given the environmental challenges faced by the AP region, adopting green investment and innovations become crucial (Adebayo et al. 2021). Similarly, use of technologies such as drones, geospatial information systems, closed-circuit television cameras, smartphone applications, have proven to enhance forest fire detection and wildlife management.

Strengthening regional cooperation is vital to meet both climate and biodiversity goals and targets through knowledge-sharing, technology transfer, and partnership programs (United Nations Educational, Scientific and Cultural Organization [UNESCO] 2023). Regional cooperation can lead to sustainable conservation and use of both terrestrial and marine biodiversity beyond national jurisdictions by strengthening synergies between climate change and ecosystems at landscape and seascape levels. {18.2.1; 18.2.3}

20.5.2.6 Implications of the transformation

20.5.2.6.1 Implication on socioeconomic systems

The transition to a clean energy system is estimated to require an investment of US$14.7 trillion by 2030 in the region, with ASEAN countries alone needing US$2.7 to 2.9 trillion by 2040 (ADB 2023b). To ensure and promote inclusive benefits, there is a need to invest in putting in place safeguard measures to address misuse of technologies. In the agri-food sector, the spread of mobile technologies, remote-sensing services and online marketing services can improve smallholder farmers' access to information, inputs and good prices increasing production, streamlining supply chains and reducing operational costs (Townsend et al. 2019).

The region needs innovative approaches to access climate investments by improving its environmental performance so that it can attract private environmental, social, and governance investments, resulting in lower costs for sustainable debt (IMF 2024).

Table 20.4: A Recycling rate for different materials

Variable	Scenario	2020 %	2030 %	2024 %	2050 %
Aluminium	Behaviour-Focused	60	62	63	65
	Current Trends	60	60	60	60
	Technology- Focused	60	66	73	80
Copper	Behaviour-focused	48	50	51	53
	Current Trends	48	48	48	48
	Technology- Focused	48	54	61	68
Industrial Roundwood	Behaviour-focused	40	42	43	45
	Current Trend	40	40	40	40
	Technology- Focused	40	46	52	60
Industrial Sand and Gravel	Behaviour-Focused	70	72	73	75
	Current Trends	70	70	70	70
	Technology- Focused	70	76	83	90
Iron Ore	Behaviour-Focused	78	80	81	83
	Current Trends	78	78	78	78
	Technology- Focused	78	84	91	98
Other Metals	Behaviour-Focused	29	31	32	34
	Current Trends	29	29	29	29
	Technology- Focused	29	35	41	49
Other Non-Metallic Minerals	Behaviour-Focused	10	11	13	15
	Current Trends	10	10	10	10
	Technology- Focused	10	14	21	30
Sand Gravel and Rock for Construction	Behaviour-Focused	70	72	72	75
	Current Trends	70	70	70	70
	Technology- Focused	70	76	83	90

20.5.2.6.2 Implications on environmental systems and unintended consequences

Adoption of technological solutions alone could drive prices high, leading to poorer access to a healthy diet and adequate food to poor and vulnerable groups. To cope with the climate crisis, food system transformation can focus on conservation-based intensification of agriculture and reducing excessive use of chemical fertilizers and pesticides in the region. Sustainable transformation of the food system must rely on green manures, methane-reducing animal feed, financial incentives such as support for certification and labelling that promotes ecological and environmentally friendly farming while eliminating harmful subsidies that encourage over-fertilization (FAO 2021).

The Asia and the Pacific region's success in increasing its forest area, countering global decline through large-scale reforestation in large economies, needs to be kept apace. Emerging challenges including deforestation, forest degradation, overexploitation of natural resources, and spikes in poverty need

Box 20.3: Climate change adaptation needs

The Asia and the Pacific region needs to prepare for adaptation to climate change and related disaster risks, as the region accounts for almost half of global natural and human-induced disasters. The expansion of informal settlements in urban areas needs to be protected from increasing urban heat island effects. Increased climate and weather extremes may further cause serious damage to local infrastructure, which in turn affects human security. (Chapter 8). This can be overcome by building climate-resilient infrastructure, using microgrid energy systems, water recycling systems, and local farm and food supply chains. Nature-based solutions can protect communities and infrastructure from coastal flooding and provide the evacuation space and sufficient ecosystem services that can potentially support to provide the human basic needs to all residents (**Figure 20.10**)

Figure 20.10: Nature-based solutions for coastal flood protection and ecosystem services provision

to be addressed through green, inclusive and resilient development actions. The estimated 500 million hectares of deforested and degraded land in Asia and the Pacific can be rehabilitated through ecosystem restoration (FAO 2023b). Transformative change is essential to address deforestation and ecosystem degradation caused by slash-and-burn and monoculture agriculture – practices driven by poverty and unsustainable lifestyles (FAO 2021; IPCC 2022).

20.5.3 Behaviour-focused Transformation Pathway

The behaviour-focused transformation pathway responds to policy questions by driving societal shifts towards sustainability, emphasizing equitable access to clean energy and ecosystem services. Using this approach, Asia and the Pacific region can transform its climate, nature and environment actions

through cross-sector, cross-scale and interdisciplinary solutions tailored to the region and subregions as described below.

20.5.3.1 Transition to green energy

In the Asia and the Pacific region, the renewable energy penetration in primary energy supply mix (**Figure 20.6**) is projected to increase about six times between 2020-2050 with 35 per cent of non-biomass renewables share by 2050 (Chapter 11). The adoption of renewable energy would also grow as more consumers start acting as prosumers, contributing energy to the grid. Demand side measures driven by lifestyle changes would drive the energy transition (KPMG Asia and the Pacific 2022), leading to decline in primary energy supply (11.3.1).

To increase electricity access, especially in rural and remote areas, establishment of decentralized energy systems with storage is essential (Asif et al. 2024, UNESCAP 2012), which could be further enabled by active and inclusive local governance that facilitates increased participation of all users especially women. Distributed electricity storage such as rooftop solar is expected to gain traction in coming years.

Concerning cooking fuels, the incremental demand in the Asia and the Pacific region is expected to be increasingly met by LPG to replace biomass and kerosene. For switch to LPG, the transition cost could be supported through government subsidies on cylinders (Sharma et al. 2019). In rural areas, increased adoption of efficient cook stoves and smaller size LPG cylinders could accelerate the transition (Gould et al. 2020). To promote electric cooking, free or subsidized electric cook stoves and associate utensils could be provided. Alternate technologies such as biogas could also be promoted to expand the clean energy basket, where local governments play major role.

The transition progress in Pacific Island countries could be accelerated using Indigenous Knowledge and local practices, such as Talanoa and Talanga, Tongan processes for participatory decision-making during project planning (Ofanoa et al. 2015; UNFCC 2022; Park et al. 2023; Chapter 11).

The final energy consumption in behaviour-focused pathways is expected to be less by about 43 per cent in 2050 in comparison to technology-focused pathways, as people are expected to adopt less-energy-consuming lifestyles, in the form of public transportation, judicious consumption, and increased use of recycled and reused materials. (Chapter 11, Chapter 16).

20.5.3.2 Sustainable agriculture and food system

Behavioural changes play a significant role in transforming the food system in the AP (FAO 2021), and the population at risk of hunger will likely fall after 2020 to just 1.06 million in 2050 (**Figures 20.7**; **20.8**). This may be attributed to the promotion of vegetarian and vegan diets that counter the expected rise in the consumption of meat and dairy products that accompany AP's growing middle class (FAO 2021). Reducing food waste is also vital to food system transformation in this pathway. These solutions include rearing regionally appropriate livestock on pasture, reusing food waste for nutrient recovery through backyard composting in rural towns, and connecting small-scale farmers with supermarkets through government-sponsored interfaces and services (FAO 2022b).

A strong commitment to developing supportive policies, market tools, and good governance to promote biodiversity-based practices, Indigenous knowledge, and local expertise in food production will drive the transformation of the food system along this pathway.

Effective governance and climate-resilient practices in the aquatic-food systems are crucial for ensuring food security and livelihoods (FAO 2023). The region can retain the position of being world's largest aquaculture producer, contributing 92 per cent of the world's supply of farmed fish and other aquatic products by maintaining resilience (FAO 2023a). To ensure sustainable growth, it's essential to curb overfishing through sustainable aquaculture intensification and expansion, manage all fisheries effectively, and upgrade aquaculture value chains. In this regard, implementing measures such as ecosystem-based fisheries management and controlling illegal fishing can help protect marine ecosystems and ensure food security in the Asia and the Pacific region (Fabian et al. 2023). Meanwhile, in the Small Island Developing States (SIDS) of the Pacific, a growing number of entrepreneurs are developing ideas such as smartphone apps, which help

Credit: crshelare/Envato

producers and consumers make informed, nutritious choices {17.2.1-17.2.5}.

20.5.3.3 Circular Economy and pollution control and prevention

A mix of regulatory measures, knowledge and good practice-based advocacy, awareness building for behavioural change can help make a huge shift in personal and organizational actions. Countries can mobilize younger generations in eco-friendly waste processing behaviour by incorporating this aspect in college education and transforming students, as enlightened future leaders, bring strong social impacts of pro-environmental behaviours to both the young and elderly citizens, while individuals' behaviour of household waste separation also matters highly (Rieckmann 2018).

Appropriate behavioural change needs to be adopted to promote citizen engagement for managing the waste at its source. Informal waste pickers can be organized by collecting segregated waste and separating recycling materials and working with local government in waste segregation. Improving the adoption of circular economy standards and practices

needs effective collaboration across various sectors and among all member economies.

Business sectors could coordinate with the upstream supply network, lobbying the government, and raising public awareness, while for local communities, there is a need to create mass awareness on the need for waste segregation and environment friendly disposal {15.2}.

20.5.3.4 Economic and financial system reforms

Countries in the AP region can accelerate climate and biodiversity action by integrating them into national finance systems. The reform can provide incentives to the private sector and set standards for emission disclosure by companies and products (OECD 2021). While strengthening disclosure systems, leveraging the pressure transmitted through supply chains to encourage collaborative carbon reduction between companies and their suppliers can gradually become a policy trend.

Several nations in the AP region have prioritized electric mobility and the reduction of carbon emissions in their transportation sectors. Forecasts from the International Energy Agency indicate that the total number of electric vehicles, encompassing cars, vans, trucks, and buses, could surge to 200 million in the region by the year 2030. However, with ambitious climate policies and financial incentives in place, this figure could potentially climb to 350 million, thereby making significant contribution to the worldwide ambition of reducing emissions (IEA 2022a){14.3-14.6}.

20.5.3.5 Conservation and restoration of nature

Integrating climate-resilient agroforestry, sustainable forest management, and conservation agriculture practices using Indigenous and local knowledge can improve ecological integrity of both agriculture and forest ecosystems (FAO 2023). Sustainable forest management and conservation agriculture programmes provide significant carbon sequestration sinks while also benefiting Indigenous Peoples and local communities. The land-sea ecosystem conservation requires integrated management and restoration plans informed by Indigenous Knowledge and Local Knowledge (UNEP 2022a). Effective management of protected areas can prevent land degradation, protect critical biodiversity areas, and help meet the Kunming-Montreal Global Biodiversity Framework targets {18.2.1-18.2.3}.

Growing numbers of nature-based solution pilot cases offer insights for potential adoption in the Pacific Small Island States. Ecosystem-based adaptation is widely recognized in the Asia and the Pacific regions as sustainable approaches to climate change adaptation. The effective use of these tools streamlines the decision-making process for planning ecosystem-based adaptation initiatives at local levels, making it easier to integrate these strategies into practical actions and behaviour (GIZ 2024).

The Asia and the Pacific region has emerged as a vibrant hub for environmental and social entrepreneurship, with a surge in initiatives addressing environmental problems. From green technologies and climate-smart practices to ventures led by women and youth, innovative solutions are flourishing across the region (**Box 20.3**).

20.5.3.6 The implications of the transformation

20.5.3.6.1 Socioeconomic system

The maintenance of decentralized energy systems in remote and rural areas, can increase employment opportunities, especially for women, who often lack good access to education and training due to cultural norms and lack of childcare support.

Countries can fast-track their net-zero and circular economy strategies to significantly affect international trade. The shift towards a low-carbon economy will directly influence resource demand, particularly reduce fossil fuel consumption and boost demand for low-carbon technologies (Yang et al. 2023). Tax incentives and policies encouraging research and development can accelerate low-carbon technology development, fostering sustainability.

20.5.3.6.2 Environmental systems / unintended positive and negative consequences

On the consumer side, products with lower environmental footprints or items made from recycled

materials can positively influence market trends and encourage businesses to adopt more sustainable practices. By adopting more sustainable practices, such as reducing, reusing, and recycling, communities can decrease the demand for new resources, thereby reducing the resource pressure on the Earth system. For instance, the efficiency of nitrogen resource use would increase from roughly 39 per cent in 2020 to almost 50 per cent by 2050 (Congreves et al. 2021). On the product side, increased recycling and better management practices are expected to reduce the waste released into the environment.

Restoring degraded ecosystems and undertaking large-scale reforestation efforts can help combat biodiversity loss and climate change in the region. These activities can contribute to carbon sequestration, enhance habitat connectivity, and provide multiple benefits to local communities (FAO 2023b). According to the IPCC (2022), a 40-70 per cent reduction in greenhouse gas emissions could be achieved by 2050 along with these behavioural changes.

20.5.4 What does that mean for the regional priorities?

By using model outputs and literature synthesis, mega-trends and policy options of major environmental issues in the region and subregions are analysed. Transformation pathways – based on Current Trends and Technological-focused and Behaviour-focused transformation scenarios – can reach subregional scale wherever data and information support are sufficient (UN 2023). Most countries in the region show continuous transformation, either in technology or behaviour, or both. Following the Current Trends Scenario is not an option. Technological transformation shapes resilient urban infrastructure and smart cities, enhancing urban resilience especially in major urban clusters of North, South and South-east Asia, accelerating transitions to renewable energy sources, amplifying energy efficiency, and promoting sustainable transportation that can significantly reduce greenhouse gas emissions in the region (ADB 2023a). Digital technologies including big data, artificial intelligence, and incorporation of citizen science observations can provide new frontiers for environment solutions in the region, including early warning systems for disaster risk reduction, cloud-based pollution monitoring networks, and smart grids for solar and wind energy. Meanwhile, lifestyle transformation is expected to accelerate across the region, with changing land-use practices, food production and processing and dietary habits. This accelerating transformation should apply both modern and Indigenous Knowledge and Local Knowledge and good practices in decision-making processes and enhance coordination among sectors and government units. The integration of the two transformation pathways, interacting synergistically using digital technology, can enhance e-commerce in the region and lead to a fundamental shift in marketing and consumption patterns (**Box 20.4)**.

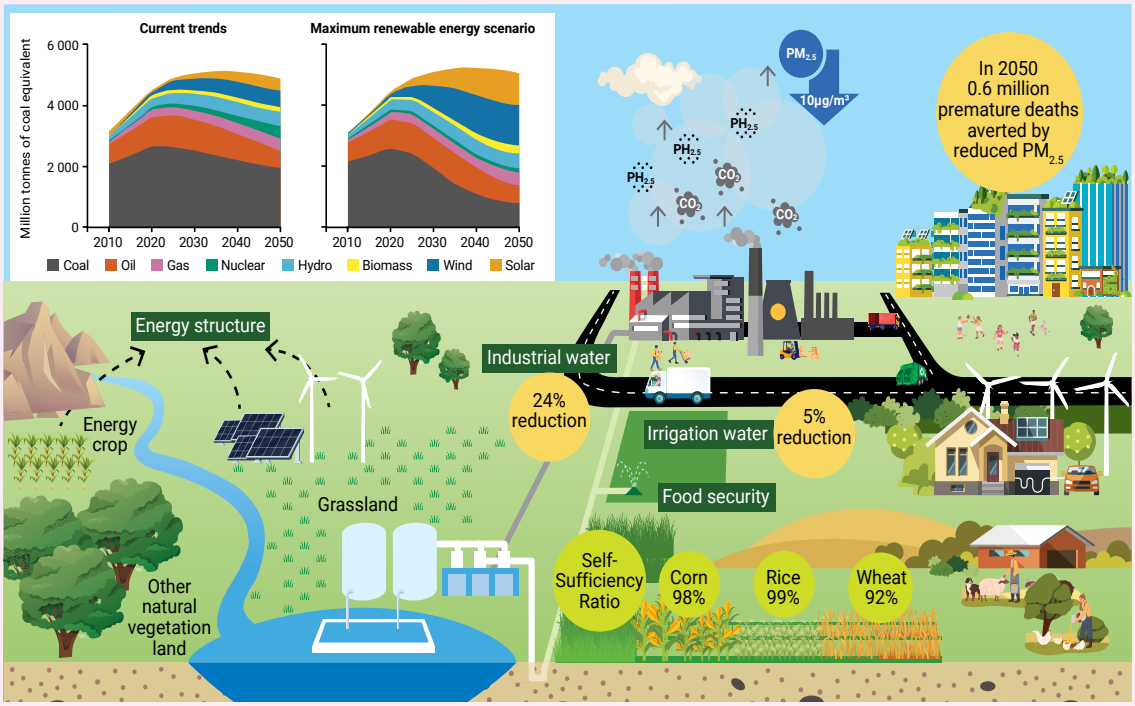
A technology-focused transformation sees energy transition driven mainly by the wide-scale deployment of renewable energies in carbon neutrality scenarios. Non-fossil energy will gain a more than 75 per cent share of total primary energy by 2050, growing from only around 17 per cent in 2020. This jointly reduces air pollution and brings human health co-benefits by avoiding 0.6 million air pollution-related premature mortalities in 2050. The West-East Energy Transfer project holds promise for future energy distribution in China, bringing significant benefits to the more densely populated and economically developed eastern and central China. Meanwhile, achieving carbon neutrality will also result in a 24 per cent reduction in the country's industrial water consumption by 2060, as renewable energy sources replace water-intensive thermal plants.

In the behaviour-focused transformation, rural residential energy for cooking and heating is shifted towards a two-stage energy transition from coal and biomass to natural gas and liquefied petroleum gas before 2040 and then to electricity by 2060. The decarbonization of cooking and heating is estimated to reduce $PM_{2.5}$ concentrations in almost all provinces and empowers individuals to contribute to reducing carbon emissions. This is particularly significant in northern China provinces, where the reduction in $PM_{2.5}$ concentrations is most pronounced. For the food system, behavioural change is essential to counter the adverse effects of land competition introduced by large-scale bioenergy deployment. Reconciling bioenergy deployment with domestic food security requires enhanced food system efficiency enabled by a bundle of sociotechnical measures including halving food loss and waste, shifting to healthier diets and, most importantly, narrowing crop yield gaps.

Box 20.4 Transformation pathways for China

The transformation pathways for China to reach carbon neutrality by 2060 are modelled using the tools recommended in Chapter 9 (**Figure 20.11**). Achieving carbon neutrality in China reveals plentiful opportunities to realize synergies in the water-energy-food nexus and the health sector. However, both technology and lifestyle transformations are needed to yield these gains while reducing consequences for land use and food security. This calls for more carefully designed strategies for China, which could also provide valuable insights for countries in the Asia and the Pacific that share similarities with some provinces in China.

Figure 20.11: Carbon neutrality transformation pathways for China and its implications for energy, environmental and food systems



Source: Hancheng Dai (PKU), Kejun Jiang (ERI), Jiayi Ng (PKU).

2.5.5 Reflections on strengthening regional interlinkages

2.5.5.1 Interlinkages

By embracing transformative pathways, the Asia and the Pacific region can achieve global goals and targets for addressing climate change mitigation and adaptation, nature conservation, and waste management – driven by factors including demographic dividends, labour-force mobility, decarbonized urbanization and industrialization, and climate-resilient development. These changes can result in mostly positive environmental consequences with notable improvement in ecosystem health, biodiversity, water resources, and human well-being (UNESCAP 2019). Protecting environment and conserving nature through ecosystem-based adaptation can result in human security and resilience of most vulnerable countries, especially climate-change-vulnerable small island nations in the Pacific region. Flood defences in the coastal areas and building resilient infrastructure and livelihoods can avert the risk of permanent submergence of island and coastal settlements (IPCC 2022; IPCC 2023).

To combat the global environmental crises, countries in the region can double their efforts towards sustainability and environmental conservation. A renewable energy transition can lead the transformation by providing affordable access to low-income communities.

However, despite these potential achievements, significant challenges remain, especially in finance, necessitating urgent action to address the complex developmental and environmental challenges in the region and subregions.

The Current Trends Scenario results in a two-fold increase in CO_2 emissions by 2050, justifying an urgency for transforming environmental and economic systems. Nature-based solutions, sustainable aquaculture and agriculture practices, and nature conservation efforts are necessary for creating resilient food, water and human systems. Efficient waste management, recycling, and tackling e-waste are crucial for sustainable materials management (Peng et al. 2023). Environmentally sound investments and green technology innovation are key strategies for economic growth while addressing environmental challenges (United Nations Framework Convention on Climate Change [UNFCCC] 2023). Multiple transformation pathways are likely to be adopted by the region's countries in the coming decades leading to 2030 and 2050 when SDGs are to be achieved. These pathways are likely to be interlinked, creating interdependence for maximizing synergies and minimizing trade-off.

20.5.5.2 Synergies and trade-offs

Technological advances, including smart-grid systems and energy-efficient appliances, complement sustainable consumer behaviours by enhancing efficiency and facilitating practices like recycling and waste reduction. This synergy can build resilience against climate impacts, as innovations in climate-resilient infrastructure work alongside responsible land use and biodiversity conservation efforts. Furthermore, the integration of technology and behavioural change can create new job opportunities in sectors like renewable energy, stimulating economic growth and establishing a positive feedback loop that benefits both the environment and the economy.

However, there are notable trade-offs to consider. Transitioning to new technologies often involves significant upfront investments that may burden lower-income communities and disrupt traditional industries, leading to job losses. Additionally, disparities in access to technology can exacerbate socioeconomic inequalities, while reliance on technological solutions might foster complacency regarding sustainable behaviours. Moreover, competition for limited land and water resources due to the introduction of new technologies may conflict with food production and ecosystem health goals.

Balancing these synergies and trade-offs is crucial for effective policymaking. By strategically navigating the interactions between technological innovations and behavioural changes, stakeholders can design interventions that drive sustainable development in the AP region and beyond. This holistic approach can foster resilience and inclusivity while addressing complex challenges such as climate change, unsustainable resource management, and economic disparity.

20.5.6 Policy implications

The region can enhance sustainable development by implementing a range of policies focused on renewable energy, sustainable land and water management, and the transformation of food systems. Key strategies include incentivizing renewable energy adoption through smart subsidies and feed-in tariffs, promoting sustainable food systems to adapt to and address land degradation and climate extremes, while ensuring equity and justice. Additionally, supporting innovative financing models and fostering public-private partnerships can increase investments in green sectors.

On the consumer side, products with a lower environmental footprint or items made from recycled materials can positively influence market trends and encourage businesses to adopt more sustainable practices. Meanwhile, significant behavioural shifts, alongside technological advancements, could help achieve net-zero emission targets of the region by 2050. As individual investors grow more environmentally aware, their investment activities are likely to shift away from resource extractive industries and towards sectors that promote sustainability and circular economy models.

Restoring degraded ecosystems and undertaking large-scale reforestation efforts are vital for combating both biodiversity loss and climate change. Creating more green parks and open spaces, wetlands, and urban agriculture can counter flood risks and urban heat island effects.

Table 20.5: Actions for Asia and the Pacific Countries

Systems	Technology-focused Transformation		Behaviour-focused Transformation 2024 %	
Economic and finance {14.3-14.6}	Innovative decarbonizing initiatives through market-based mechanisms	Apply novel technology for green finance	Scaled up Finance and integration of Indigenous and local solutions into modern ones	Apply carbon tax and polluters pay principles
Material and waste {15.2}	Reduce e-waste with reuse and life cycle assessment	Digital innovations for supply chains traceability	Change market and pricing signals for used products and secondary materials	Increase awareness on circular lifestyle choices
Energy {16.2-16.4}	Scale-up adoption of renewable technologies	Increased investment in electric cars and energy saving technology	Raise awareness to the benefits of lower energy lifestyles	Enable availability of sustainable mobility choices
Food {17.2.1-17.2.5}	Enhance localized technology in farming and food processing	Strengthen food market structure and regulations in international trade.	Conservation agriculture practices with Indigenous and local knowledge	Encourage local knowledge based diverse and healthy diet
Environment {18.2.1; 18.2.3}	Prioritize technological innovation for ecosystem protection and restoration	Advance digital technology for monitoring and forecast	Coordinate nature-based climate and ecosystem solutions	Climate-resilient agroforestry, sustainable forest management

20.5.7 Conclusion

The outlook for the AP region presents a mixed picture. With the Current Trends Scenario, the region will not achieve the sustainable development goals nor fulfil net-zero ambitions by 2030 and 2050, respectively. However, by undertaking transformative actions the region can accelerate progress by capitalizing on its fast economic growth, advanced technological innovation and regional cooperation. Greater and diverse challenges exist at subregional levels to embrace transformation – the East Asia and West Asia subregions provide promising outlooks, in addition to a few fast-growing economies in the South Asia and Southeast Asia subregions. Therefore, sub regionally customized transformative options can address the global environmental crises. What is critically needed is striking a strategic balance between socioeconomic growth and sustainability through a judicious application of diverse knowledge systems, technology and behavioural change options.

20.6 Eastern European Region

20.6.1 Introduction

Eastern Europe (EE) is part of the fastest warming continent in the world. Climate risks are threatening energy and food security, ecosystems, infrastructure, water resources, financial stability and human health (European Environment Agency [EEA] 2024). The region's key priorities are:

- Climate change
- Land degradation
- Heavy fossil fuel usage and abusive pricing generating high levels of energy poverty
- Loss of biodiversity and key habitats (Chapter 8)

This chapter proposes transformative pathways to meet these priorities, providing recommendations to

the region's policymakers to achieve environmentally sustainable, socioeconomically sound, and climate-resilient futures by implementing solutions that optimize synergies and trade-offs. Most of the region's countries are either European Union (EU) member states, candidate countries, or partnership countries that follow EU legislation and policies. Non-EU countries follow their national policy and regulatory frameworks. The war in Ukraine is a major factor affecting the future of the region's ecosystems and environments (UNGCRG 2022; UNEP 2023). Analysis and policy recommendations for the future, presented in the next sections, answer this Chapter's policy questions, based on modelling results and a literature review and with specific input from Indigenous Knowledge and Local Knowledge experts.

20.6.2 Technology-focused Transformation Pathway

20.6.2.1 System transformations

This pathway focuses on technology solutions to drive systemic change across energy, agriculture, and materials sectors.

The region is influenced by EU policies. However, climate neutrality targets are to be achieved at different speeds depending on expectations for each country. Russia and Belarus follow different legal frameworks to achieve global goals and targets (Lafortune et al. 2022; Bashmakov 2023; Interreg Europe 2023; Nurcan Kilinc-Ata and Dolmatov 2023; IRENA 2023a-e; European Commission 2023a-h; Energy Monitor 2024; Yakov and Partners 2024; Climate Action Network Europe [CAN] 2024; IEA 2025).

Under this scenario, the transformative, integrative and cross-sector solutions tailored to the needs of the region are described below:

20.6.2.2 Economic and financial system reforms

The EE region needs tighter environmental regulations for foreign direct investments, to combat foreign investors' interest in profit maximization and promote the use of green technology for environment protection. Governments can provide incentives for adopting clean technologies to enhance renewable green infrastructure, reduce economic and energy poverty, and create job opportunities (Simionescu and Gavurová 2023; European Commission 2023a-h; Chapter 7). The region recorded progress on sustainable and digital finance, which must be intensified. By 2030, green finance will contribute to reductions in carbon emissions and material footprints – this trend will accelerate between 2030 and 2050 (European Commission 2023a-h; Kantor et al. 2023; UNDP 2023). Innovative green finance and carbon tax measures will boost investments and consumption towards sustainability (Chapter 14). The national legal framework alignment to EU banking requirement is ongoing in most EE countries, Russia manages to keep its green finance agenda relevant, while Belarus facilitates green finance development collaborating with UNDP (Kopalkina and Arustamyan 2024; Martirosyan 2024) {14.3-14.6}.

20.6.2.3 Circular economy, pollution control and prevention

Most of EE countries focus on managing waste rather than on preventing it through circular design. It is expected that a 23 per cent circularity rate target will be achieved by 2030 (European Court of Auditors [ECA] 2023). Russia and Belarus follow different legal frameworks to achieve national targets, mainly in the waste sector (Maalouf et al. 2021; Republic of Belarus 2024). The technology-focused pathway generates a decrease in total material demand through improved design, material substitution, a high recycling rate and reduced waste (Chapter 15) (**Figure 20.12**). **Figure 20.12** Total material demand scenarios in Eastern Europe (Chapter 11-12).

To achieve the transition to a circular economy and climate neutrality by 2050, binding targets, which only exist in the waste sector – municipal waste, construction and demolition waste, and the deposit return system – must be introduced in all sectors (Gassiy and Novikov 2022; National Recovery Council 2022; United Nations Conference on Trade and Development [UNCTAD] 2022; European Commission 2023a-h; Bitsadze 2023; Barseghyan 2023; EU4Environment 2023; Todasca 2023; European Union 2025). The technology-focused pathway reduces demand for industrial roundwood by 11 per cent between 2020 and 2030 and by 25 per cent between 2020 and 2050, providing opportunities for improvements in conservation and ecosystem service (**Figure 20.13**) {15.2.5}.

Figure 20.12: Total material demand scenarios in Eastern Europe

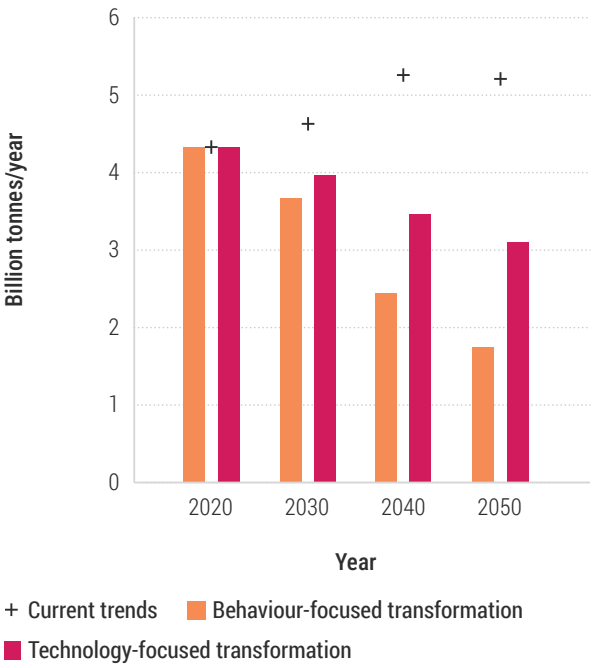
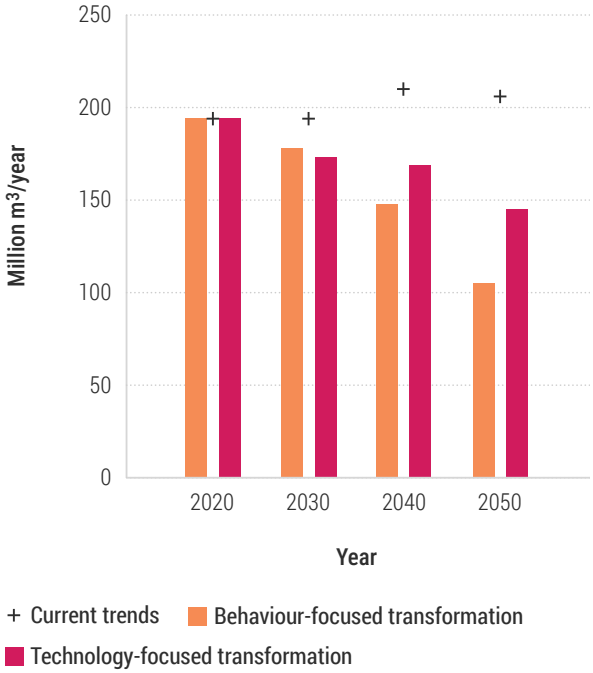


Figure 20.13: Forestry production scenarios in Eastern Europe



20.6.2.4 Transition to renewable energy

Different policy frameworks for EE countries explain the uneven nature of low-carbon energy transitions (International Renewable Energy Agency 2023; IRENA 2023a-e; European Commission 2023a-h; Energy Monitor 2024; Yakov and Partners 2024; Eurostat 2024; IEA 2025). An energy transition is completed by 2050 based on a transition to renewable energy, carbon capture and storage (CCS) strategies and enhancing energy efficiency (Chapter 11).

In this scenario, primary energy production declines by 28 per cent between 2020 - 2030 but rises by 19 per cent between 2030 - 2050 due to the rapid increase of renewable energy use. Production of renewables is expected to rise sharply between 2020 - 2050. Solar energy production could increase by 468 per cent between 2020 and 2050 (**Figure 20.13**). Nevertheless, the share of renewables as a proportion of the total primary energy supply remains relatively low, at 27 per cent by 2050. Meanwhile the fossil energy supply share declines slowly by 2050, therefore promoting CCS as a solution to climate change is essential (**Figure 20.14**; Chapter 11-12; 16.2-16.4).

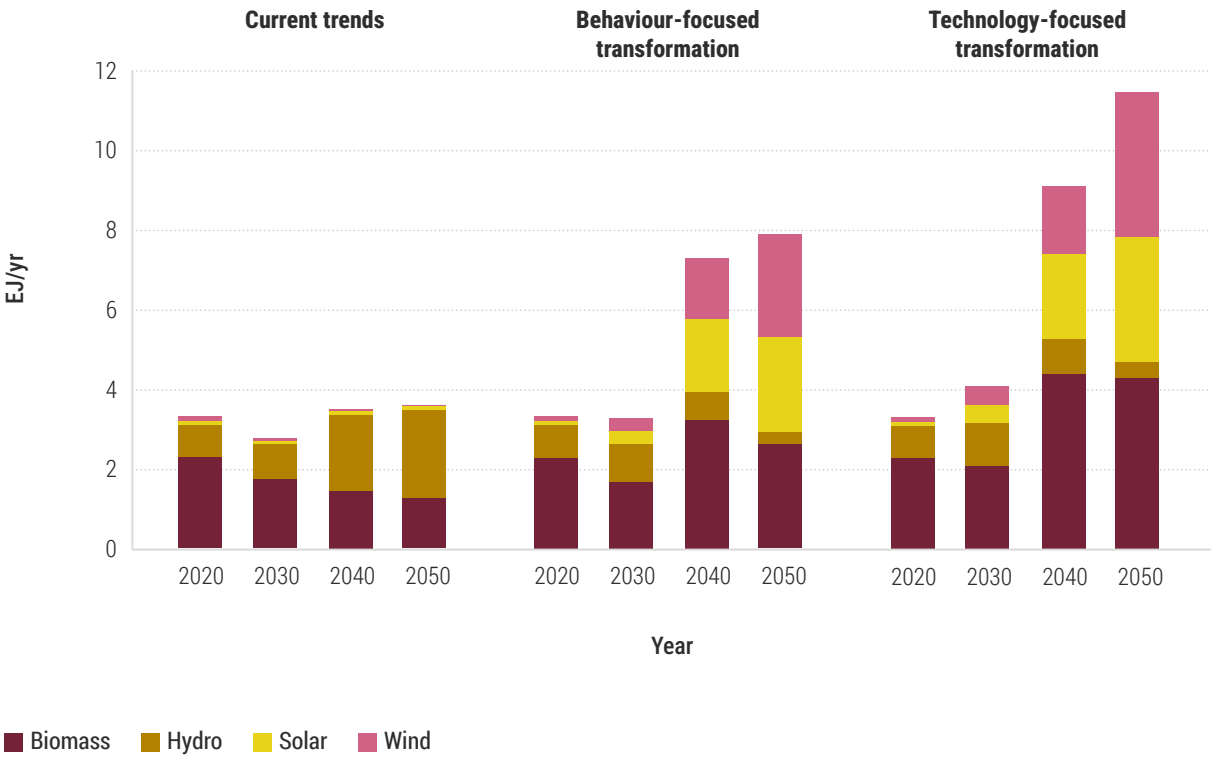
To reach EU Renewable Energy targets (2030–2050) for improving the environment, public health, and reducing energy poverty, the EE should implement the following policies:

- Expanding renewable energy while phasing out fossil fuels
- Utilizing the EU Social Climate Fund and emissions trading systems revenues to lower energy bills, promote clean transport, and invest in energy-efficient housing across regions' most in need
- Breaking energy monopolies and regulating unfair pricing
- Preventing speculative trading in energy markets; (European Commission 2023i; Widuto 2023; European Environmental Bureau 2024)

20.6.2.5 Sustainable Agriculture and Food System

The technology-focused pathway is based on efficiency, sustainable intensification, and precision farming (Chapters 16 to 18). A shift towards sustainable diets is promoted through nature-based solutions and new production techniques boosting the introduction of novel foods. Digital agriculture and

Figure 20.14: Renewable energy supply scenarios in Eastern Europe



biotechnology pose a significant barrier to small and medium enterprises facing difficulties in innovating (European Economic and Social Committee [EESC] 2022; European Academics Science Advisory Council [EASAC] 2022; Masi et al 2023; Konfo et al. 2023).

By 2030 in most EE countries, the economy will remain heavily reliant on the agricultural sector in terms of contribution to GDP and total employment, while small-scale agriculture will continue to be an important food source and safety net (Eurostat 2022; Yakovlev and Alexseev 2022; IPCC 2022; European Commission 2023a-h; The GlobalEconomy.com 2023a-d; Eurostat 2024). Extreme weather events and political instability will continue to threaten food security in several subregions of the EE.

Demand for food crops increases by five per cent by 2030 and 14 per cent by 2050 compared to 2020. By 2030 and 2050, demand for livestock declines by one per cent and 15 per cent, respectively, while demand for feed crops by seven per cent and 24 per cent reflecting a shift towards sustainable diets promoted by nature-based solutions, new production techniques for novel food and higher crop yields. However, demand for energy crops records a sharp increase with 473 per cent by 2030 and 546 per cent by 2050). Increasing crop yields offsets this effect (**Figure 20.15**; 17.2.1-17.2.5).

Due to high efficiency, precision farming and reducing food waste, this scenario generates the highest increase in agricultural production, by 13 per cent between 2020 - 2030 and by 41 per cent between 2020 – 2050 (**Figure 20.16**) The region's agricultural production exceeds demand leading to trade surplus between 2020 and 2050. Sustainable food system transformations can be achieved under this pathway.

20.6.2.6 Conservation and Restoration of Nature

Generally, EE follows the EU Biodiversity Strategy for 2030 by protecting nature and reversing the degradation of ecosystem, while Russia and Belarus have different legal frameworks and coordinate biodiversity strategy with global goals and national targets (Elias 2021; EASAC 2022; EEA 2023; Republic of Belarus 2025).

Numerous sites in EE – mining areas, heavy industry zones, contaminated lands – require revitalization, where principles of natural succession must be applied to achieve a higher quality of future ecosystems (Chapter 8). The level of biodiversity is significantly

Figure 20.15: Agricultural demand scenarios in Eastern Europe

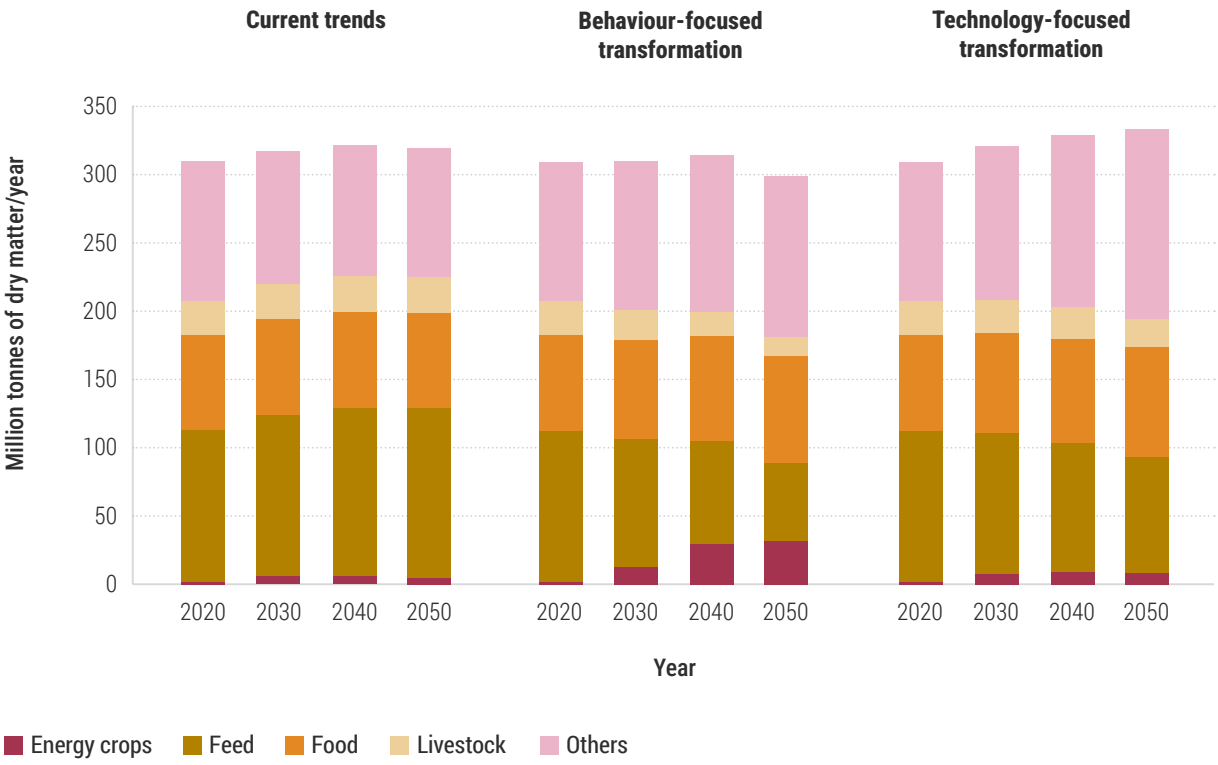
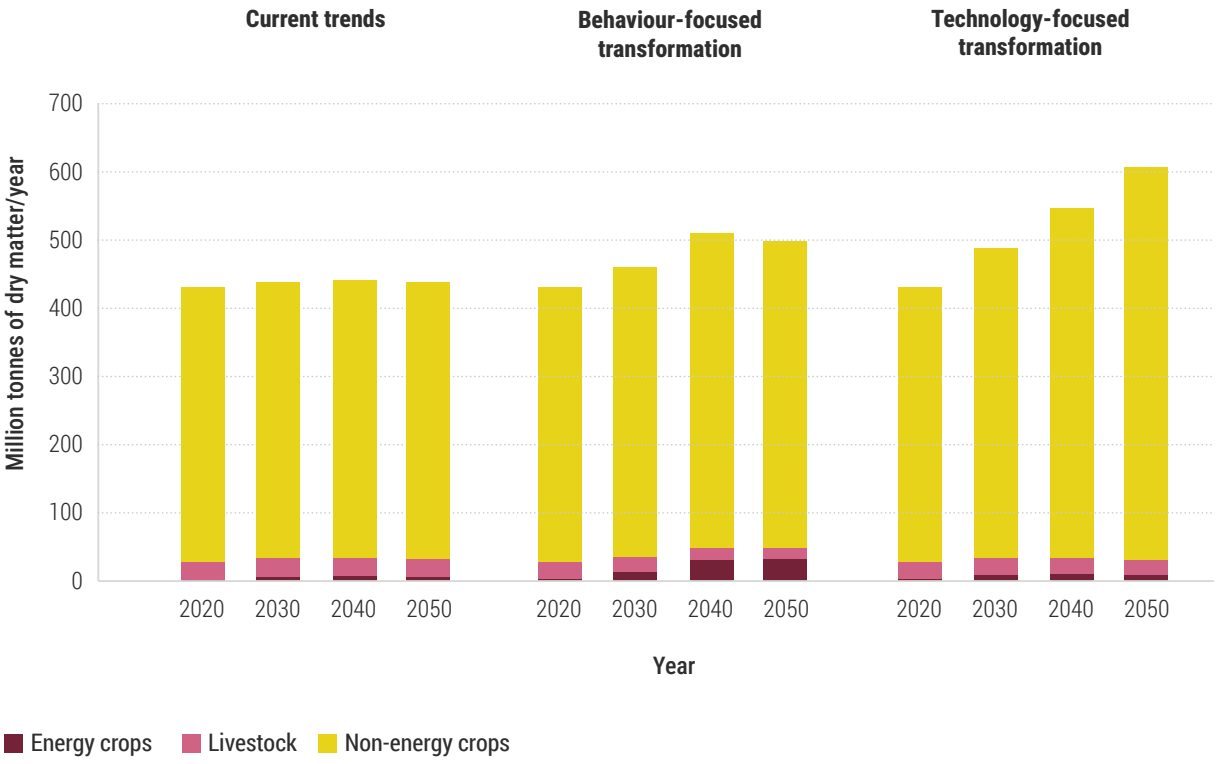


Figure 20.16: Agricultural production scenarios in Eastern Europe



higher compared to other regions of the world. A trend of further reduction in mean species abundance is projected by 2030 (Chapters 11 and 12). Sustainable agricultural practices contribute to mitigate land degradation, biodiversity loss and climate change, aligned to the EE priorities (Chapter 8).

The technology-focused pathway generates an increase in cropland cover, with two per cent by 2030 and 10 per cent by 2050 due to the rising demand for energy crops. Forest cover records no change by 2030 and one per cent increase by 2050. Pastureland decreases by nine per cent by 2030 and by 33 per cent by 2050, due to a shift towards sustainable diets promoted by nature-based solutions and new production techniques. By managing cropland expansion, this scenario can mitigate land-use changes, enhance biodiversity conservation, and support sustainable farming {18.2.1; 18.2.2}.

20.6.2.7 Implications of the transformation

The EE region is shifting to digital applications quickly (McKinsey and Company 2023). The technology-focused pathways offer substantial benefits, including economic growth, jobs creation, improved human well-being, resource efficiency and waste minimization. While technology-focused pathways can create new jobs in high-tech and service sectors, they may also generate unintended negative consequences and displace workers in traditional industries, leading to higher unemployment, informal employment, brain drain, high old-age dependency and income inequality, if adequate retraining is lacking. Targeted investment in education and training promoting green and digital skills can bridge income inequality gaps and enhance workforce adaptability (Simionescu and Gavurová 2023).

In these pathways, continued heavy fossil fuel use to 2050 would require large-scale industrial CCS deployment – including capture at power plants, industrial facilities, and direct air capture – to achieve CO_2 reduction targets of 37 per cent by 2030 and 86 per cent by 2050 (**Figure 20.17**). While afforestation and ecosystem restoration are important complementary sinks (20.7.2.6), their potential is addressed separately within the biodiversity framework. The reductions presented here therefore assume CCS as the primary offset technology, which would require a massive scale-up beyond today's capacity and must be combined with natural sinks and systemic reforms to be sufficient.

A portfolio of solutions — CCS + renewables + forest expansion + governance reforms — is required to meet the 2030 and 2050 targets.

Compared to the Current Trends Scenario, both transformation scenarios foresee lower GDP loss from climate damage which will increase by less than one per cent of GDP by 2050. Meanwhile avoided damages, measured as a percentage of GDP, are also expected to reach one per cent by 2050. According to the GEO-7 data modelling procedures, both scenarios are projected to follow the same trend (**Figure 20.18**). Internalizing damages associated with carbon emissions can encourage decarbonization in addition to the implementation of the Emissions Trading Systems and the EU Carbon Border Adjustment Mechanism.

The two pathways are not modelled as concurrent or competing simulations but as distinct and complementary strategies.

Figure 20.17: Net-emission of Kyoto greenhouse gases for scenarios in Eastern Europe

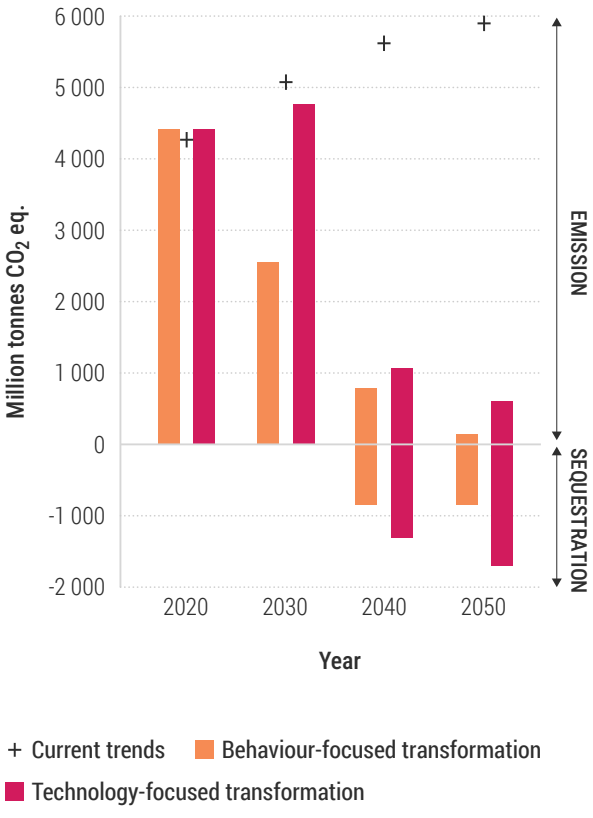
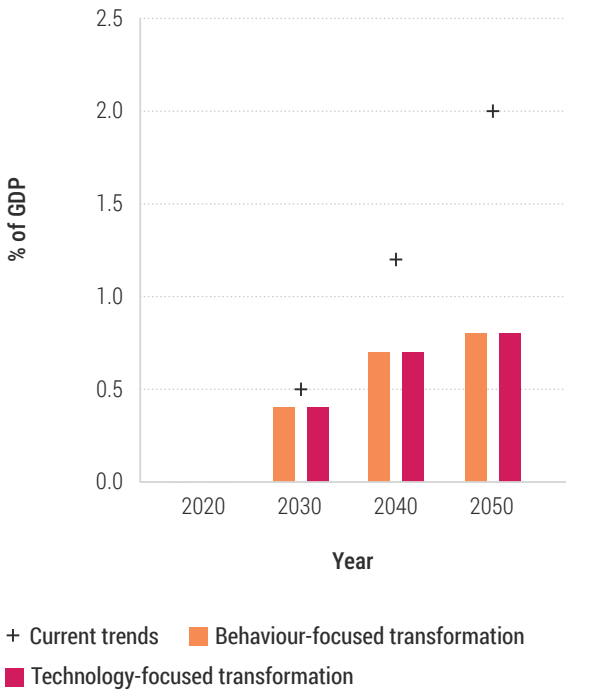


Figure 20.18: Climate damage corrected by loss relative to GDP in Eastern Europe



Source: CCCCCCC

The five systems are interdependent, and achievements in one generate co-benefits for the others. Implementation of new technologies can shape individuals' and firms' behaviour and consumer decisions, while behaviour-driven change can create demand for clean and efficient technologies.

Overall, the technology-focused pathway delivers innovations – such as renewable energies, precision agriculture, and circular production – to address regional priorities, whereas the behaviour-focused pathway reinforces sustainable consumption and social norms.

Taken together, these pathways provide independent yet synergistic solutions that mitigate Eastern Europe's environmental challenges and support achievement of the modelled targets.

20.6.3 Behaviour-focused Transformation Pathway

20.6.3.1 System transformations

This pathway emphasizes behaviour change, social norms, and community-driven actions, focusing on local and individual-level actions to drive transitions. Examples include prosumer activities and decentralized renewable energy solutions fostering community-based renewable energy generation and consumption, reducing energy poverty, dependence on centralized systems and enhancing local resilience. It also responds to policy questions by driving social shifts towards sustainability emphasizing equitable access to energy.

The behaviour-focused pathway offers transformative, integrative and cross-sector solutions and policy recommendations tailored to the EE region and are presented below.

20.6.3.2 Economic and financial system reforms

Behaviour-focused pathway aims at greening the finance systems and internalizing externalities (14.3 to 14.6). In most parts of the region, EU policies and environmental regulations are applicable. For example, the Polish energy sector applies structural changes to achieve internalizing of externalities by 2050 (Kudelko 2022).

Existing EU policies and financial mechanisms are important, but EE needs solutions for the future to ensure access and effective use of financing for green economy transition (OECD 2022). Good-practice examples include better water management strategies at user level aiming at minimizing water demand (OECD 2022) and policies for green infrastructures as blue-green corridors (European Commission 2021). The implementation of nature-based solutions supporting financial mechanisms also has strong social value (Bockarjova et al. 2022) that can compensate for lower public acceptability of a transitions' high-costs.

Policy recommendations for behaviour-focused transformation may aim at communication strategies to influence social norms and behaviours and improved citizens' and small businesses' access to financial capital and investments.

20.6.3.3 Circular economy, pollution control and prevention

Repairing, refurbishing, and recycling can be the norm for the behaviour-focused pathway (Chapter 15). Material systems in EE lack mechanisms for a circular economy.

In many EE countries the circular rate of material use (EEA 2024) is lower compared to other European countries, while in some other is even decreasing. The current EU target for 2030 is 23.4 per cent (EEA 2024), while in 2021 it was 11.7 per cent.

In the behaviour-focused pathway, material demand per capita is projected to decline by 14 per cent by 2030 and by 54 per cent by 2050 compared to 2020, representing a significant reduction compared to the technology-focused pathway (**Figure 20.12**). The behaviour-focused pathway for the materials system should seek to reduce the need for conspicuous consumption that would lead to lower material footprints (Chapter 10).

The pandemic and the war in Ukraine have significantly reduced consumption of luxury goods (Statista 2024a). However, the prediction for the short and long term is a gradual increase of the EE luxury goods market (Statista 2024a).

Policy measures may focus on preventing e-waste and stimulate the related e-waste collection and recycling rate and on promoting sustainable production and consumption, coupled with lifestyle change to reduce over consumption in the importing country and environmentally friendly production in exporting countries. Efforts should be made to achieve SDG12 through better teleconnections, sustainable trade, and targeted communication strategies (Chan et al. 2018). It is worth mentioning that stopping the decline of traditional repair shops – watch repair, cobbler services, electronics, home appliance repairs – which were common in EE, is important for enabling the new societal practices of circular lifestyle choices.

20.6.3.4 Transition to renewable energy

One of the main drivers of the behaviour-focused pathway in the energy system is the emergence of prosumers – in this context, prosumers are consumers who also produce energy, typically through renewable sources like solar panels, and are encouraged by feed-in tariffs or other support schemes (Brown et al. 2020; Korsnes et al. 2024). The potential of prosumers in EE is very high (EEA 2022; IEA 2023). For example, out of 10 EU countries with highest potential electricity production by prosumers, four countries are from EE (EEA 2022).

In the behaviour-focused pathway, primary energy production could decline by 35 per cent between 2020 to 2030 and by another 30 per cent between 2030 and 2050 (Chapters 11 and 12) and the share of renewables, especially solar and wind, is projected to increase from 6.7 per cent in 2020 to 10.4 per cent by 2030 and 35.6 per cent by 2050 due to behavioural change (**Figure 20.14**, Chapters 11 and 12). The policy measures in EE may introduce incentives for decentralized green energy production that historically was lacking in the region, with Poland already rapidly implementing these changes (EEA 2022). In Eastern Europe, civic energy prosumerism is growing in popularity and value (Żuk and Żuk 2022), because it attempts to break state monopoly on energy production. Nonetheless challenges remain – particularly in terms of sociopolitical mechanisms, given efforts to maintain centralized monopoly.

However, there is a significant potential in the region to shift prosumerism from individual to collective action via establishing energy communities (Chapter 16). Solutions levers include raising awareness of the benefits of lower energy lifestyles, mechanisms to finance expansion of energy efficiency, and renewable energy facilities at household level, as well as enabling the availability of sustainable mobility choices for the public {16.2 to 16.4}.

20.6.3.5 Sustainable agriculture and food systems

Behavioural change in food systems can stimulate a strong shift to plant-based foods and promote policy incentives to preserve the vitality of local ecosystems (Chapter 13). The behaviour-focused pathway indicates significant increase in the demand for food crops by three per cent by 2030 and 11 per cent by 2050 (**Figure 20.15**), caused by shifts to more sustainable diets at the individual level.

Behavioural transformation in agriculture and food system will also affect agricultural demand inducing the decrease of crops for livestock – 11 per cent and 42 per cent by 2030 and 2050, respectively – and crops used as feed – 16 per cent and 49 per cent by 2030 and 2050, respectively – due to a switch to plant-based and sustainable diet (**Figure 20.15**). This will require change in social norms and collective actions towards achieving more sustainable food consumption and practices (Chapter 17).

The EE region is a large producer and exporter of agricultural products, especially grains (Garazha et al. 2023). However, the scope of the land allocation to traditional agriculture increases pressures on local ecosystem services. Small and subsistence agriculture should be supported and encouraged through policies and markets, rather than eliminated or transformed. The food practices in EE need to build on rich traditions of community-based local food production that can be transferred to modern settings. For example, urban farming and gardening provide possibilities for disadvantaged citizens to participate in the production of food and empower women as agents of change. The behavioural transformation can promote significant reduction of food waste in the food chain, and dietary change will tackle the obesity problem that is visible in EE {17.2.1-17.2.5}.

20.6.3.6 Conservation and restoration of nature

Behavioural change in the environmental system can be guided by the principles of sharing resources for the reconciliation of human and ecosystem well-being. Transformation pathways indicate the possibility of achieving CO_2 emissions targets by 2050 in EE (**Figure 20.17**). The behaviour-focused pathway indicates increase of cropland, by 10 per cent by 2030 and by 12 per cent by 2050 compared to current trends (**Figure 20.19**, Chapters 11 and 12). This scenario reduces pasture lands and promotes land-use practices that protect water quality and access. By expanding protected areas and reducing pasture lands, behaviour transformation addresses land degradation challenges through ecosystem conservation and water resource management achieved through nature-based solutions. In some parts of EE, the management of protected areas lacks participatory decision-making, and systematic change is needed for nature conservation models (Yakusheva 2019). This change should encompass cultural appreciation of nature, including Indigenous and local traditions. The behavioural approach also offers the potential to enhance ecosystem quality in landscapes outside protected areas, making them more resilient to climate change and weather fluctuations (Chapter 18).

Behavioural change is a bottom-up process driven mostly by individual and community actions (Chapter 10). The conceptualization of public and private environmental actions includes waste sorting as an individual action and to participating in civil advocacy a community action. Usually, individual action is stronger than community action (European Commission 2020).

In EE, environmental activism is weak both at individual and community levels compared to other European countries, creating significant obstacles for future behavioural transformation. There are significant subregional differences in terms of social inequality (UNDP 2024), and the gap between the poorest and the richest is projected to increase. This could indicate barriers to the behavioural change that would require economic sacrifices at individual level such as paying higher prices for renewable energy (Chwialkowska and Flicinska-Turkiewicz 2021).

The behaviour-focused pathway foresees transformation guided by the principles of sharing resources for the reconciliation of ecosystem and human well-being (Chapter 12; 18.2.1; 18.2.2). By 2050, this pathway could nearly eliminate CO_2 emission in EE region – 44 per cent decrease in CO_2 emissions by 2030 and 106 per cent decrease by 2050 (**Figure 20.17**).

20.6.3.7 Implications of the transformation

Methane emissions in the energy sector would decrease more compared to the technology-focused pathway due to a significant shift from energy production reliant on fossil fuels (Chapters 11 and 12). These projections can be affected by increasing CO_2 emissions generated by the war in Ukraine (Bun et al. 2024; Statista 2024b). Awareness-raising and behavioural changes are not enough to minimize carbon footprints. There is also a need for structural changes in how the food, housing, energy, and transport networks are organized (Liobikienė and Poškus 2019), as well as motivation to update vehicle fleets for public and private businesses (Stecenko et al. 2022; The European Automobile Manufacturers' Association [ACEA] 2023).

The EU's Green Deal fosters incentive mechanisms to take policy actions towards the 2050 net-zero emission target, among the EU countries in the EE region. This can play a role as motivation for taking similar actions in the non-EU region, addressing possible future regional inequalities in the scale and speed of change.

Policy recommendations should be applied to a broad range of actors, guided by strong institutions, who

engage in dialogue to explore new ways of interacting and protecting nature. Successful implementation of EU legal frameworks, directives and guidelines in member countries can act as a model for what works and adapted by non-EU countries.

20.6.4 Regional priorities

Given the unique challenges and priorities of the region, a balanced hybrid approach integrating both Technology-focused and Behaviour-focused transformations is essential to address the region's socioeconomic and environmental goals which include reducing greenhouse gas emissions, preserving biodiversity, and restoring degraded land. Each pathway offers distinct advantages but also limitations when applied independently (**Figure 20.19**).

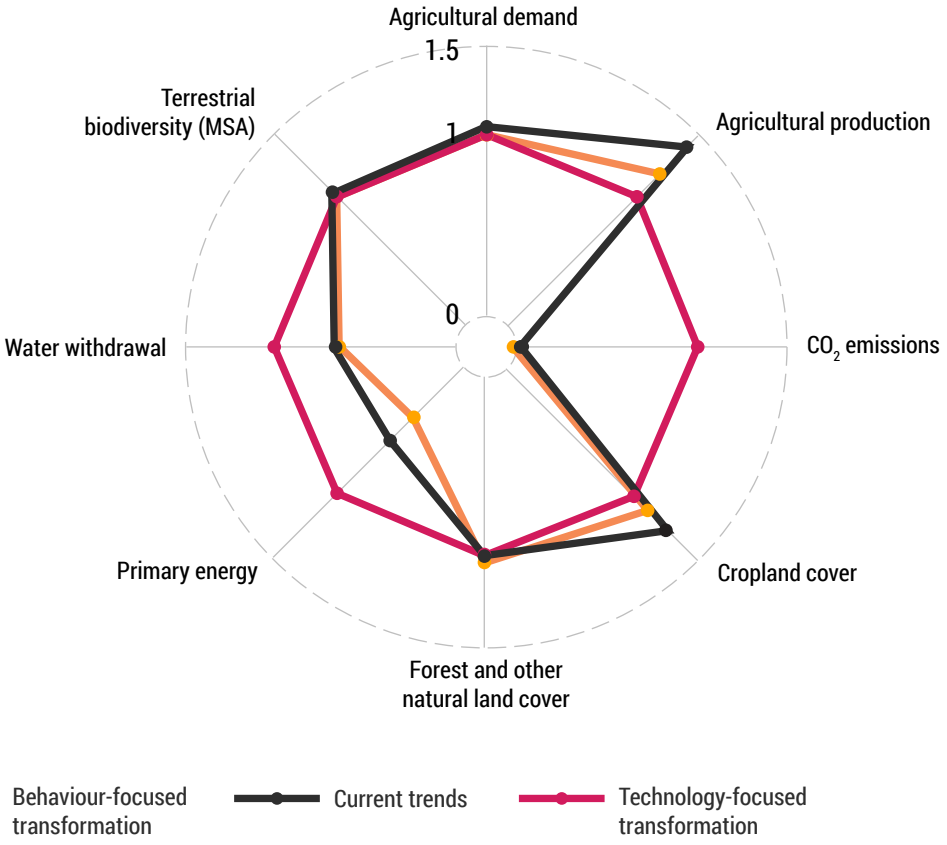
20.6.4.1 Socioeconomic effects

A major socioeconomic challenge is EE's heavy reliance on fossil fuels (Radovanović et al. 2022), which is currently a significant source of employment and economic stability. The emphasis on carbon capture and storage technologies is crucial for the transition from fossil fuels (**Figure 20.17**). Simultaneously, behavioural changes focus more on energy use reduction. The share of EE's renewable energy (Chapters 11 and 12) is the lowest of the five regions in all scenarios despite ambitious EU targets. However, a significant potential is demonstrated in the Behaviour-focused scenario by the emergence of prosumerism, facilitated through small-scale electricity generation (Chapter 10). When introducing new technologies, consider energy costs to avoid worsening energy poverty (Chapters 11 and 12) and adopt measures if needed, such as support for vulnerable groups. Adoption of circular economy principles presents another area with social impact.

20.6.4.2 Environmental impacts

The technology-focused transformation's reliance on CCS technology is indispensable for managing fossil fuel use emissions (**Figure 20.17**). Implementing CCS would help curb emissions while renewable energy capacity is scaled up. However, this technology alone cannot solve issues related to biodiversity loss and land degradation.

Figure 20.19: Effects of alternative pathways and reference scenarios



YuriArcursPeopleimages/Envato

The behaviour-focused pathway's emphasis on transforming agriculture through sustainable practices is critical for addressing soil degradation and enhancing biodiversity. The adoption of precision farming, regenerative agriculture, organic farming and sustainable forestry can restore soil health and reduce chemical inputs, promoting a healthier ecosystem. However, a blanket application of these practices is not feasible across the entire region due to varying local conditions.

Moreover, enhancing the network of protected areas is a crucial component. Although the region has a relatively large number of protected areas, they often lack effective management and connectivity (Chapter 8). By improving their management and interconnectivity, the region can ensure more effective conservation outcomes.

20.6.5 Reflections

For the 21 EU member-candidate-partnership countries within the EE region, utilizing the tools provided by the EU, such as the European Union's Green Deal, is crucial for implementing systematic changes across various sectors while respecting regional specifics, if supported by substantial financial and policy resources. Continuation of dialogue with partner countries and resumption of communication is necessary with the remaining two states – Russia and Belarus – after the end of the war in Ukraine. Given the interconnected nature of modern economies, a coordinated approach to implementing these changes is essential. Uncoordinated changes could lead to unintended socioeconomic impacts, such as temporary increases in food prices due to the agricultural sector's transformation (Chapter 17, **Figure 20.16**, **Figure 20.17**). However, in the long term, these costs are expected to stabilize as the benefits of sustainable practices become evident, particularly in terms of cost savings from avoiding the current pathway (**Figure 20.19**).

20.6.5.1 Synergies and trade-offs

Achieving synergies between various sectors and policies will be key. The transformation of the agricultural sector will result in long-term benefits, such as reduced environmental degradation, improved soil health, and increased biodiversity. This will also have a positive impact on water withdrawal and help in mitigating the adverse effects of climate change (**Figure 20.19**).

The synergies between pathways help reinforce sustainable transformation as, together, they yield co-benefits for human well-being to promote long-term

sustainability and maximize the effects of sustainable solutions across all five systems.

The trade-offs between t pathways involve balancing initial investments in renewable energy supply, circular business models and digital agriculture with the long-term benefits for sustainability and resource efficiency, alongside the adoption of behavioural changes.

20.6.6 Policy implications

The successful implementation of these transformations requires strong political support and well-targeted investments (Chapter 14). The role of public awareness and education is also paramount, as integrating green principles into educational systems from the earliest levels to university can foster a culture of sustainability and environmental stewardship.

Policy measures should be tailored to respect the diverse natural, socioeconomic, and cultural conditions across the region. Local and individual solutions must be prioritized, as a one-size-fits-all approach is unlikely to succeed in a region as diverse as EE.

Economic and political tools will be the most effective instruments for driving these changes. Economic policies must consider vulnerable populations, ensuring that the benefits of these transformations are equitably distributed. Incentives for green investments should prioritize projects that provide opportunities for marginalized communities or regions. Both transformation pathways emphasize the critical role of green finance, but from complementary perspectives.

The technology-focused pathway (20.7.2.5) highlights financial incentives to accelerate the deployment of renewable energies, precision agriculture, and other green technologies. The behaviour-focused pathway (20.7.3.5) underscores financial inclusion and the creation of accessible green investment opportunities for households, communities, and small enterprises. Together, these approaches enable socially equitable and environmentally sustainable economic growth, while promoting inclusive green finance and directly addressing the GEO-7 Policy Questions (PQs) assigned to Chapter 20.

In addition, private sector participation should be actively encouraged through targeted incentives and public-private partnerships, including innovative instruments such as green bonds, debt-for-nature swaps, and blended finance mechanisms that expand investment flows into climate adaptation and resilience projects.

Green Investment and Technology Adoption – Policy Highlights

- Technology-focused pathway (20.7.2.5): stresses financial incentives for scaling renewable energy, precision agriculture, and other green technologies
- Behaviour-focused pathway (20.7.3.5): prioritizes financial inclusion and accessible green investments for households, communities, and small and medium-sized enterprises
- Shared outcome: supports socially equitable, sustainable economic growth and advances inclusive green finance, in line with Chapter 20 PQs
- Private sector engagement: should be expanded through incentives and public-private partnerships
- Innovative financing instruments: green bonds, debt-for-nature swaps, and blended finance can mobilize large-scale investment into climate adaptation and resilience projects

Enhanced Circular Economy: Technology-focused pathway's advances in recycling and circular material use rates (20.2.3) are complemented by the behaviour-focused pathway's interventions reducing consumption and waste generation (20.3.3), maximizing resource efficiency, minimizing environmental impacts, and promoting sustainable consumption habits, answering PQ2 and PQ3.1

Building Socioeconomic Resilience: Both pathways highlight sustainable agricultural practices, focusing on productivity and efficiency (20.2.2 and, respectively emphasizing local, small-scale agriculture and sustainable consumption (20.3.2). This synergy helps enhance food security, local employment, and rural livelihoods while protecting ecosystem services, thus answering PQ3.

Balancing Investments and Behaviour Change: Large-scale technology investments in renewable energy,

infrastructure, and agriculture, could result in social inequities if not balanced with behavioural inclusive approaches, and eliminating energy poverty leading to a balanced approach that answers PQ3, PQ3.1, PQ3.2

Agricultural Land Use and Biodiversity: Technology-focused pathway's increased agricultural production to meet food and energy crop demand (20.2.2) may conflict with behaviour-focused pathway's focus on ecosystem conservation (20.3.4). Policy integration is required thus answering PQ2 and PQ3.1.

Decarbonization Costs and Economic Impacts: The transition to low-carbon energy and adoption of new technologies entail high initial costs, which vulnerable communities could not afford. The behavioural changes' help distribute these costs more evenly, thus answering PQ3.2 (20.7.2.7; 20.7.3.7).

Policy Harmonization: **Table 20.6** below illustrates the types of policies that need harmonization.

20.6.6.1 Enhancing synergies and reducing unintended consequences

Regional Cooperation:

Regional cooperation is essential for realizing the full potential of these changes. For instance, EE has the potential to produce agricultural commodities and

Table 20.6: Levers and policy recommendations for Eastern Europe

	(Technology-focused)		(Behaviour-focused)	
Systems	**Type of lever**	**Levers/actions**	**Type of lever**	**Levers/actions**
Economy and Finances (ch14)	Economic and financial	Improve access to financial capital and investment	Innovation and diverse knowledge system	Focus on indigenous systems and local knowledge for resilience
	Science, tech, innovation	Research into sustainable food system and methods for transformation	Social and cultural	Provide social behaviour change communication strategies to influence social norms and behaviors
	Capabilities	Strengthen farmer knowledge and agricultural extension to improve agronomic techniques for greater productivity and sustainability	Economic and Financial	Improve access to financial capital and investment
Circularity (ch15)	Economic and financial	De-risk finance for circular business models	Economic and Financial	Change market and pricing signals for used products and secondary materials
	Science, tech, innovation	Research into new materials and novel industrial processes for circularity	Social and cultural	Promote traditional and new societal practices for reuse, sharing and repair
	Science, tech, innovation	Digital innovations for supply chains traceability and transparency	Capabilities	Increase awareness of consumers to make circular lifestyle choices

Systems	(Technology-focused) Type of lever	Levers/actions	(Behaviour-focused) Type of lever	Levers/actions
Energy (ch16)	Governance	Develop long-term mitigation pathways with accountability and transparency	Individual and collective action	Raise awareness of the benefits of lower energy lifestyles
	Science and technology	Scale up adoption of different technologies	Economic and Financial	Finance for expansion of facilities
		Increased investment in energy R&D	Individual and collective action	Enable availability of sustainable mobility choices
Food (ch17)	Science, technology and innovation	Advancing technology and genetics for increased yield, nutritional quality, resilience and climate adaptation/ mitigation	Economic and Financial	Change food industry practices to encourage sustainable consumer behaviours
	Institutional and political	Joined-up and strengthened food system governance	Individual and collective action	Change in social norms and collective actions
	Capabilities	Enhanced knowledge sharing of agricultural and food technologies and genetic materials	Skills and capabilities building	Increase public awareness and knowledge of food health and actions
Environment (ch18)	Economic and financial	Equitable access to finance	Social and cultural	Multiple partnerships for behavioural change and action
	Institutional and political	Localise national and international policies	Economic and Financial	Local economic opportunities for protection of nature
	Science, tech, innovation	Biotechnology for ecosystem improvement	Capabilities	Improved science literacy of wider society

food products exceeding regional demand, providing opportunities for export to other parts of the world. Conversely, the region's challenges in transitioning its energy system could be alleviated by collaborating with other regions to gain access to more renewable energy resources and technologies.

Conversely, the region's challenges in transitioning its energy system could be alleviated by collaborating with other regions to gain access to more renewable energy resources and technologies through sharing best practices, support policy alignment, and enhance transboundary sustainability efforts thus answering PQ3.

Public Engagement and Awareness Building:

Public engagement and awareness-raising campaigns drive social acceptance and demand for both pathways' options, fostering adoption of sustainable lifestyles.

Credit: anatoliy_gleb/Envato

The education, information and communication aided behaviour change is crucial for achieving SDG12, while application of modern technologies can achieve SDG1 and 2. ILK based innovations can achieve adaptation and mainstreaming of global environmental crisis in national policies and plans for SDGs 13, 14 and 15 thereby answering policy questions PQ2 and PQ3. Appendix 20.1 lists EE's key trends, conclusions and strategic recommendations across 2030-2040-2050.

20.6.7 Conclusion

By addressing regional priorities holistically, these pathways maximize synergies, enhance resilience, and minimize trade-offs, fostering equitable and sustainable futures.

The region continues to be shaped by two distinct influences: EU-driven policies and the different policies and legal framework followed by Russia and Belarus. As a result, changes are expected to occur at different speeds and scales, but aligning and coordinating these policies with global goals and targets will be paramount for the future. Tailored policy recommendations, sensitive to each country's specific context, are essential for achieving long-term resilience and balancing economic development with climate adaptation, social justice and environmental integrity.

20.7 Latin America and the Caribbean Region

20.7.1 Introduction

The Latin America and Caribbean (LAC) region supports approximately 60 per cent of the Earth's terrestrial species, over 30 per cent of its freshwater resources, and stores an estimated 100–120 billion metric tons of carbon. Yet, despite its rich biodiversity and natural resource endowment, the region faces unprecedented sustainability challenges from the intricate and interconnected effects of the global environmental crises. Consequently, regional priority issues such as changes in land cover dynamics, changes in freshwater quality and availability, and degradation of coastal and marine resources require urgent attention. These priorities are closely linked to multiple systems, including food production, energy generation, waste management, socioeconomic development, and the environment. The Technology-focused Transformation Scenario pathways and Behaviour-focused Transformation Scenario pathways illustrate transformation of these systems across LAC by 2050.

The technology-focused pathway is projected to expand production and improve food availability but at

the cost of increased emissions, water withdrawals, and land-use pressure. In contrast, the behaviour-focused pathway reduces agricultural and livestock footprints while maintaining calorie availability through dietary shifts and agroecological practices. Caloric availability increases while the number of undernourished people falls significantly across LAC. Both transformation scenario pathways show a major shift away from fossil fuels by 2050, with different trajectories across LAC. The technology-focused pathway projects significant reductions in coal and oil use through carbon capture and large-scale electrification, while the behaviour-focused pathway decentralizes energy systems and expands renewables.

Across LAC, environmental systems are under pressure but can deliver major co-benefits through integrated land-use policies. The behaviour-focused pathway projects greater biodiversity recovery, forest expansion, and reductions in methane and nitrous oxide emissions, higher than global averages. The technology-focused pathway shows improvements in air quality and carbon stocks but estimates increased water demand and low biodiversity gain. Coastal and freshwater ecosystems – especially vulnerable in the Caribbean and Central America – would require nature-based solutions, adaptive governance, and stronger restoration finance. In terms of material use and waste generation, the technology-focused pathway's gains in recycling by 2050 are offset by continued extraction and rising e-waste, while the behaviour-focused pathway shows throughput reduction, improved recycling, and enhances water quality. Both pathways improve recycling rates, but only the behaviour-focused pathway reduces overall material throughput and waste generation across LAC. Economic and financial systems require reoriented to support inclusive, low-carbon development across LAC. Both pathways avoid significant climate damage by 2050, but the behaviour-focused pathway does so with lower policy costs and greater equity.

20.7.2 Technology-focused Transformation Pathway

20.7.2.1 Transition to renewable energy

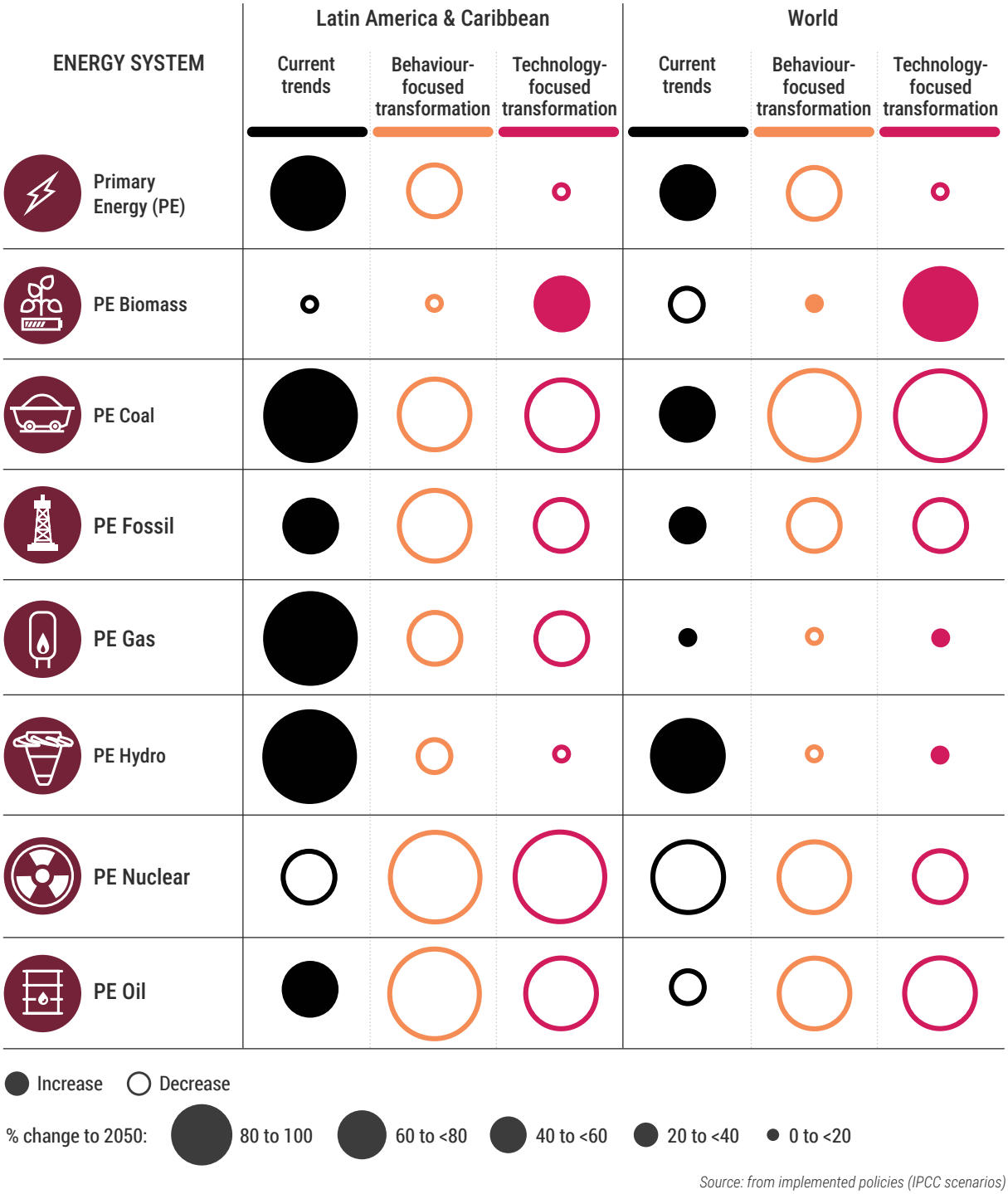
The LAC region is a significant player in the global sustainable energy landscape, particularly in biofuels, hydropower, and emerging renewable energy capacities (Lino and Sáez 2023; Kariuki 2024; Icaza-Alvarez et al. 2024), critical in achieving the project 2050 targets. In the Caribbean, carbon neutrality can be achieved by 2050 primarily through solar PV, wind, battery storage, and strategic importation of e-fuels, with integrated planning across electricity, transport, and cooking sectors to ensure cost-effective decarbonization (Oyewo et al. 2024). The technology-focused pathway projects substantial declines in fossil fuel use, rapid growth in non-biomass renewables, and sector-wide electrification. However, realizing these gains will require integrated strategies to address land-use trade-offs, infrastructure constraints, water resource pressures (Palacios et al. 2024), and socioeconomic disruptions (Allub et al. 2024). **Figure 20.20** shows technology-focused pathway projections for key energy systems indicators.

Fossil fuel dependency is projected to decline sharply by 2050, but land-use trade-offs from renewable expansion require carefully managed (Icaza 2024; Gálvez 2025). By 2050, coal use in the region is projected to decline by 87 per cent, oil by 43 per cent, and total fossil fuel demand by 60 per cent, which put the region in line with global decarbonization targets (UNEP 2021; Lino and Sáez 2023). While the accelerated path to decarbonization by 2050 involves higher initial costs, estimated at 3-12 per cent more than a gradual transition (Oyewo et al. 2024; Kalra et al. 2024), the long-term benefits of a carbon-neutral energy system are significant.

Non-biomass renewables – including solar, wind, and hydro – are projected to increase by 56 per cent, which exceeds the global estimate of 45 per cent (Camargo-Bertel et al. 2024). Coal and oil trade are projected to decrease by 92 per cent and 54 per cent, respectively; however, this transition may displace workers in fossil fuel-dependent subregions (Rodríguez-Arce et al. 2024). Reductions in fossil fuel extraction and combustion could also lower risks of marine oil pollution and terrestrial ecosystem degradation, provided they are accompanied by strong environmental safeguards and integrated spatial planning to prevent biodiversity loss and adverse social impacts (Hampl 2024; Icaza 2024; Gálvez 2025).

Electrification and distributed energy systems are projected to expand substantially across LAC, yet universal access and grid resilience remain persistent challenges (Camargo-Bertel 2024). Regional electricity demand is also expected to increase by approximately 52 per cent by 2050, relative to a global average increase

Figure 20.20: Current Trends, Technology-focused and Behaviour-focused Scenario pathway projections for key energy systems indicators



Source: from implemented policies (IPCC scenarios)

of 44 per cent (IEA 2023). This demand growth is anticipated to be driven primarily by the electrification of transport, industry, and buildings (Allub et al. 2024; Icaza 2024). Large-scale investments in renewable generation, distributed resources, smart grids, and storage systems are required to achieve these targets while ensuring reliability and equitable access (Gálvez 2025).

Final energy demand in LAC is projected to increase by approximately 15 per cent by 2050, which reflects notable gains in energy efficiency relative to economic and population growth (Camargo-Bertel et al. 2024). Industrial demand is projected to increase by 12 per cent, while residential and commercial demand could increase by approximately 20 per cent, supported by efficiency improvements and behavioural shifts

towards energy sufficiency (Camargo-Bertel et al. 2024; Gálvez 2025). In contrast, transport energy demand is projected to decrease by 11 per cent, primarily from the electrification of mobility systems and modal shifts in urban subregions (Yépez-García 2024; Icaza 2024).

Achieving a 100 per cent renewable energy mix by 2050 requires regional cooperation among LAC countries to effectively leverage collective resources and sustainability advantages (Icaza et al. 2024). One promising option is the deployment of offshore floating photovoltaic systems, which can help overcome land constraints while enabling effective use of the Caribbean's extensive marine areas for power generation (Breyer et al. 2023; Oyewo et al. 2024). This approach could also reduce fuel imports by approximately 70 per cent by 2050 relative to current levels, which reduces dependence on fossil fuels and strengthen energy security (Oyewo et al. 2024). {16.2-16.4}.

20.7.2.2 Sustainable agriculture and food system

The technology-focused pathway projects significant agricultural productivity gains in LAC by 2050, with increased food availability and limited cropland expansion through sustainable intensification. However, uneven reductions in malnutrition and modest improvements in calorie inequality highlight the need for stronger policy measures to ensure equitable food access and nutritional outcomes across the three subregions (FAO et al. 2024; Díaz-Bonilla & Piñeiro 2024). Regional agricultural demand is projected to increase by 22 per cent by 2050 – below the global increase of 37 per cent – driven by a 21 per cent increase in crop demand and a 25 per cent increase in livestock consumption. Livestock production is projected to increase by 50 per cent, which significantly exceeds the global average of 10 per cent, while effecting a 40 per cent increase in methane emissions (Caron et al. 2018; Wang et al. 2021; World Bank 2024). Malnutrition is projected to decrease by 75 per cent, however, this falls short of the global estimate of near eradication, at 98 per cent, by 2050. Calorie inequality is projected to decrease by 12 per cent – well below the 54 per cent global average – which underscores the persistent disparities in food access (**Figure 20.21**) (FAO et al. 2024; Sandoval 2024).

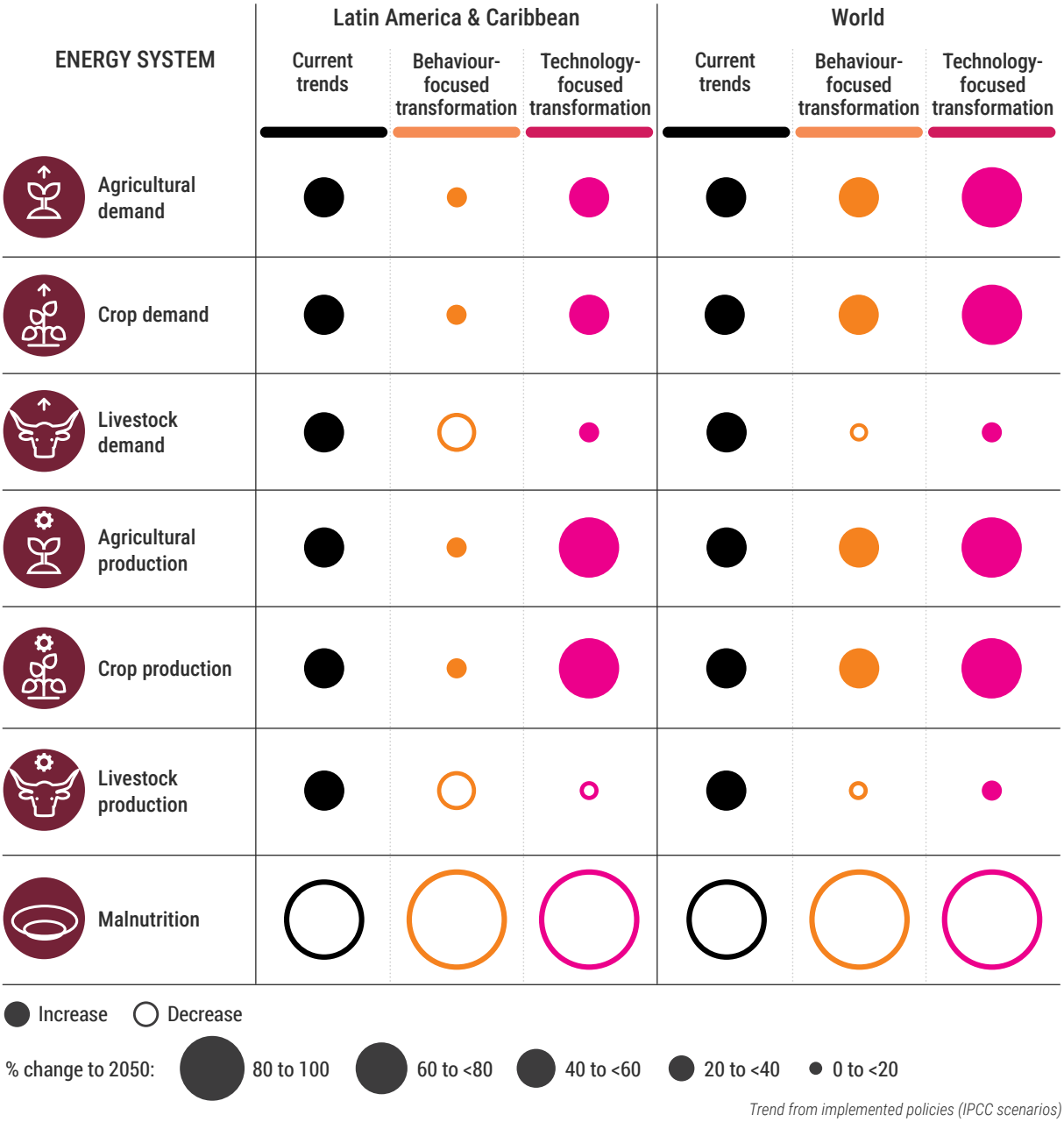
While intensification under a technology-focused pathway can increase land-use efficiency and limit cropland expansion in LAC, it could risk increasing freshwater stress and nutrient run-off, which undermines the long-term sustainability of agriculture and ecosystem health (Lentini 2022). By 2050, cropland expansion is projected to remain constrained at 12 per cent; however, agricultural water demand is expected to increase by 9 per cent, relative to a 12 per cent global decline. This pressure on freshwater resources can be compounded by higher fertilizer application, which is projected to increase by 17 per cent to sustain crop production demand. Such intensification is likely to exacerbate nitrogen and phosphorus run-off, with serious implications for both freshwater and marine ecosystems (Jaax et al. 2024). {17.2.1 to 17.2.5}.

20.7.2.3 Circular economy and pollution control and prevention

By 2050, circularity in LAC shows modest improvements in material efficiency and recycling, which are offset by persistently high material footprints, increased resource demand, and inadequate waste management under the technology-focused pathway. While total material demand in the region is projected to decline by five per cent – compared to a two per cent global increase – this reflects only limited improvements in material efficiency. The per capita material footprint is expected to reach 14–25 tons, exceeding the recommended sustainability threshold of 6–8 tons (UNEP 2021). At the same time, landfill waste is projected to increase by nine per cent and e-waste by 15 per cent, primarily from growing consumption and insufficient waste infrastructure (Gallego-Schmid et al. 2024).

The technology-focused pathway projects improvements in nutrient management and recycling in LAC but lags behind global progress, as increased industrial water use and material extraction continue to strain freshwater systems and aquatic ecosystem health. Nitrogen and phosphorus balances are projected to decline by 19 per cent and 25 per cent, respectively, yet nitrogen use efficiency is expected to fall by 15 per cent compared to a 21 per cent global improvement. Freshwater concentrations of nitrogen and phosphorus are projected to decrease by 12 per cent and 23 per cent, respectively, relative to global reductions of 25 per cent and 27 per cent. Industrial water use in the region is projected to increase by 15 per cent by 2050, compared to a global decline of approximately 10 per cent per year, shaped by growth in the energy, manufacturing, and resource extraction sectors. Extraction of industrial sand,

Figure 20.21: Current Trends, Technology-focused and Behaviour-focused Scenario pathway projections for key food systems indicators



gravel, and biomass also is projected to intensify, with wild catch rising by 36 million metric tons per year. These pressures threaten water availability and aquatic ecosystems across the regions (Jaax et al. 2024) {15.3}.

20.7.2.4 Economic and financial systems reforms

Targeted economic and financial reforms – centred on resilient infrastructure investment, fiscal realignment, and green finance – are essential for LAC to avoid climate damages equivalent to 100 per cent of GDP by 2050. These reforms are also critical to securing a more inclusive, climate-resilient future, despite disproportionately high policy costs. The region is highly exposed to climate-related economic shocks, with potential losses of 83 per cent of GDP by 2050, well above the global average (Salazar et al. 2024). Under the technology-focused pathway, LAC could avoid climate damages equivalent to its entire GDP or US$2.5 trillion by 2050, aligning with global estimates. Achieving this, however, requires scaling investments in climate-resilient infrastructure – including water, sanitation, and energy – at levels estimated between 7 and 19 per cent of GDP annually by 2030 (Yarlagadda

et al. 2023). Without such investments, climate-related GDP losses could reach US$232 trillion, or 83 per cent of regional GDP, far exceeding the global average of 129 per cent (ECLAC 2023). Although policy costs are steep – projected at 200 per cent of GDP by 2050, double the global average under the technology-focused pathway – expanding green finance and carbon pricing mechanisms can help unlock sustainable growth. {14.3-14.6}

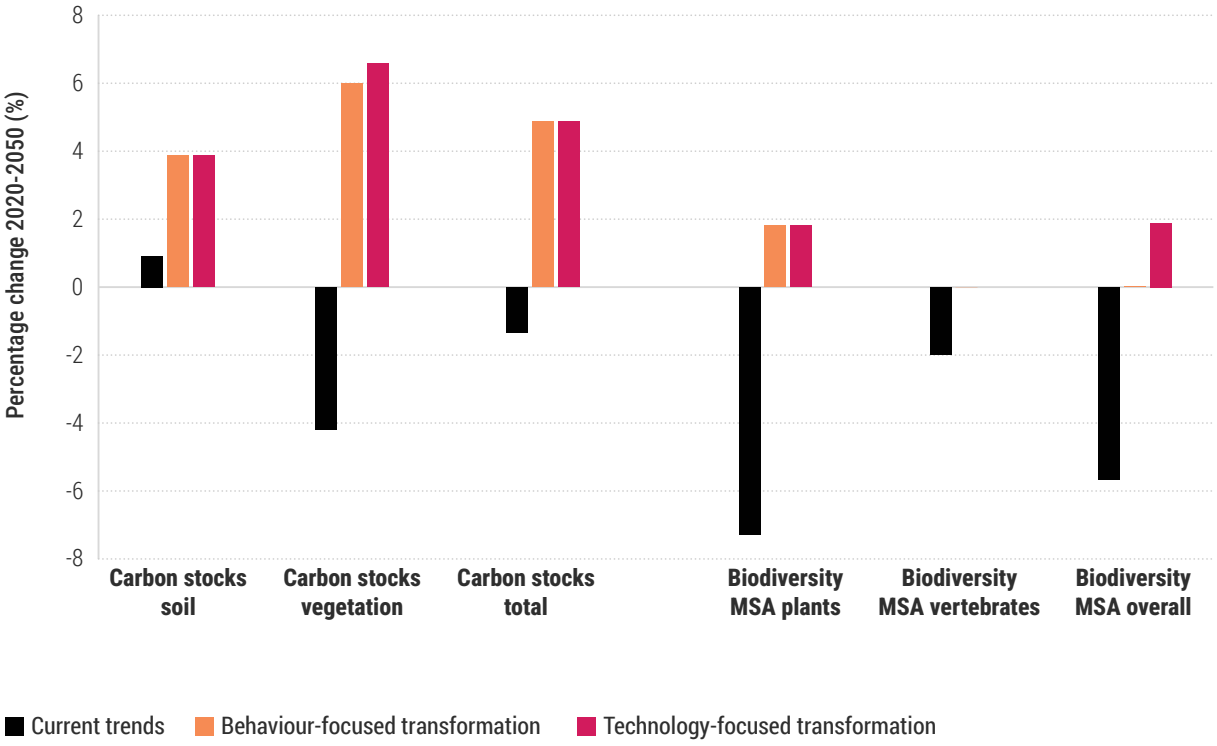
20.7.2.5 Conservation and restoration of nature

The technology-focused pathway projects that conservation and restoration of nature in LAC by 2050 is achievable, but only through coordinated, cross-sectoral action {18.2.1; 18.2.2; 18.2.4}. For example, air quality is projected to improve substantially, with nitrogen oxides emissions declining by around 50 per cent, leading to significant public health benefits, particularly in urban areas (Vélez-Henao 2025). Similarly, freshwater quality is also projected to improve by 14 per cent, due to improved land-use practices and reductions in pollutants. However, these gains contrast with the continued vulnerability of ocean ecosystems, where acidification and warming are projected to persist, posing severe risks to marine biodiversity and coastal livelihoods, especially in the Caribbean. **Figure 20.22** illustrates the projected changes in biodiversity and carbon stocks across LAC by 2050 under the technology-focused pathway.

The technology-focused pathway projects measurable gains in forest stability, carbon sequestration, and modest biodiversity recovery in LAC, outperforming global trends. By 2050, forest cover in the region is projected to remain stable at + one per cent, with targeted reforestation leading to significant carbon sequestration. Total carbon stocks are projected to increase by approximately five gigatons of carbon (GtC), including about seven GtC stored in vegetation and four GtC in soils, both above global averages (Cerri et al. 2024). Biodiversity outcomes are more modest: mean species abundance is projected to increase by around one per cent, with plants improving by roughly two per cent, while vertebrate biodiversity remains unchanged. Even so, these trends contrast with global averages, which show declines across all biodiversity indicators.

The technology-focused pathway also projects a 63 per cent reduction in CO_2 emissions, due largely to the adoption of carbon capture technologies. The scenario also estimates a 29 per cent increase in forest and natural land cover, supporting biodiversity conservation and ecosystem resilience, alongside a

Figure 20.22: Projected changes to carbon stocks and biodiversity from 2020 to 2050



16 per cent rise in water withdrawals linked to growing industrial and agricultural demands (Rodríguez et al. 2022). Carbon capture and storage (CCS) capacity is projected to expand to 271 million metric tons of carbon dioxide per year, which contributes to net-zero targets. However, achieving this outcome requires robust groundwater monitoring, strict siting controls, and strong environmental oversight to prevent unintended harms (Palacios et al. 2024).

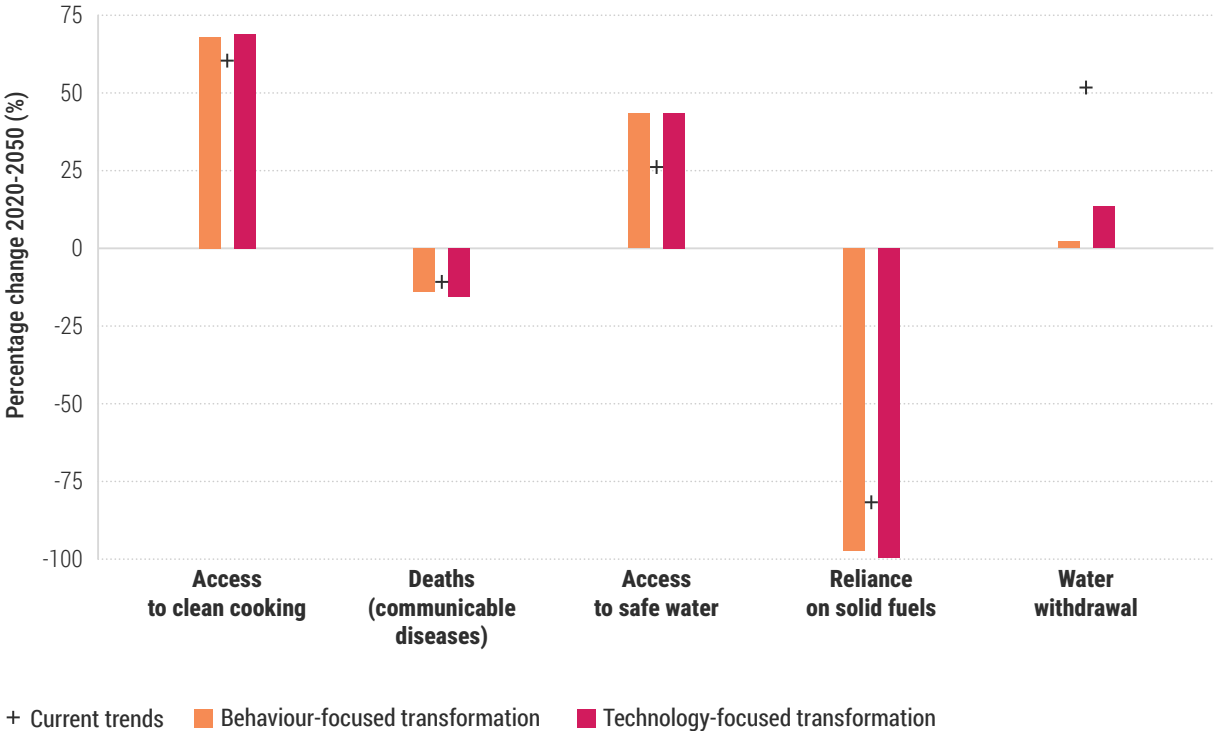
20.7.2.6 Implications of the Technology-focused Pathway

20.7.2.6.1 Socioeconomic system

Despite technological advances that increase productivity, reduce emissions, expand energy access, improve air quality, and increase carbon storage in LAC, the socioeconomic system remains at risk. Unequal electrification, ecosystem degradation, and unsustainable fiscal burdens continue to threaten the well-being and livelihoods of millions who depend on natural resources and public services for survival. These vulnerabilities are compounded by persistent inequalities, high informality, and fiscal constraints. Under the technology-focused pathway, malnutrition is projected to decrease by 75 per cent and agricultural demand to increase by 22 per cent by 2050. However, reductions in calorie inequality are limited to 12 per cent – relative to the global average of 54 per cent – which underscores the persistent marginalization of rural and low-income populations. **Figure 20.23** presents the projected changes in key socioeconomic indicators for LAC and the world by 2050.

In the energy sector, electrification and decentralized systems risk deepening energy poverty unless accompanied by inclusive finance and institutional reform. Electricity demand in LAC is projected to increase by 52 per cent by 2050 – exceeding the global increase of 44 per cent – yet 17 million people, mainly in rural Central America and the Caribbean, still lack reliable access. Under the technology-focused pathway, nitrogen oxides emissions are projected to decrease by about 50 per cent, forest cover to stabilize at about one per cent, and carbon stocks to increase by approximately five GtC. Despite these gains, ecosystem services remain highly vulnerable: biodiversity shows only modest improvements, vertebrate biodiversity stagnates, and ocean acidification persists. These pressures threaten the well-being of 140 million people who rely on ecosystem services for water, food,

Figure 20.23: Projected changes in key socio-economic indicators for LAC and the World from 2020 to 2050



and livelihoods, particularly in coastal and forested regions (Hernández-Blanco et al. 2020). Although the technology-focused pathway avoids climate damages, policy costs are projected to reach 200 per cent of GDP – twice the global average – amid rising debt and constrained fiscal space (Eguino et al. 2024).

20.7.2.6.2 Environmental systems

The accelerated transition under the technology-focused pathway provides limited environmental benefits while intensifying ecosystem stress across LAC, as increasing livestock production, nutrient run-off, and freshwater withdrawals undermine biodiversity, water quality, and land resilience. Livestock production is projected to increase by 50 per cent, resulting in a 40 per cent increase in methane emissions and putting substantial pressure on water and land systems (Seijger et al. 2024). In South America's forested areas, grazing expansion threatens biodiversity-rich transitional ecosystems, increasing risks of habitat loss and fragmentation. These impacts are compounded by nutrient run-off – particularly nitrogen – resulting from a 15 per cent decline in efficiency, which further degrades freshwater systems. Although forests are projected to remain stable, this could conceal stagnating biodiversity and increasing vulnerability to climate extremes. Targeted measures such as water efficiency technologies and pollution reduction in subregions with intensive agriculture and high water demand, are required to ensure that the projected 16 per cent increase in freshwater withdrawals (~13 km³/year) does not undermine sustainability goals (**Figure 20.24**).

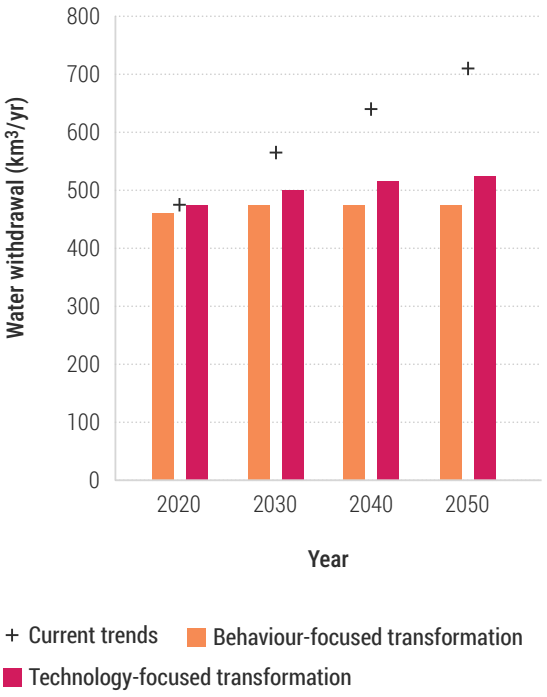
Environmental outcomes under the technology-focused pathway in LAC reflect modest gains in forest cover and overall biodiversity, however, persistent pressures from waste, nutrient run-off, and stagnating vertebrate recovery underscore the importance of strong land-use, pollution, and ecosystem protection policies to protect freshwater and coastal systems. Overall biodiversity is projected to increase by four per cent, yet vertebrate biodiversity remains stagnant. The expansion of non-biomass renewables by 56 per cent significantly reduces fossil fuel emissions and oil-related marine pollution. However, growing waste and poor nutrient cycling continue to threaten aquatic ecosystems: landfill waste is projected to increase by nine per cent and e-waste by 15 per cent, which intensify risks for coastal and inland waters. Phosphorus and nitrogen concentrations are projected to decrease by 23 per cent and 12 per cent, respectively, however, these reductions remain below global averages (27 per cent and 25 per cent) and are insufficient to prevent eutrophication in estuaries and lagoons (Cindrella & Renjith 2025).

20.7.3 Behaviour-focused Transformation Pathway

20.7.3.1 Transition to renewable energy

The behaviour-focused pathway is characterized by sharp declines in fossil fuel use, increased electrification, expanding community-based systems, and greater reliance on renewables and bioenergy. By 2050, fossil fuel demand in LAC is projected to decrease by 73 per cent – including a 72 per cent drop in coal and a 59 per cent decline in gas – higher than the global reduction of 63 per cent and indicate a structural shift towards energy independence and climate mitigation. Electricity demand is projected to increase by 49 per cent, primarily from electrification across buildings, mobility, and industry. Yet total final energy demand is projected to decrease by 40 per cent – well above the global average decline of 32 per cent – which could be linked to behaviour change, such as increased use

Figure 20.24: Water withdrawal scenarios for LAC and the World



of energy-saving technologies (Vélez-Henao 2025). **Figure 20.25** illustrates the projected energy mix in LAC by 2050 under this pathway.

LAC can achieve inclusive energy access and deep decarbonization by 2050 through a behavioural transition that scales decentralized renewables, doubles wind and solar deployment, and drives a 92 per cent surge in bioenergy – positioning the region as a global leader in sustainable energy transformation. The behaviour-focused pathway promotes decentralized systems, including solar home systems, microhydro, and mini-grids, enabling energy access for over 20 million people currently underserved in rural LAC. Beyond expanding access, these investments also stimulate economic opportunities, with every US$1 million invested in clean energy and energy-efficient buildings across LAC generates an average of 5.5 full-time jobs (Esteves et al. 2024). Biomass energy demand is projected to increase by 92 per cent, surpassing global projections of +65 per cent and positioning LAC as a key bioenergy producer (IRP 2019; Holechek et al. 2022; IEA 2023). The behaviour-focused pathway projects a 100 per cent increase in non-biomass renewable energy, such as wind and solar, which underscores the region's potential to diversify its energy mix and reduce its carbon footprint, with wind turbines and solar photovoltaic estimated to constitute significant shares of the energy mix by 2050 (França et al. 2023; Camargo-Bertel et al. 2024) {16.2.-16.4}.

20.7.3.2 Sustainable agriculture and food system

Transformative shifts in consumption, production, and rural equity can enable LAC to increase food production by 10 per cent while stabilizing demand and reducing livestock-related pressures by 2050. Under the behaviour-focused pathway, food demand stabilizes, and dietary shifts reduce environmental stressors while maintaining production growth. By 2050, agricultural demand in LAC is projected to increase by 0.35 per cent – compared to global estimates of 33 per cent – due to a 25 per cent decline in livestock demand and strong shifts towards healthier diets (Robinson 2024). Despite this, agricultural production grows by 10 per cent, with crop output increasing by 12 per cent while livestock production declines by 27 per cent (**Figure 20.26**).

The behaviour-focused pathway projects a 98 per cent reduction in malnutrition across LAC by 2050, higher than global averages and would effectively eliminate hunger risk in the region. Calorie inequality is expected

Figure 20.25: Share of total energy use by source in LAC from 2020 to 2050

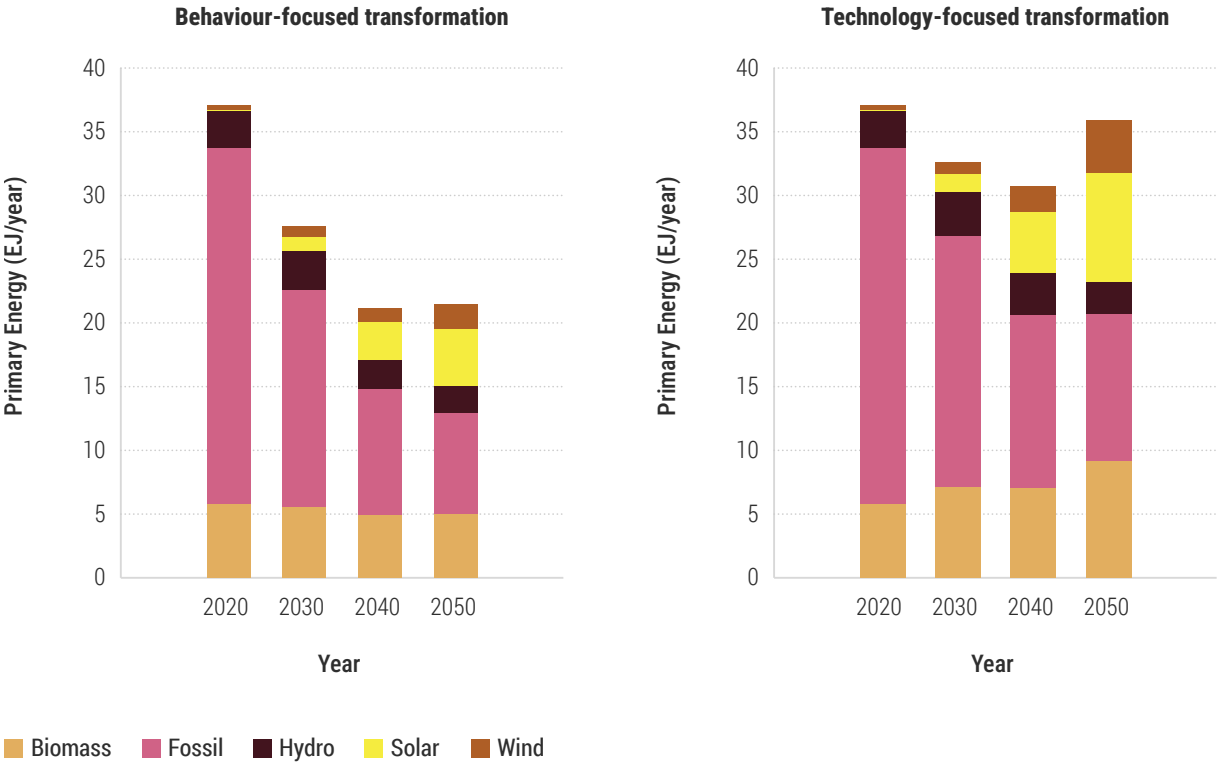


Figure 20.26: Projected trends in agricultural demand and production in LAC from 2020–2050

to improve by 58 per cent, supported by expanded local food production, stronger social safety nets, and reduced food waste. While cropland area is projected to grow by 12 per cent, the pathway also enables the restoration and conversion of 190–296 million hectares to regenerative farming. Agricultural water demand is projected to decrease by 12 per cent and nutrient run-off by 20 per cent by 2050 – a significant improvement given that agriculture currently consumes more than 70 per cent of freshwater and is a major source of pollution in key river basins {17.2.1-17.2.5}.

20.7.3.3 Circular economy and pollution control prevention

By 2050, the behaviour-focused pathway positions LAC to achieve significant circular economy gains, reducing material demand by 10 per cent and waste generation by 19 per cent, comparable to the projected global waste reduction of 20 per cent. However, increased extraction of metals and marine resources threatens to offset these improvements, which underscores the need to align pollution control and resource governance with sustainable consumption and trade. Regional extraction of aluminium is projected to increase by 57 per cent, copper by 86 per cent, and wild catch by more than 92 million tons per year mainly due to export-oriented demand and increased infrastructure requirements.

Despite advances in recycling and water discharge quality, persistent gaps in infrastructure, nutrient management, and the formal recognition of informal waste systems continue to limit the full potential of circular economy and pollution prevention in LAC. Under the behaviour-focused pathway, recycling and reuse increase, however, inadequate collection, processing, and infrastructure remain major barriers (Gallego-Schmid et al. 2024). By 2050, recycling rates in LAC are projected to reach 30 per cent for iron ore and 15 per cent for construction materials; however, many countries in the region will continue to fall below global averages in both capacity and efficiency. Informal recycling systems, particularly in urban areas, continue to play a central role, with waste pickers making substantial contributions yet lacking formal recognition and support (Vélez-Henao 2025). E-waste is projected to increase by 15 per cent without adequate recovery infrastructure. The pathway also reduces industrial water use by 12 per cent and improves water discharge quality by nine km^3/year. Phosphorus concentrations are projected to decrease by three per cent and nitrogen by seven mg N/L, however, these gains remain below global reductions of 25 per cent and 18 mg N/L, respectively.

Moreover, nitrogen use efficiency in croplands are projected to decrease by 17 per cent, relative to a global improvement of nine per cent. {15.3}.

20.7.3.4 Economic and financial systems reforms

By 2050, economic and financial reforms in LAC under the behaviour-focused pathway indicates a rapid transition towards inclusive, low-carbon development. Despite an estimated 2 per cent GDP loss from climate risks, the region is projected to achieve a 60 per cent increase in overall GDP alongside expanded trade, which demonstrates that sustainable finance and institutional strengthening can enable equitable growth while addressing demographic and environmental pressures. Exports and imports are projected to increase by 50 per cent and 45 per cent, respectively, while per capita GDP is projected to increase by 28 per cent. Population growth could reach 14 per cent, with urbanization levels increasing to 87 per cent. Market interventions, combined with strengthened institutional capacity in public agencies, are critical to managing these transitions (Eguino et al. 2024). The behaviour-focused pathway also advances sustainable finance, community-led investment, and inclusive financial practices to accelerate the shift to a low-carbon economy and improve social equity {14.3-14.6}.

20.7.3.5 Transformative conservation and restoration of nature

The behaviour-focused pathway positions LAC as a global leader in conservation and restoration, by achieving net-negative emissions through a 50 per cent reduction in CO_2, a 16 per cent expansion in forest and natural land, and a five GtC increase in carbon stocks – driven by reforestation, regenerative agriculture, and Indigenous-led ecological stewardship {18.2.1; 18.2.2; 18.2.4}. These outcomes exceed global averages and are supported by large-scale reforestation, regenerative agriculture, and afforestation across 190–296 million hectares. Forest and natural land cover is projected to expand by 16 per cent, reversing decades of degradation and fragmentation. This restoration, combined with reduced livestock-driven land conversion, is projected to increase mean species abundance by 1.5 per cent, with stronger gains among plants (+1.8 per cent) than vertebrates (+0.4 per cent) (**Figure 20.27**). Central to this pathway is the empowerment of local communities and Indigenous Peoples, whose knowledge and stewardship underpin sustainable and resilient environmental practices (Gallego-Schmid et al. 2025).

20.7.3.6 Implications of the Behaviour-focused Pathway

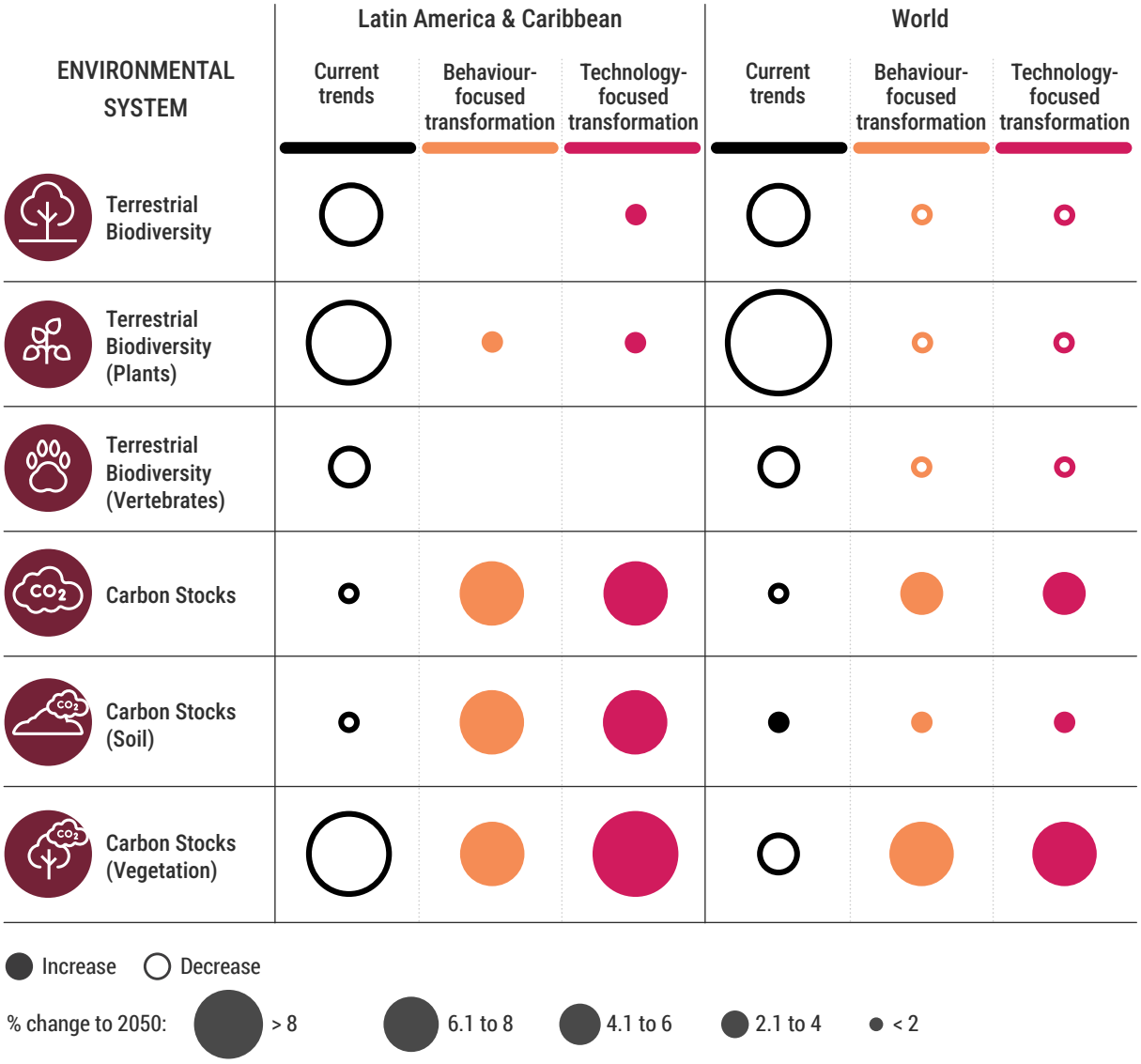
20.7.3.6.1 Socioeconomic system

Under the behaviour-focused pathway expansion of forest and natural land cover, improved water security, and renewable energy transitions can protect ecosystem service values while creating new livelihood opportunities and transformative routes to reduce poverty, inequality, and vulnerability across LAC (Batista et al. 2024; Cabieses and Huerta 2024). By 2050, the behaviour-focused pathway projects a 16 per cent increase in forest and natural land cover which could improve biodiversity, reduce wildfire risks, and significantly strengthen the region's climate change adaptation and mitigation capacity. The behaviour-focused pathway model suggests that increased opportunities in renewable energy sectors can have a transformative impact on social structures, contributing to reducing inequality and poverty (Tundys and Bretyn 2023).

Under the behaviour-focused pathway, livestock demand in LAC declines by 25 per cent, while plant-based consumption increases, resulting in a modest 10 per cent increase in total agricultural production. However, smallholder farmers – who produce over 60 per cent of food in LAC – require targeted investments in capacity-building, market access, and agroecological extension services to benefit from this transition (Kraak et al. 2024). Similarly, decentralized renewables expand access and create jobs, however, equity mechanisms are required to ensure inclusion. The behaviour-focused pathway projects a 49 per cent increase in electricity demand and a 155 per cent rise in non-biomass renewables, particularly solar and wind, with decentralized systems expanding across rural and underserved areas.

Forest and natural land cover expand by 16 per cent under the behaviour-focused pathway, which supports carbon sequestration and ecosystem services. These environmental gains support livelihoods in forestry, tourism, and watershed protection. However, for these co-benefits to translate into tangible socioeconomic gains, nature-based solutions must be embedded within local development strategies. The behaviour-

Figure 20.27: Implications of the Current Trends, Behaviour-focused and Technology-focused Scenario pathways for key environmental system indicators



focused pathway projects a 10 per cent decline in material demand and a 19 per cent reduction in waste, accompanied by improved recycling systems and a 30 per cent iron ore recycling rate. Incorporating nature-based solutions and circular economy strategies into local development planning offers LAC the opportunity to achieve more equitable, resilient, and low-carbon growth – but realizing these gains will depend on retraining labour forces and integrating environmental progress with inclusive economic reforms (Kraak et al. 2024).

20.7.3.6.2 Environmental systems

The behaviour-focused pathway shows wide-ranging environmental gains in LAC by 2050 – cutting CO_2 emissions by 50 per cent, reducing agricultural and energy pressures, and restoring ecosystem functions through reforestation, agroecology, and a shift to decentralized, low-impact renewables. Agroecological food systems reduces environmental degradation and restore ecosystem functions. Under the behaviour-focused pathway, agricultural production in LAC increases modestly by 10 per cent while food demand remains stable at 27 per cent. This could enable a 12 per cent reduction in agricultural water use and a 20 per cent decline in nutrient run-off, improving soil and freshwater quality. Decentralized renewables and lower energy demand reduces pollution and protect natural ecosystems. Under the behaviour-focused pathway, final energy demand decreases by 40 per cent, which limits the need for new energy infrastructure

Credit: Edovideo/Envato

and minimize environmental disturbance. Fossil fuel use decreases by 73 per cent, while biomass increases by 92 per cent, thereby displacing more sources of pollutants.

The adoption of circular economy principles under the behaviour-focused pathway directly addresses pollution at its source, particularly in industrial areas, by reducing material demand by 10–15 per cent and scaling up recycling efforts. By 2050, forest and natural land cover in LAC is projected to expand by 16 per cent, which supports an additional five GtC in carbon stocks and higher than global averages. CO_2 emissions decline by 50 per cent and methane by 65 per cent, resulting in improved air quality and easing ecosystem stress. Biodiversity also benefits: mean species abundance increases by 1.5 per cent, while reforestation and ecosystem restoration strengthen biodiversity corridors. Circular material flows reduce land and marine pollution, though nutrient inefficiencies remain a challenge across the region. Material throughput is projected to fall by nine per cent and waste generation by 19 per cent, supported by advances in recycling – including iron ore recycling reaching 30 per cent – and expanded composting initiatives especially in rural and underserved urban areas (Vélez-Henao 2025).

20.7.4 Implications for Regional Priorities

20.7.4.1 Land cover dynamics

By 2050, contrasting pathways in LAC (**Table 20.7**) highlight that behavioural shifts can enable forest regeneration and large-scale carbon sequestration, while technology-focused approaches may only stabilize land cover without reversing ecosystem degradation. Under the behaviour-focused pathway, forest and natural land cover are projected to expand by 16 per cent, which is supported by dietary change. A 25 per cent decline in livestock demand, and agroecological practices are projected to restore up to 296 million hectares to regenerative agriculture and sequester between 12–20 GtC equivalent annually.

Cropland expansion is limited to 12 per cent, with crop production increases estimated at 12 per cent, largely through diversified, low-input mixed farming systems rooted in traditional knowledge (Gallego-Schmid et al. 2025). In contrast, the technology-focused pathway depends on land-sparing intensification: although cropland also expands by 12 per cent, total agricultural production increases by 53 per cent, due to technological innovation. However, livestock production increases by 50 per cent under this pathway, resulting in increased

Table 20.7: Land cover dynamics related results, response options and regional considerations

Result (% change to 2050)	Land Cover Dynamics	Response Option	Levers*	Subregional Considerations/Actions
Agricultural demand grows by 22%. (Technology-focused pathway)	Increased land pressure risks cropland expansion into natural areas.	Promote sustainable intensification and land-sparing technologies.	G, K&I, E&F	• Caribbean: Urban agriculture and coastal zone protection (Galaitsi et al. 2024) • Central America: Precision farming to minimize deforestation (Ivale et al. 2024) • South America: Strict zoning to avoid Amazon conversion (Messias et al. 2024)
Energy crop demand expands 25%. (Technology-focused pathway)	Moderate expansion reduces land competition compared to global trends.	Prioritize multi-use bioenergy landscapes and agroforestry.	K&I, G, E&F	• Caribbean: Use marginal lands for bioenergy (Mohan 2025) • Central America: Agro-forestry for dual benefits (Villanueva-González 2024) • South America: Integrate biofuel into existing pasture and avoid high-biodiversity areas (Escobar et al. 2024)
Agricultural production grows 22%. (Technology-focused pathway)	Increased output may intensify pressure on ecosystems if not decoupled from land use.	Decouple productivity from land expansion via regenerative and high-efficiency practices.	K&I, C, G	• Caribbean: Emphasize local food systems (Hernández-Moreno et al. 2024) • Central America: Promote soil restoration (Blanton et al. 2024) • South America: Incentivize no-deforestation supply chains and land-use monitoring (Lambin 2022)
Forest area remains stable (+1%). (Behaviour-focused pathway)	Land cover maintained through conservation and reforestation efforts.	Strengthen forest governance, expand protected areas, and support community-led reforestation.	G, S&C, E&F	• Caribbean: Restore mangroves and dry forests (Rull 2023) • Central America: Reconnect Forest corridors (McCullough 2024) • South America: Expand Amazon and Atlantic Forest buffers (Vancine 2024)
Biodiversity index stabilizes (+4%). (Behaviour-focused pathway)	Modest recovery suggests limits in habitat restoration and ongoing fragmentation.	Integrate biodiversity into land-use planning and expand ecological corridors.	G, K&I, S&C	• Caribbean: Protect coral-linked terrestrial habitats (Villarroel-Lamb 2024) • Central America: Scale ecological farming (Ewert 2023) • South America: Prevent fragmentation in biodiversity hotspots (Schmitz 2023)
CCS expansion (+271%); CO_2 emissions (+6%). (Technology-focused pathway)	May reduce emissions but poses land-use and water-use trade-offs for storage sites.	Apply land-use safeguards and integrate CCS with existing infrastructure to minimize land pressure.	G, K&I	• Caribbean: Prioritize offshore or low-impact CCS (Barranco et al. 2024) • Central America: Limit CCS to brownfield sites (Signoria & Barlettani 2023) • South America: Avoid CCS deployment in forested and Indigenous-managed areas (Egerer et al. 2024)

** (Governance-G, Economic and financial-E&F, Social and Cultural- S&C, Knowledge and Innovation- K&I, Capability - C)*

Credit: wirestock/Envato

pressure on pastureland and concerns about emissions and ecosystem fragmentation. Forest area remains stable at one per cent, which reflects effective land-use regulation, but with fewer biodiversity gains compared to the behaviour-focused pathway. Both pathways demonstrate the potential to decouple food production from deforestation, however, the behaviour-focused pathway offers greater co-benefits for carbon storage, biodiversity, and ecosystem restoration (**Table 20.7**).

20.7.4.2 Freshwater quality and availability

The state of freshwater quality and availability in LAC by 2050 depends on how efficiency gains under the technology-focused pathway are balanced with systemic demand reductions under the behaviour-focused pathway (**Table 20.8**). This dynamic is reflected in the need for integrated water governance to manage increasing withdrawals in the technology-focused pathway while advancing improved water use efficiency in the behaviour-focused pathway. In the technology-focused pathway, agricultural intensification and industrial expansion drive a nine per cent increase in freshwater demand, with total withdrawals increasing by 13 km³/year – compared to a global decline of withdrawal of four km³/year. This change is further amplified by a 17 per cent increase in fertilizer use, which exacerbates nutrient run-off and increases eutrophication risks, particularly in agro-industrial regions of Central and South America. Although regional freshwater quality improves by 14 per cent, nitrogen use efficiency declines by 15 per cent, compared to a 21 per cent global improvement.

The two pathways demonstrate that although both improve freshwater outcomes in LAC, only the behaviour-focused pathway achieves meaningful reductions in withdrawals and run-off. Under the behaviour-focused pathway, freshwater withdrawals decrease by 2 per cent, enabled by behavioural shifts, dietary change, and adoption of agroecological practices. Nutrient run-off decreases by 20 per cent, while agricultural water demand decline by 12 per cent, which is higher than global averages. Nonetheless, challenges remain: Wild catch extraction increases under both pathways, increasing by 36 million tons per year in the technology-focused pathway and 92 million tons per year in the behaviour-focused pathway, resulting in additional pressure on coastal and freshwater ecosystems. Outcomes also diverge across subregions, with Central America facing greater water stress, the Caribbean constrained by limited freshwater availability, and South America managing trade-offs between hydropower expansion and watershed protection.

20.7.4.3 Coastal and marine resources

Under the technology-focused pathway, coastal and marine ecosystems in LAC are exposed to increasing nutrient and water stress as accelerated agriculture and bioenergy expansion increase run-off and freshwater withdrawals by 2050 (**Table 20.9**). These pressures pose significant risks to nearshore ecosystems, which could offset gains from reduced fossil fuel emissions and trade. While accelerated agriculture, bioenergy production, and fossil fuel decarbonization collectively lower overall emissions, they also introduce new risks to coastal systems. Fertilizer use is projected to increase by 17 per cent, which could exacerbate nutrient run-off and eutrophication in sensitive marine zones. Bioenergy development could further increase

Table 20.8: Freshwater Quality and Availability related results, response options and regional considerations

Result (% change to 2050)	Freshwater Quality & Availability	Response Option	Levers*	Subregional Considerations/Action
Water quality improves (+14%), but nutrient run-off remains high. ***(Technology-focused pathway)***	Moderate water quality gains, but high nutrient loads continue to stress freshwater ecosystems, particularly in agriculturally intensive areas.	Expand riparian buffers and implement precision nutrient management strategies.	G, K&I, C	• Caribbean: coastal nutrient run-off control (Bolaños-Alvarez et al. 2024); • Central America: upstream pollution reduction (Gu et al. 2023); • South America: target intensive farming regions (Grondona et al. 2023).
Water use in industrial processes increases (+15%) ***(Technology-focused pathway)***	Increased pressure on water resources from industrial processes may reduce water availability, especially in already water-stressed regions.	Adopt water reuse systems and industrial water efficiency standards.	G, E&F, K&I	• Caribbean: industries integrate circular water use (Van Hoof et al. 2023); • Central America: prioritize efficiency in agro-processing (Saravia-Matus et al. 2018); • South America: improve management of extractive sectors (Sarmiento et al. 2025).
Water demand in agriculture declines (12%). ***(Behaviour-focused pathway)***	Improved water efficiency in agriculture reduces pressure on freshwater sources, contributing to long-term water availability.	Support water-saving irrigation technologies and sustainable land management.	E&F, K&I, C	• Caribbean: scale drip irrigation and rainwater harvesting (Van Hoof et al. 2024); • Central America: scale rainwater harvesting (Stewart et al. 2021); • South America: invest in large-scale irrigation retrofits (Houspanossian et al. 2023).
Nutrient run-off declines (20%) ***(Behaviour-focused pathway).***	Reduced run-off enhances water quality, particularly in river basins vulnerable to agricultural pollution.	Promote agroecological practices and vegetative buffer zones.	S&C, G, K&I	• Caribbean: enhance agroecological zones (Alexandre et al. 2021); • Central America: integrate landscape restoration (Kumar et al. 2022); • South America: target degraded agricultural lands (Zalles et al. 2021).
Nitrogen (-25%) and phosphorus (-19%) ***(Behaviour-focused pathway)***	Lower nutrient concentrations help restore freshwater bodies and reduce eutrophication, supporting aquatic ecosystem health.	Strengthen nutrient management regulations and monitoring systems.	G, K&I, E&F	• Caribbean: nutrient monitoring systems (Clark et al. 2022); • Central America: enforce conservation buffer zones (Sze et al. 2022); • South America: support farmer-led forest monitoring initiatives (Londres et al. 2023).

Result (% change to 2050)	Freshwater Quality & Availability	Response Option	Levers*	Subregional Considerations/Action
Agricultural production grows 22% (versus 36% World), far below Current Trends (53%). (Technology-focused pathway)	Increased agricultural activity may heighten water use and run-off without parallel improvements in water management practices.	Incentivize climate-smart agriculture and improved watershed governance.	E&F, G, K&I	• Caribbean: integrated water r esource management (Roopnarine et al. 2021); • Central America: regulate fertilizer run-off (Bundschuh et al. 2021); • South America: enforce basin-level governance mechanisms (Espíndola & da Silva 2024).

** (Governance-G, Economic and financial-E&F, Social and Cultural- S&C, Knowledge and Innovation- K&I, Capability - C)*

freshwater withdrawals by 13 km³/year, which could exert additional pressure on coastal aquifers. Although coal use decreases by 87 per cent and oil use by 43 per cent, oil trade would remain a persistent source of marine contamination risk in 2050.

LAC's coastal and marine ecosystems are exposed to divergent pressures under both pathways; however, long-term water quality gains and ecosystem resilience are dependent on aligning marine resource governance with nature-based solutions, reduced nutrient run-off, and sustainable wild catch management. The behaviour-focused pathway emphasizes nature-based solutions, traditional knowledge, and dietary shifts, which could significantly reduce stress on marine ecosystems. The pathway projects a two per cent decline in freshwater withdrawals and a 20 per cent reduction in nutrient run-off, which would improve water quality and lower risks of coastal hypoxia. However, the projected 92 million ton increase in wild catch under this pathway increases concerns of potential overexploitation of marine stocks if not supported by strong fisheries governance.

20.7.5 Strengthening regional linkages

Regional cooperation in LAC can maximize the benefits of both technological and behavioural transformations. Coordinated policies, shared resource management, and harmonized environmental governance can strengthen collective capacity to achieve sustainable development and climate resilience (Mahadeo & Del Savio 2023; Santos & Colgan 2023). Decisions in one domain – such as energy, food systems, or materials and waste management – often produce cascading effects across borders through trade dependencies, ecosystem linkages, and transboundary resource use (IPBES 2024). Strong cooperation mechanisms, including transboundary water management agreements, are critical to reducing conflict risks and protecting shared resources. The Amazon Cooperation Treaty Organization provides a practical example of how regional institutions can mediate competing interests and foster equitable, sustainable management of shared ecosystems (Martynov et al. 2020).

Effective transboundary policy coordination is critical for protecting biodiversity and managing natural resources in LAC. Regional mechanisms such as the Central American Integration System and the Caribbean Community provide platforms to align national strategies, reduce policy fragmentation, and accelerate transitions under the technology-focused and behaviour-focused pathways (Echebarria Fernández 2021; De Marco et al. 2023; Fernandes et al. 2024). Successful models already exist: the Caribbean Large Marine Ecosystem and Adjacent Regions initiative demonstrates how coordinated marine protection policies can strengthen conservation outcomes and promote sustainable use of shared marine resources (Ganase et al. 2023). Scaling such cooperative frameworks will be essential for addressing cross-border ecological challenges and advancing regional resilience.

Regional collaboration in energy systems offers a unique opportunity to harness the renewable energy growth projected under both the technology-focused and behaviour-focused pathways. Shared infrastructure – such as interconnected smart grids and regional energy markets – can enhance system efficiency, balance supply across countries, and strengthen energy security while reducing greenhouse

Table 20.9: Coastal and Marine Resources-related results, response options and regional considerations

Result (% change to 2050)	Coastal and Marine Resources-related results, response options and regional considerations	Response Option	Levers*	Subregional Considerations/Actions
Water quality improves (+14%), but nutrient run-off remains high. ***(Technology-focused pathway)***	Moderate improvements in marine water quality; continued run-off threatens coral reefs and estuaries.	Improve nutrient management in upstream agriculture and expand buffer zones.	G, K&I, E&F	• Caribbean: Strengthen coastal buffers to protect coral systems (Soanes et al. 2021); • Central America: Enforce riparian buffers in agro-industrial zones (Saravia-Matus et al. 2018); • South America: Target nutrient hotspots in river basins (Sheikholeslami et al. 2024).
Landfill waste rises (+9%) due to increased industrial activity. ***(Technology-focused pathway)***	Increased leachate and plastic pollution impacting coastal ecosystems.	Scale landfill regulation and invest in waste diversion infrastructure.	G, E&F, C	• Caribbean: Prioritize coastal landfill closures (Nicholls et al. 2021); • Central America: Improve rural landfill management (García et al. 2022); • South America: Expand urban waste sorting and capture (Ferronato et al. 2021).
Industrial recycling rates improve (+13%) ***(Technology-focused pathway)***	Reduced coastal waste leakage but limited impact without marine-focused systems.	Incentivize industrial recycling linked to coastal protection schemes.	E&F, K&I	• Caribbean: Promote sustainable industrial practices in port cities (Vera et al. 2023); • Central America: Build recycling value chains in coastal regions (Soto-Rios et al. 2023); • South America: scale marine litter programmes (Belli et al. 2024).
Nutrient run-off declines (–20%), reducing freshwater contamination. ***(Behaviour-focused pathway)***	Lower nitrogen loads in river mouths improve estuarine health and mangrove systems.	Promote regenerative agriculture and nutrient recycling practices.	K&I, G, S&C	• Caribbean: Expand composting and regenerative agriculture (Gallego-Schmid et al. 2024); • Central America: Incentivize nutrient management for smallholders (Chivenge et al. 2021); • South America: Integrate nutrient reduction into watershed plans (Pacheco et al. 2021).
Nitrogen (–25%) and phosphorus (–19%) levels decrease, protecting water bodies. ***(Behaviour-focused pathway)***	Eutrophication risk falls in key deltas and bays, supporting fisheries recovery.	Regulate fertilizer inputs and promote agroecological nutrient use.	G, K&I, E&F	• Caribbean: Monitor nutrient flows into freshwater and marine ecosystems (Londres et al. 2023); • Central America: promote agroecological practice (Alexandre et al. 2021); • South America: Scale transboundary nutrient management system (Pacheco et al. 2021).

Result (% change to 2050)	Coastal and Marine Resources-related results, response options and regional considerations	Response Option	Levers*	Subregional Considerations/Actions
Waste generation decreases (–19%) (Behaviour-focused pathway)	Less solid waste entering waterways and coasts; improved marine habitat quality.	Implement upstream consumption reduction and recycling incentives.	S&C, G, K&I	• Caribbean: Support zero-waste coastal tourism initiatives (Wang et al. 2021); • Central America: Establish circular industries in rural areas (Bundschuh et al. 2021) • South America: Strengthen municipal waste collection in coastal cities (Ferronato et al. 2021).

** (Governance-G, Economic and financial-E&F, Social and Cultural- S&C, Knowledge and Innovation- K&I, Capability - C)*

gas emissions (Levy et al. 2023). Such cooperation is essential to achieving regional decarbonization targets and advancing broader sustainable development objectives. Beyond energy, coordinated strategies, harmonized standards and cross-border regulatory frameworks for managing pollution and waste are increasingly urgent, particularly as material circularity expands and iron ore recycling rates increase. Investments in renewable energy – including binational hydropower projects such as the Itaipu Binational Dam, the Yacyretá Dam, and the Binational Border Hydropower – demonstrate the potential for multiple co-benefits across the food, energy, water, climate, and biodiversity nexus (Berkhout and Warner 2023; IPBES 2024). Achieving these outcomes depends on regional cooperation that safeguards human rights (Reyes-García et al. 2022; Aguilera 2023) and empowers Indigenous Peoples. Additionally, green investment strategies supported by international cooperation (Battistello Espíndola and Batista da Silva 2023) can lead to significant advances in sustainable technology and infrastructure development (Yalew et al. 2020).

20.7.6 Conclusion

Achieving a resilient, equitable, and climate-smart future in LAC by 2050 requires integrated reforms across economic, financial, and governance systems. Under Current Trends, the region faces irreversible environmental degradation and compounding socioeconomic risks by mid-century. Strategic investments in resilient infrastructure, fiscal realignment, and green financial instruments – including social protection systems, debt-for-nature swaps, and sustainable bonds – can enhance financial stability and buffer systemic shocks. Mechanisms such as sovereign risk pools, public-private partnerships, and carbon pricing offer scalable tracks to mobilize capital and accelerate low-carbon transitions. Transformational change in LAC also requires sectoral shifts aligned with both Behaviour-focused and Technology-focused Transformation pathways. Reversing environmental degradation in LAC by mid-century hinges on strengthening governance and integrating sustainability practices to halt deforestation, restore degraded landscapes, and reduce pollution. Circular economy strategies – such as biogas production, regenerative agriculture, and closed-loop manufacturing – offer actionable solutions to waste and pollution challenges while creating jobs and resilient supply chains. Smart electrification through decentralized renewable energy and regional cooperation supports rural energy access and reduces fossil fuel dependency, particularly in small island and underserved communities. In food systems, integrated approaches centred on agroecology, Indigenous stewardship, and sustainable supply chains can restore ecosystems and strengthen food security. Collectively, these cross-sectoral actions demonstrate how LAC can align economic transformation with environmental sustainability and social inclusion to address the multiple crises facing the region.

Credit: fokkebok/Envato

20.8 Western Europe and Other Groups

20.8.1 Introduction

The global environmental crises adversely affect countries of the Western Europe and Other Groups (WEOG) through weakened ecosystem function (World Wide Fund for Nature [WWF] 2022) and reduced human well-being (IPCC 2021; IPCC 2022; European Commission 2022). WEOG is experiencing the interlinked crises of impaired biodiversity, climate change-driven extreme events, air and water pollution and excessive waste production. Heat-related mortality was extreme in Europe in 2022 and recent fires in Los Angeles resulted in damages that likely exceed US$250 billion. While WEOG countries have the capacity to protect their populations from these existential threats, aged infrastructure and increasing intersectional inequalities contribute to increased vulnerability for some communities and groups. The challenges of the global environmental crises are the indirect results of a failure of governance at many geographic scales. To mitigate these changes, key priorities for WEOG should involve the five systems investigated in the Outlooks Part of GEO-7, that require five lines of action.

- Energy System: Decarbonization, rapidly reducing carbon emissions through renewable energy adoption and carbon dioxide removal strategies, electrifying transportation, and enhancing energy efficiency {16.2-16.4}.
- Food System: Promoting sustainable farming practices that prioritize soil and livestock health, reduce chemical inputs, protect water resources, and reduce air pollution. Shifting towards more plant-based diets and reduce food loss and waste and conserving Indigenous Peoples' and local communities' sustainable and adaptive ways of life {17.2.1-17.2.5}.
- Material System: Shifting towards circularity that minimizes waste and maximizes resource efficiency.
- Economic and Financial System: Increased role of government towards revising and incentivizing taxes and subsidies towards sustainable and inclusive practices {14.3-14.6}.
- Environmental System: Protecting and restoring ecosystem health.

20.8.2 Technology-focused Transformation Pathway

Technology-focused pathways for transformative, integrative and cross-sector solutions suitable for WEOG can address the global environmental crises moving forward.

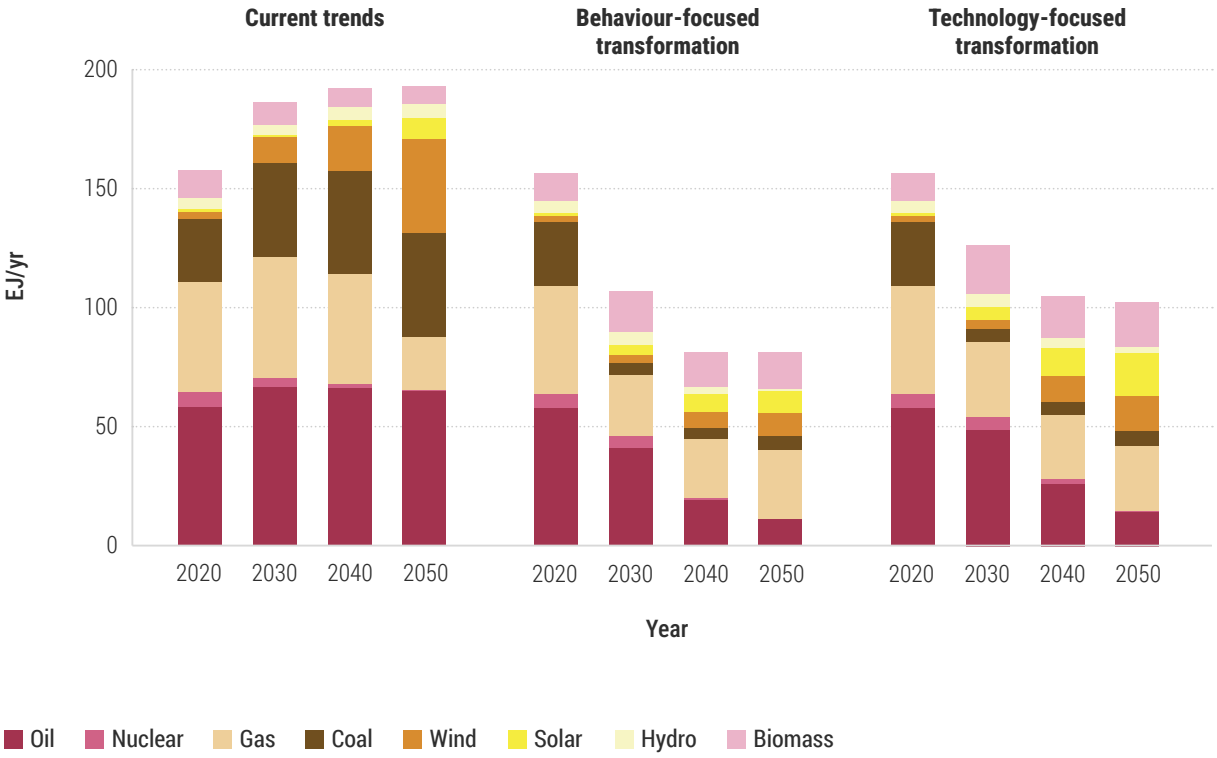
20.8.2.1 Transitions to renewable energy

The technology-focused pathway enables WEOG countries to achieve rapid carbon emission reductions through a transition to renewable energy, carbon dioxide removal strategies, electricity-based transportation, and enhancing energy efficiency. To achieve this, the following actions may be needed {16.2-16.4}:

- Complete the energy transition away from fossil fuels well before 2050.
- Invest in renewable energy infrastructure such as insulation, heat pumps, solar energy, wind power, green hydrogen, geothermal, and tidal energy.
- Invest and implement carbon dioxide removal strategies and technologies such as direct air carbon capture and storage and bioenergy with carbon capture and storage.
- Develop the workforce through education and training of people to implement the above.
- Improve governance by establishing monitoring capacity, target definition, and effective incentives, taxes, and subsidies.

Primary energy use is projected to decline in both the technology-focused and the behaviour-focused pathways. Furthermore, the share of renewable energy – solar, wind, hydro and biomass – in primary energy use in the WEOG region is expected to rise (**Figure 20.28**). Modelling foresees the share of carbon capture and storage (CCS) technologies in energy production to rise to 34 per cent by 2050, however there is a caveat in this forecast as this technology has not yet been implemented in practice (**Figure 20.28**). The IPCC models that meet the 1.5°C target include direct air carbon capture and storage and bioenergy with carbon capture and storage with significant contributions from agriculture, forestry and other land uses. However, current rates of CCS are far below the potential modelled in the IPCC pathways, even if those pathways show that the CO_2 storage requirement is smaller than

Figure 20.28: Primary energy use for the three pathways in Western Europe and Other Groups



the geological CO_2 storage capacity (IPCC 2022). Bioenergy with carbon capture and storage bears the potential risk of reducing biodiversity by introducing intensive monoculture plantations. Therefore, careful land-use planning is required to leverage synergies that support biodiversity while mitigating climate change (IPCC 2022).

The WEOG countries have taken measures in this direction by committing to the energy transition and announcing political agendas focusing on renewable energy and increased energy efficiency. The European Union fixed its goal of carbon neutrality at 2050 (European Commission 2022), and New Zealand and Australia demonstrate significant commitments to renewable energy (DCCEEW 2022; MBIE 2023). Thus, policies are focusing on the energy transition, while the use of renewable energy, especially in transport and heating, still poses challenges. This is evident in the European Union, where planned renovation rates fell short compared with needs (Maduta et al. 2023). As well, carbon dioxide removal measures are falling short of targets (Galán-Martín et al. 2021).

20.8.2.2 Sustainable agriculture and food system

If the WEOG countries embrace the promotion of sustainable food production practices and shift towards more sustainable diets along the technology-focused pathway, the following actions should be considered {17.2.1-17.2.5}:

- Prioritize preserving and improving soil and livestock health
- Reduce chemical inputs
- Protect water resources
- Reduce air pollution
- Develop new plant varieties or use indigenous varieties suited to emergent environmental conditions
- Diffusion of innovative production techniques

The technology-focused pathway for the food system is guided by principles of efficiency, intensification, and technological intervention. Solutions need to be found regarding the loss of arable land, the reduction of available fresh water, reduction of food loss, the rise of food demand, and food waste. New plant varieties will be developed through genetic selection or bioengineering with the aim to be better suited to emergent environmental conditions and to have higher yields and provide better nutrition. Innovative production techniques for soil, water, and crop management, such as precision agriculture and micro irrigation, will be applied. Food production will pursue a form of automation, relying on environmental and crop and livestock monitoring, the use of remote stations, rovers, drones, and artificial intelligence applications that complement human action.

Efficiency enhancement of the food supply chain, with a focus on limiting waste, will take place through technological intervention. In the face of growing demand for protein products, novel foods will be introduced once they are developed based on plant, animal and insect proteins, as well as the introduction of new varieties through genetic selection (**Figure 20.29**).

The modelling results suggest agricultural demand and production will increase, while land cover will remain constant due to increases in production efficiency and sustainable land management practices. Food prices will rise by 28 per cent from 2020 to 2050 and this pathway has the highest increase in food prices.

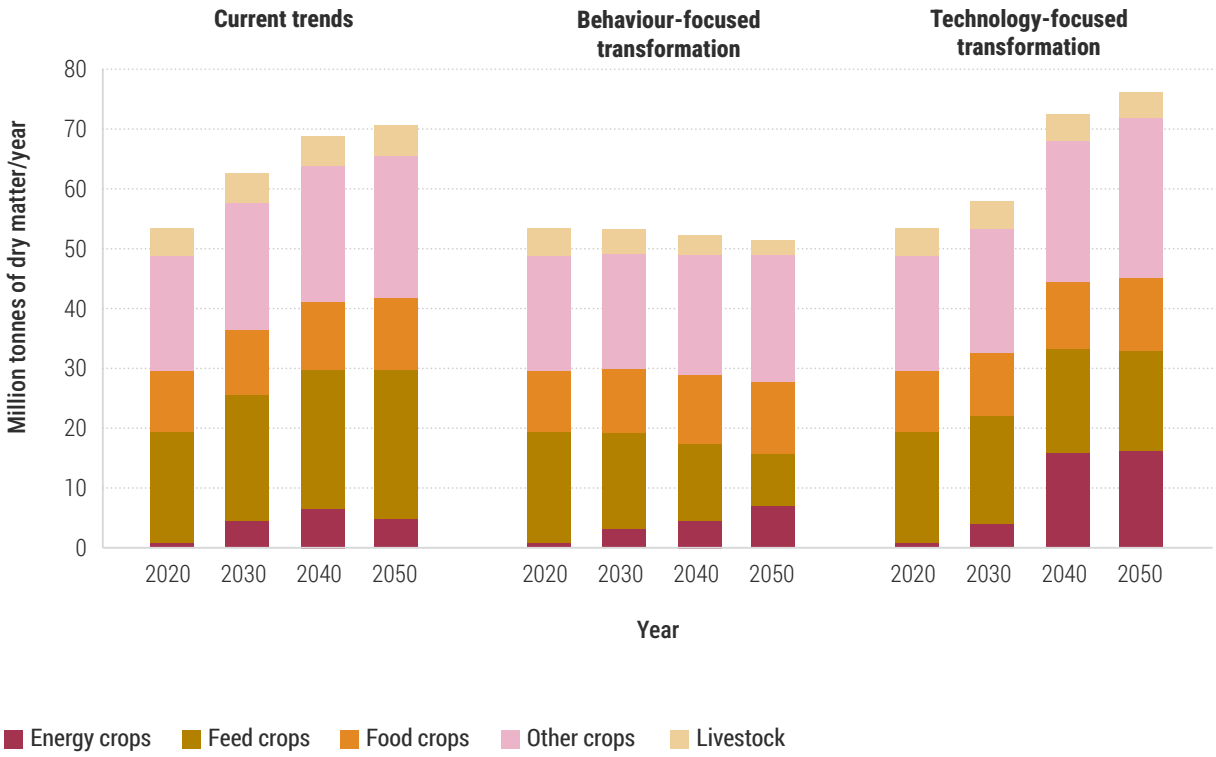
20.8.2.3 Economic and financial systems

If WEOG countries embrace the technology-focused pathway to fully embrace circularity, implementation of the following actions may be needed {14.3-14.6}:

- policies that support a transition to circularity
- eco-taxation
- specific waste reduction targets

In 2020, the European Union approved the Circular Economy Action Plan, aimed at imposing sustainable practices across various sectors. It enforces eco-design directives for energy-efficient products, champions consumer rights for product repair, and advocates for updated directives that target industrial emissions and urban wastewater treatment (Watkins and Meysner 2022). European countries have been slow to implement

Figure 20.29: Agricultural demand for the three pathways in Western Europe and Other Groups



circular economy technologies, and it is unlikely that a doubling of recycled materials in the system by 2030 will occur (ECA 2023). Similarly, in the United States, the Environmental Protection Agency is developing new circular economy strategies, having issued drafts for comments (US-EPA 2022).

20.8.2.4 Conservation and restoration of nature

Technological transformation in food, energy, material, and financial systems can enhance sustainability by promoting resource efficiency and reducing waste. Innovations in agricultural practices can lead to lower emissions and better soil health {18.2.3; 18.2.4}. Renewable energy sources and smart grids lower greenhouse gas emissions. Advancements in materials science foster the development of biodegradable, environmentally benign, and sustainable products. Improved financial systems incentivize eco-friendly investments and circularity practices. Together, these transformations contribute to a more resilient ecosystem.

20.8.2.5 Economic and financial system reforms

The financial system likely holds many of the primary levers of control for bringing about the desired transformations of the energy, material, food, and environmental systems. The WEOG countries represent roughly 10 per cent of the world's population while they own almost 60 per cent of the world's wealth and enjoy more than half of the world's annual income. Consequently, WEOG countries have a responsibility to demonstrate and facilitate desired transitions at home and abroad. Chapter 11 and Chapter 14 identify five solution pathways {14.3 to 14.6}:

- Internalizing externalities – getting-prices-right
- Green finance – getting-incentives-right
- Regulations to foster green behaviour and increased role of government
- Circularity informed by macrolevel energy and material accounting
- Introducing carbon tax and green tax to incentivize the private sector for innovative financing of circularity measures such as waste-to-energy

To varying degrees in the WEOG region, existing economic systems are currently accelerating economic

inequality, social injustice, and environmental degradation (Piketty 2014; US-EPA 2022). It is becoming increasingly clear that a new economic operating system is needed that adopts elements of all five of the solution pathways. Research that integrates nature and ecosystem services into a food-water-energy nexus helps policymakers advance just transitions (Subedi et al. 2020). It is likely that the geographic extent of policies will vary but WEOG countries need to design, experiment with, and facilitate bold new policies and practices to foster these systemic changes. Some areas of promise are:

Increase the role of governments to use subsidies as green finance and taxes as disincentives for certain unsustainable economic activities, while internalizing external costs and incentives for labelling, certification, and carbon neutrality.

Reorient the international financial system towards achieving the SDGs particularly those related to human health and well-being. This would likely involve WEOG governments reducing risks associated with foreign direct investment in low-income countries, cancelling debt, and developing and expanding financial tools used for redistribution and investment, such as the EU's Green Bonds.

20.8.2.6 Technology-focused pathway implications

These technology-focused pathway actions can have positive and negative socioeconomic and environmental implications that should be carefully monitored.

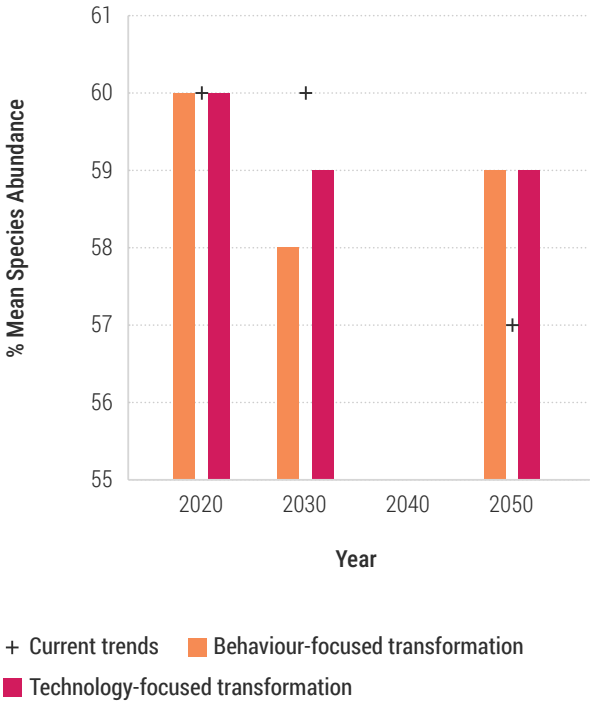
Implementing the technological pathway may stimulate economic growth and job creation and enhance human well-being. Increased use of remote-sensing technologies can contribute to behavioural change around renewable energy uptake. Increasing penetration of renewable energy requires significant policy interventions (Chen et al. 2019). Circularity opens job opportunities in repair, refurbishment, and recycling. This boosts social resilience and inclusivity (McGinty 2021); however, there is limited knowledge of the magnitude of these opportunities (Aguilar-Hernandez et al. 2021). Economic system shifts will support progress towards a just, sustainable, and desirable future (IPBES 2019; Turnhout et al. 2021). Legal frameworks and eco-taxes can encourage eco-friendly practices and discourage harmful products.

There are many positive benefits, however unintended negative consequences could include under-employment, work-profile obsolescence, and increasing inequality.

20.8.2.6.1 Environment aspects

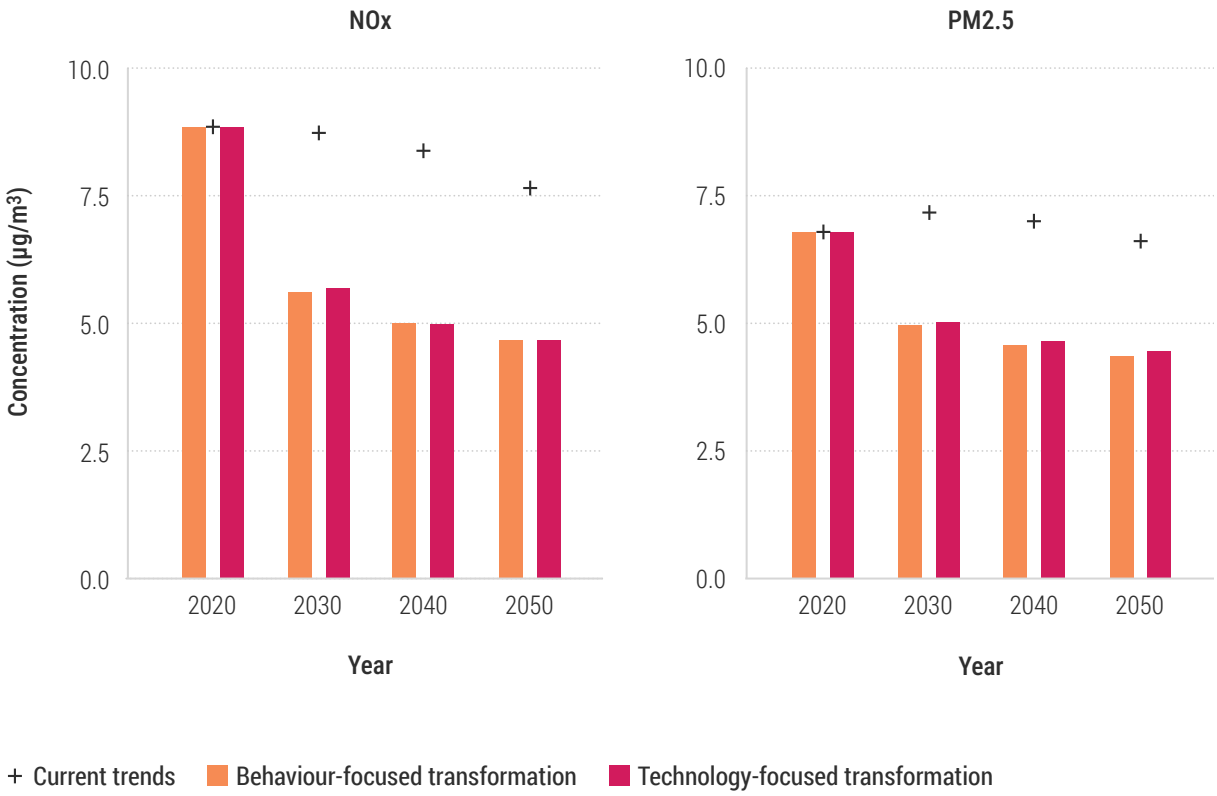
The technology-focused pathway can increase resilience, decrease GHG emissions, and better improve ecosystem and human health. Renewable energy shifts should decrease GHG emissions and likely reduce threats to the environment generally (Gielen et al. 2019). The circular economy and extended product-lives can lead to improved water quality, reduced pollution, and greater biodiversity (**Figure 20.30**) and to improved air quality (**Figure 20.31**), fostering a healthier, more sustainable environment. Direct interventions to restore and encourage biodiversity have been shown to be viable (Pereira and Navarro 2015). This approach can conserve resources, prevent habitat destruction, and cut pollution. The existing economic system fails to account for or acknowledge that our economy, our society, and our civilization fundamentally depend on the natural world to exist. Thus, economic

Figure 20.30: Terrestrial biodiversity for the three pathways in Western Europe and Other Groups



Model output data was not available for biodiversity for the year 2040 and for clear comparison across the years, the values of the vertical axis start at 55% MSA

Figure 20.31: Air pollution for the three pathways in Western Europe and Other Groups



system shifts involve increased acknowledgement of the value of nature.

20.8.3 Behaviour-focused Transformation Pathway

Behaviour-focused pathways for transformative, integrative and cross-sector solutions suitable for WEOG that can address the global environmental crises moving forward are described below:

20.8.3.1 Transition to renewable energy

Under this pathway, WEOG countries achieve decarbonization, rapid carbon emission reduction through renewable energy adoption, carbon dioxide removal strategies, electrification of transportation, and enhanced energy efficiency. These can be achieved through {16.2-16.4}:

- Reduction of home energy usage, with the adoption of low-energy consumption and energy-efficient technologies and appliances, home insulation, and reduction of water heater temperature.
- Shift towards domestic prosumerism, adopting domestic energy production and storage solutions, implementing rainwater harvesting, and growing home gardens.
- Modal shifts in urban mobility and urban planning, mobility shift towards more public transport.
- Reducing demand on energy, materials, food, and other environmental systems by eliminating non-essential and wasteful consumption.

The modelling results suggest that following the behaviour-focused pathway, primary energy production decreases by 41 per cent by 2050, compared to 2020. The share of renewables increases but is lower than the technology-focused pathway for WEOG.

The WEOG countries are transitioning along the behaviour-focused pathway as rising costs are pushing consumers to adopt energy-efficient solutions (Camarasa et al. 2021). Prosumer behaviours have spread, showing an emergence of new attitudes towards domestic energy production

(Parra-Domínguez et al. 2023). Similarly, an increasing interest in home and collective vegetable gardens reflects concerns related to food scarcity, food and environmental contamination, and climate change (Raneng et al. 2023). These events emerge while cities across the region are implementing urban strategies responding to demand for more sustainable urban spaces (Alberti 2023).

20.8.3.2 Sustainable agriculture and food system

Under the behaviour-focused pathway, benefits will be achieved by the shift towards more sustainable diets and by the reduction of food losses and waste. These can involve arrangements such as farm-to-fork strategies that bring food producers closer to consumers through knowledge campaigns on regional food production, urban and peri-urban agriculture, permaculture, and local marketing.

As consumers reduce household food waste and diversify their diets, they gradually emerge as prosumers. This results in a higher demand for plant-based food and lower demand for livestock products. Polycropping, agroforestry, integrated crop and livestock systems, organic and agroecological farming, urban agriculture, use of local varieties, and development of organic value chains are ways forward. This will reinforce the resilience of food systems. The risks of pests and diseases and the need for external inputs are reduced through the practice of integrated pest management and biological control of pests and diseases {17.2.1-17.2.5}.

20.8.3.3 Circular economy and pollution control and prevention

WEOG countries can embrace the behaviour-focused pathway to implement circularity through waste/material system transformation for which the following actions may be considered:

- Shifting towards green consumerism (White et al. 2019), prioritizing sustainable and eco-friendly products and services
- Downscaling of consumption patterns in a shift towards sustainable lifestyles that prioritize quality over quantity, sharing, and reducing material consumption
- Fostering local sustainability movements to raise the general awareness of consumers to ensure that all WEOG members achieve SDG 12 addressing sustainable consumption and production
- Ensuring that the Industrial Production Processing and Utilization (IPPU) sector achieves carbon neutrality by 2030 as the IPPU is one of the high carbon emitting sectors.
- Prioritizing the purchase of recycled materials over virgin materials.

For over two decades, practices of green consumerism have proliferated in WEOG countries (Sachdeva et al. 2015). There has been a notable increase in consumer awareness regarding sustainability issues (Bassi 2023). This shift has intensified the need for regulatory oversight of advertising messages, as acknowledged by the European Circular Economy policy (Watkins and Meysner 2022). A discernible change in consumption patterns towards high-quality and sustainable products is evident in markets such as fashion and food, particularly among more affluent segments. Additionally, practices of the sharing economy have become widespread in WEOG countries. These sharing economy practices are linked to the growing utilization of online exchange platforms (Panniello et al. 2022). This proliferation is generating new regulatory needs for these emerging market forms (European Commission 2016).

20.8.3.4 Economic and financial system reforms

There are three fundamental ways in which the Behaviour-focused pathway will interact with the financial system:

- A change in our understanding of the value of nature and the nature of value
- A rebalancing of the public and private spheres that is accompanied by a rebalancing of cooperation and competition as producers of value
- A shift away from the growth imperative and a move towards designing an economy to produce sustainable well-being rather than ever increasing GDP (Costanza 2023)

Box 20.5 Indigenous Knowledge, technology, behaviour and governance: Sustainable whaling

Indigenous Knowledge is a knowledge-belief-practice complex (Berkes 2010) in which behaviour, technology, and other cultural domains (e.g. ethics, governance) are intricately intertwined. For example, the toggle harpoon, perfected by Indigenous Peoples of the Arctic for hunting marine mammals, became associated with a rich and sustainable regional economy and culture that has persisted for millennia. However, the harpoon's mechanization and unregulated industrial application by commercial whalers in the 19th century proved unsustainable, endangering many whale populations by the 20th century and setting the stage for a conflict between Western science and Indigenous Knowledge over the governance of subsistence whaling.

The Alaska Eskimo Whaling Commission (AEWC) was established in 1977 following an IWC ban on bowhead whaling. The ban was based on a survey conducted without consultation with Indigenous hunters concerning the timing and pathways of the bowhead migration, resulting in an estimate of the Bering Sea stock of bowheads far lower than the actual population. Based on Indigenous Knowledge of when, where, and how to count whales, a resurvey was carried out. This IK-informed study found the population to be considerably higher than the original survey supporting the ban.

Consequently, an exemption to the whaling ban was crafted for Alaskan Inupiaq and Siberian Yupik villages, based on a sustainable hunting quota for customary subsistence uses. Thereafter, AWEC was given a role on the scientific committee of the IWC that monitors populations and sets catch quotas. Local knowledge governance of whaling is a major conservation success story for both the bowhead whale and the Indigenous whaling cultures of Alaska and beyond (cf. Huntington et al. 2021).

Since 1981, the AEWC has carried out management and enforcement responsibilities pertaining to sustainable and ethical bowhead whale hunting under a cooperative agreement with the US government and in compliance with IWC regulations.

The AEWC case shows why subsistence whaling still makes sense in the modern world of industrialized, agriculturally oriented food system. It meets the food security criteria of accessibility, affordability, availability and desirability (GPAFSN 2020).

It is a sustainable niche that supports Indigenous food sovereignty and circular economies, ecocultural health and diversity, and traditional knowledge and values (cf. Burn Silver et al. 2016). More broadly, Indigenous whalers' knowledge has proven indispensable to contemporary understanding and responses to climate change in the Arctic. Indigenous-led monitoring programs are tracking Arctic environmental changes and their impacts. With scientists, Indigenous community members co-produce and interpret data on permafrost and sea ice thickness, animal migration patterns, and weather conditions to arrive at nuanced, locally contextualized understandings of climate impacts. This approach is being scaled up through The Arctic Council's Arctic Monitoring and Assessment Programme (AMAP) which collaborates with Inuit communities to gather data on environmental changes and their effects on communities (AMAP 2024). Paired with co-governance, this co-learning aids in developing more effective resilience and adaptation strategies tailored to local conditions throughout a region that is experiencing among the world's highest rates of environmental change. It is a case where incorporation of Indigenous Knowledge has proven transformative for environmental research, monitoring, and adaptive governance.

Credit: Galyna_Andrushko/Envato

In addition, circular economy practices will produce new jobs.

Currently nature is undervalued. Multiple conceptualizations of value, including non-material aspects such as the intrinsic values of ecosystem goods and services, can be internalized by the nature and climate finance system. This will provide incentives for sustainable consumption and production of natural resources (IPBES 2022). Therefore, changes to our financial system must recognize the immense value of functioning ecosystems and incorporate the value of the natural world in a serious way. Modelling projections suggest the behavioural transformation will involve a less urbanized world with greater societal awareness of humanity's fundamental dependence on functioning ecosystems and a stable climate. The WEOG countries are some of the most urbanized in the world. This is a challenge for WEOG countries because increasing levels of urbanization are contributing to increasing disconnection from nature (Turner et al. 2004). There is growing recognition that Indigenous People have a greater appreciation of human connection to, and dependence upon, the natural world according to the IPBES report on valuation of biodiversity and ecosystem services assessment (IPBES 2019). Changes to our financial system that will increase resilience, efficiency, and equity involve rediscovering, internalizing, and formally recognizing the value of the natural world and developing mechanisms to share the wealth of the natural world more equitably and democratically. There are myriad policies to achieve these objectives which will likely vary in scope, geographic extent, and cost.

20.8.3.5 Conservation and restoration of nature

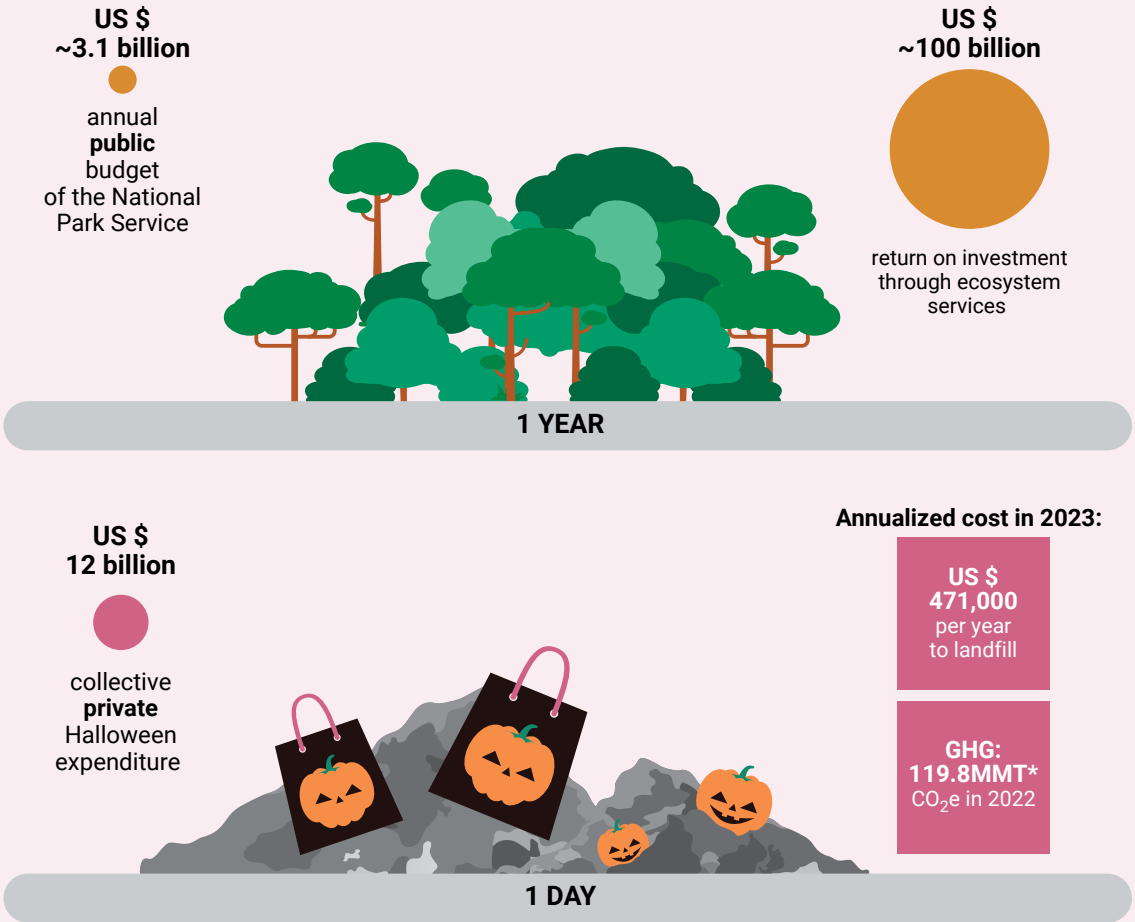
Behavioural and lifestyle changes, such as adopting plant-based diets, reducing energy consumption, and embracing minimalism, can significantly alleviate pressure on environmental systems. By prioritizing sustainable choices – such as using public transport, supporting local economies, and minimizing waste – individuals can reduce their carbon footprints and resource use. Engaging in community initiatives and advocating for eco-friendly policies can further amplify these efforts, creating a ripple effect that promotes collective action. Ultimately, these changes foster

Box 20.6 The Inflation Reduction Act as an example of financial-system change

One prominent example is the Inflation Reduction Act (H.R. 5376) that the US Congress passed into law in August 2022. Although its name suggests that it is an inflation control act, its actual intent and impact lie in its capacity to reform key aspects of the financial and regulatory systems in the US (IRS 2022). This legislation incorporates tax incentives aimed at reducing carbon emissions by 40 per cent. It promotes renewable energy and energy efficiency, as well as economic equity by taxing large corporations and the ultrawealthy while avoiding new taxes on families earning less than US$400,000. Aligning financial incentives with environmental goals can stimulate investment in sustainable practices across various sectors of the US economy.

WEOG countries, by transforming their financial systems, can lead by example, inspiring other regions to adopt similar practices. This leadership can facilitate international cooperation on climate initiatives, technology transfer, and SDGs, creating a more unified and inclusive global response to environmental challenges. One specific example that cries for leadership and communication related to the misallocation of resources is the juxtaposition of private spending on the single day of Halloween in the United States of about US$12 billion compared to the entire annual budget of the National Park Service of about US$3.1 billion (**Figure 20.32**).

Figure 20.32: Pumpkins or Parks – Behaviour-focused pathway implications



a culture of sustainability, encouraging industries to adopt greener practices and enhancing overall environmental health.

Changing the financial systems in WEOG countries is crucial for achieving changes in food, energy, material, and environmental systems worldwide. By reorienting financial incentives, WEOG governments can shift how resources are managed.

20.8.3.6 Socioeconomic aspects

The behaviour-focused pathway can have varied social and economic effects on people, particularly in terms of their consumer behaviours. In terms of renewable energy, there could be a shift towards more decentralized energy systems and prosumerism approaches, where consumers install their own renewable energy generation capacity, such as solar panels. These actions may have higher upfront costs but are likely to generate economic returns. Prosumerism raises equity issues, where renters may not be able to become prosumers, disadvantaging them (Dodd and Nelson 2022). Solar panels and electric vehicles may stimulate the circular economy through increased demand for key elements in these products. Regarding urban mobility, this pathway may underline modal shifts towards the use of more public transport and soft mobility, which entails significant health benefits (Zapata-Diomedi et al. 2017; Rodrigues et al. 2020).

Material systems can promote sustainable lifestyles including gender inclusion and empowerment, reducing socioeconomic effects of consumerism. It aligns purchasing decisions with socioenvironmental values, fostering a cycle of sustainability awareness that leads to healthier and inclusive communities and cleaner environments. This approach particularly engages youth, women and older people ensuring long-term ecological stewardship.

Through changes to the financial system, WEOG countries should model and facilitate the establishment of rules-based systems that foster regionally specific desired changes to food, energy, material, and environmental systems. This will necessitate a change in the mind-set of individuals and policymakers who have been raised in a socioeconomic system that favours competition over cooperation, individualism over collectivism, and exploitation of nature over stewardship of nature.

20.8.3.7 Environmental aspects

The 28th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28) of the UNFCCC decided to triple the production of renewable energy and double the energy efficiency by 2030. This is expected to help UNFCCC parties achieve another milestone COP28 decision on transitioning away from fossil fuels by 2050 (UNFCCC 2023). The WEOG members are expected to lead in implementing these decisions and achieve targets. Reducing food waste and postharvest production loss can decrease the area needed for agriculture, potentially reducing pressure on biodiversity loss (Guo et al. 2023). Preferences for integrated pest management can deliver lower GHG and nitrogen emissions through decreased livestock production. Large-scale plant protein monocultures may decrease biodiversity and water quality unless agroecological practices are implemented (Bourke et al. 2021).

By reducing consumption and waste, material system changes decrease resource use and environmental degradation as demonstrated by Indigenous Peoples' high circularity practices (Vijayan et al. 2022). Initiatives include minimizing single-use plastics and promoting waste reduction, resulting in cleaner oceans and less landfill waste. Additionally, community-driven efforts enhance local sustainability, while the sharing economy decreases the environmental footprint of production and transportation {18.2.3; 18.2.4}.

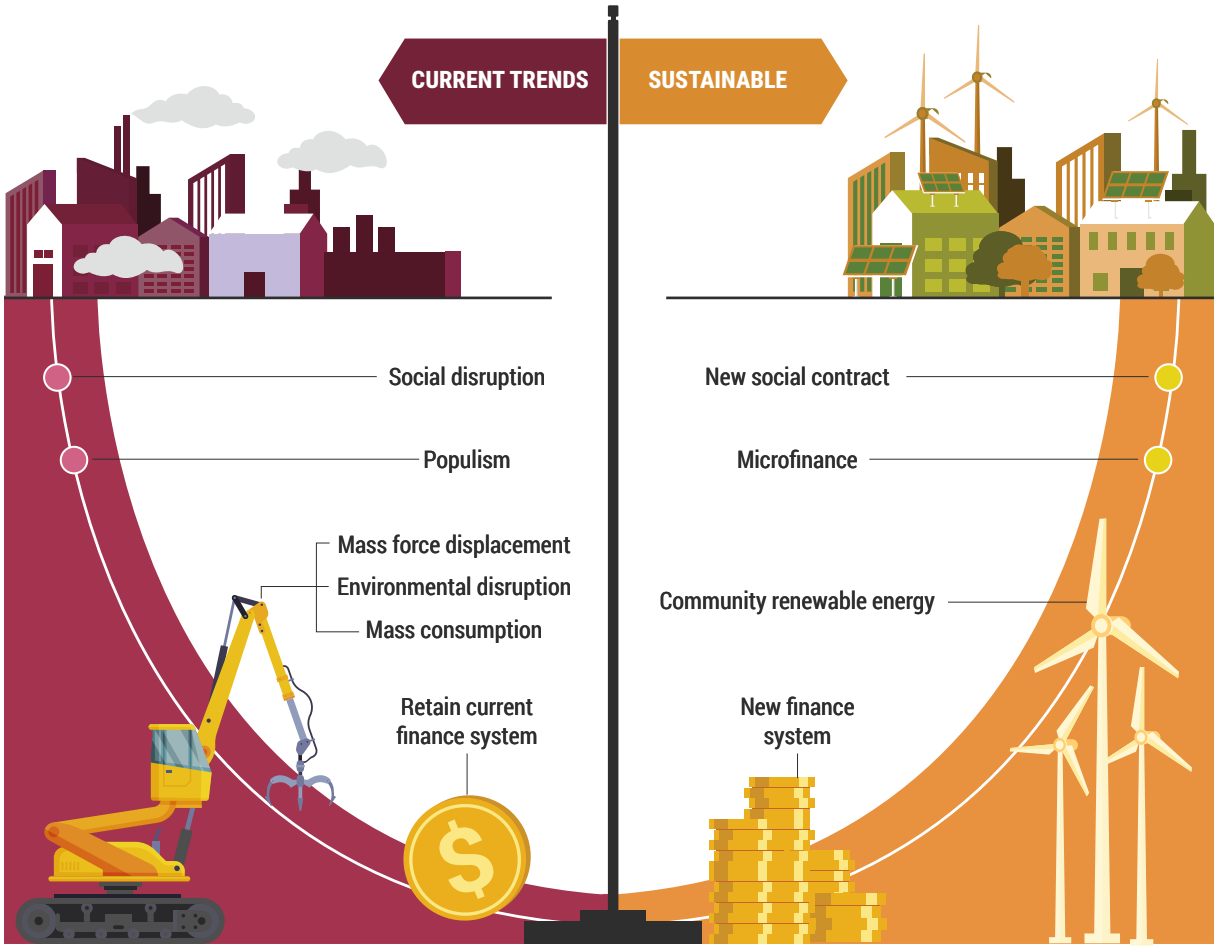
20.8.4 Regional priorities, synergies and trade-offs

The outlined pathways for societal and environmental transformation carry multifaceted implications that are both promising and challenging (Figure **20.33**, **20.34**).

20.8.4.1.1 Positive societal impacts

- Economic Growth: Industries involved in renewable energy, sustainable agriculture, circularity, and clean technologies experience growth, creating jobs and stimulating innovation.
- Job Creation: The adoption of sustainable practices, such as circularity initiatives and community-based actions, generates employment opportunities.

Figure 20.33: Behavioural-LIFE focused path showing two directions



- Consumer Well-being: Encouraging responsible consumption patterns benefits consumers by reducing the financial strain and health issues associated with excessive and wasteful consumption.
- Education and Awareness: Understanding the impact of consumption on the environment promotes responsible decision-making and sustainable lifestyles.
- Community Engagement: Community-based actions, such as neighbourhood composting programmes, repair cafés, and local swap events, encourage social cohesion and shared responsibility.

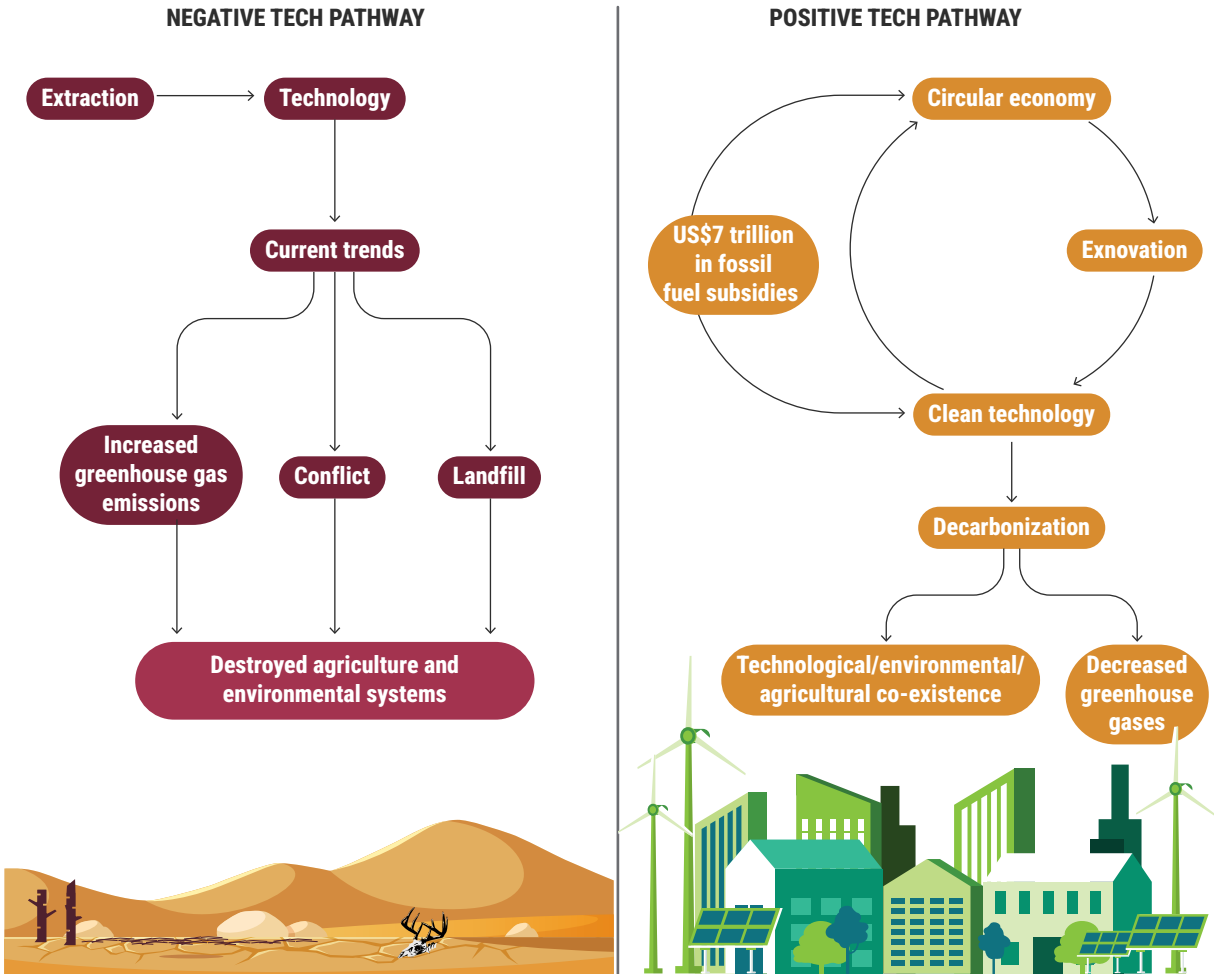
20.8.4.1.2 Positive environmental impacts

- Resource Conservation: Resource-efficient manufacturing, recycling, and circularity principles contribute to the conservation of finite resources.
- Waste Reduction: Less waste in landfills and oceans minimizes pollution, preserves natural habitats, and supports biodiversity.
- Greenhouse Gas Emission Reduction: This mitigates climate change and contributes to a healthier planet.
- Pollution Mitigation: Eco-friendly product design and circularity initiatives minimize pollution at various stages of production and consumption.
- Conservation of Ecosystems: Sustainable agriculture practices, such as agroecological farming, prioritize soil fertility, water retention, and biodiversity.

20.8.4.1.3 Challenges and unintended consequences:

- Economic Challenges: The transition to sustainable practices, particularly in the food system, may lead to higher production costs and

Figure 20.34: Implications from a positive and a negative approach to a technological pathway



potentially increased food prices at the level of individual consumers. Higher food costs are a consequence of internalizing external costs of food production.

- Regional variability: Local specific systems may conflict with the need for standardized quality and quantity required for global trade. Striking a balance between local sustainability and global trade dynamics is a challenge.

- Implementation Hurdles: Effective implementation of these initiatives relies on supportive policies, financial investments, and public engagement. Ensuring that these measures are carried out successfully can be a complex process.

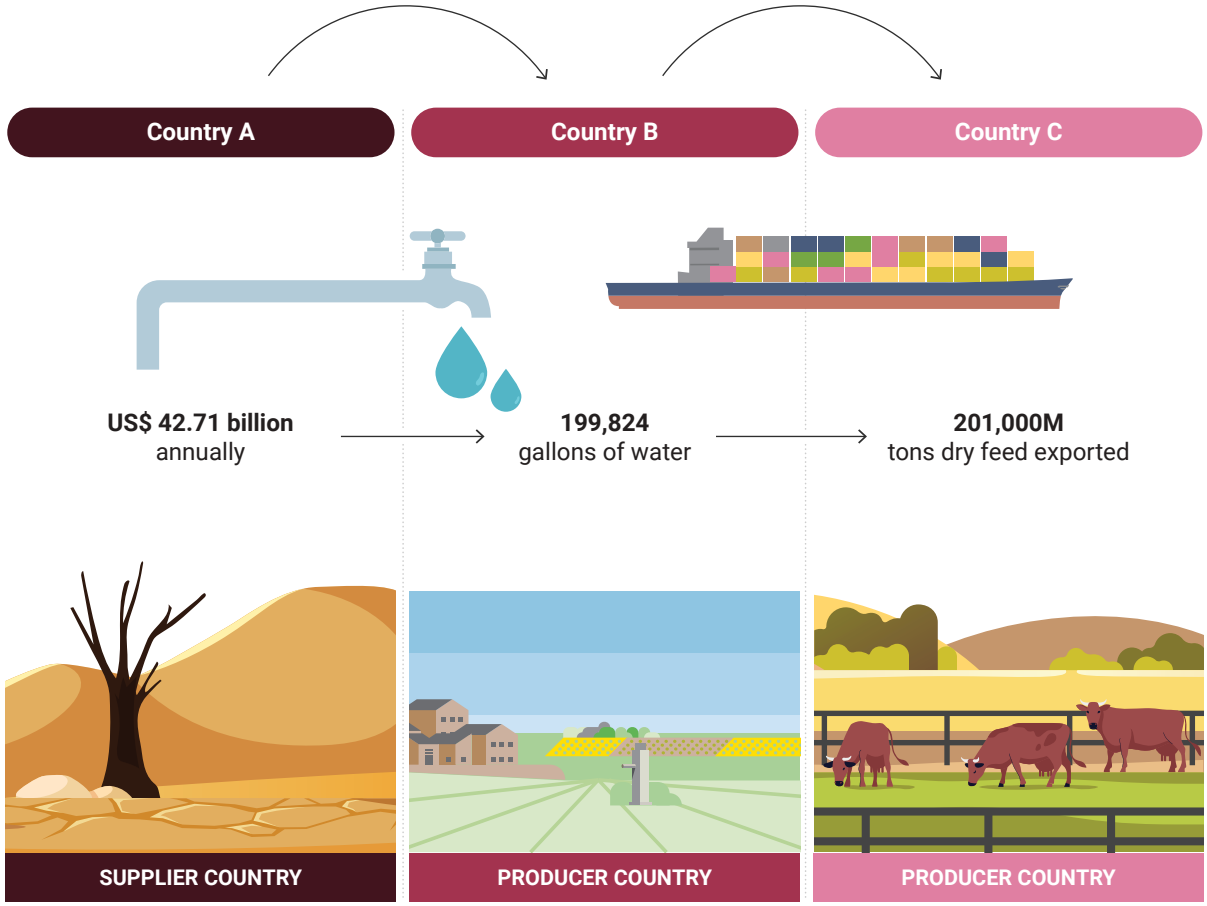
- Equity Concerns: While sustainability efforts aim to benefit society as a whole, there may be equity concerns. Vulnerable communities face barriers in accessing sustainable products and services, potentially exacerbating existing inequalities. Proactive action must be directed towards the inclusion of marginalized groups within the WEOG countries with a focus on gender issues, people with disabilities, cultural minorities, and migrants.

- Transboundary Issues: Money, material, air, energy, and labour cross international boundaries, which raise many moral, ethical, and practical questions with respect to building an integrated social-environmental-economic accounting system that must be resolved (**Figure 20.35**).

20.8.5 Reflection on strengthening regional interlinkages

Energy System and Materials System: Both the technology-focused and behaviour-focused pathways emphasize sustainability through changes in consumption and production. The energy system

Figure 20.35: Transboundary issues, virtual water, and the food-water-energy nexus



needs to transition away from fossil fuels, based on enhanced production and efficient use of renewable energy, while the materials system needs to embrace circularity practices to reduce waste and optimize consumption. The use of sustainable consumption and production and use of energy-efficient technologies is necessary.

Food System and Materials System: The food system transformation means countries must follow a combination of conservation agriculture-based sustainable intensification (CIMMYT 2019) that can scale-up sustainable agriculture practices, including agroecological farming and the use of high yielding native varieties. These practices, together with climate-resilient agriculture, align with the food and materials systems' goals of transformation and sustainability. Additionally, both pathways can address food waste reduction through different approaches including circularity and dietary changes (Agamuthu and Babel 2023; FAO 2023).

Synergy among Food, Environment and Economic Systems-Overall, the solutions can lead to following synergies:

- Both pathways promote resource efficiency, nature protection, and waste reduction, contributing to environmental sustainability.
- Energy systems and the behaviour-focused pathways align in encouraging reduction of energy use, energy conservation, and renewable energy adoption.
- The materials system and the behaviour-focused pathway share goals of promoting sustainable products and consumer education.

In terms of policy implications, it is increasingly recognized that mixtures of policies, particularly price-based instruments, are most effective in achieving SDGs (Lecocq et al. 2022; Stechemesser et al. 2024; Winkler et al. 2024). It is likely that mixtures of policies

rooted in the financial system will be most effective in bringing about desired changes in the food, energy, environmental, and material systems across WEOG. In addition, the success of these policies often have to be fine-grained from sectoral, geographic, and sociodemographic contexts.

20.8.6 Conclusion

A summary of key intervention points is provided in **Table 20.10.** Ongoing support and development of social, economic, and environmental monitoring capabilities is vital for the adaptive management need to face the challenge of the global environmental crises and is an area in which WEOG countries have made significant contributions. Among these, addressing transboundary issues such as migration, nature conservation and pollution control will need strong political will, vibrant regional cooperation and integration of economic and trade policies (McIntyre 2025).

These are the key messages from the WEOG region's perspective:

Energy System:

- Policies should support the adoption of renewable energy sources and energy efficiency measures.
- Incentives for prosumer participation and investment in renewable energy infrastructure are essential.
- Regulations should align with EU climate targets and promote the reduction of energy consumption.

Food System:

- Policies should encourage sustainable farming practices, sustainable plant-dominated diets, and reduced food loss and waste.
- Initiatives promoting direct producer-consumer interaction and local production should be supported.

Table 20.10: Main actions for each system

System	Actions	Actions	Actions	Actions
Energy {16.2-16.4}	Governance and capacity-building	Eco-Taxation and end fossil fuel subsidies	Investment in renewable energy infrastructure	Modal shifts in urban mobility
Food {17.2.1-17.2.5}	Governance and capacity-building	Promote regenerative agriculture	Promote precision agriculture and optimize logistics	Built trust and capacities through communication and food education
Material {15.2.2}	Governance and capacity-building	Implementation of circular economy	Eco-Taxation	Promotion of green consumerism
Economic and Financial {14.3-14.6}	Governance and capacity-building	Green finance	Implementation of economic models to prioritize sustainable well-being over GDP growth	Debt relief for developing countries

- Balancing local production with global trade requirements may require policy adjustments.

Materials System:

- Policies should promote circularity principles, sustainable materials, and extended producer responsibility.
- Eco-taxation and incentives for recycling and reuse can be effective in reducing waste.
- Economic and Financial System:
- Support the introduction of green finance, including eco-taxation, green subsidies, ensuring an inclusive recycling scheme, etc.
- Develop an integrated economic-environmental accounting system that uses economic models that prioritize sustainable well-being over GDP.
- Provide debt relief for developing countries.

20.9 Changing Interrelationships Across Regions

The findings from all regions conclude categorically that remaining on the current path has negative and unsustainable implications for all the regions. Global goals and targets cannot be met leading to large economic and environmental implications.

To build synergies based on interdependencies and shared relationships between and among different regions, there is a need for a coordinated and integrated economic and environmental systems transformation. This can be explored in the future using tele-coupling analysis. Understanding the future dynamics of tele-coupling is essential for developing effective solutions to global environmental crises.

20.9.1 Future tele-coupling dynamics and implications

Given the available simulation results from modelling the transformative pathways, our analysis builds on the state and trends tele-coupling introduced in Chapter 8, to explore the future potential of interregional dynamics through the trade of energy and crops (2020-2050). Simulation results, which group regions together, indicate that in the future, tele-coupling trajectories will vary substantially among regions, tele-coupling types, and over time under the pathways derived from all three Scenarios (**Figure 20.36**). Two specific types of tele-coupling dynamics were explored, namely energy and food, and their trade among the five regional groups.

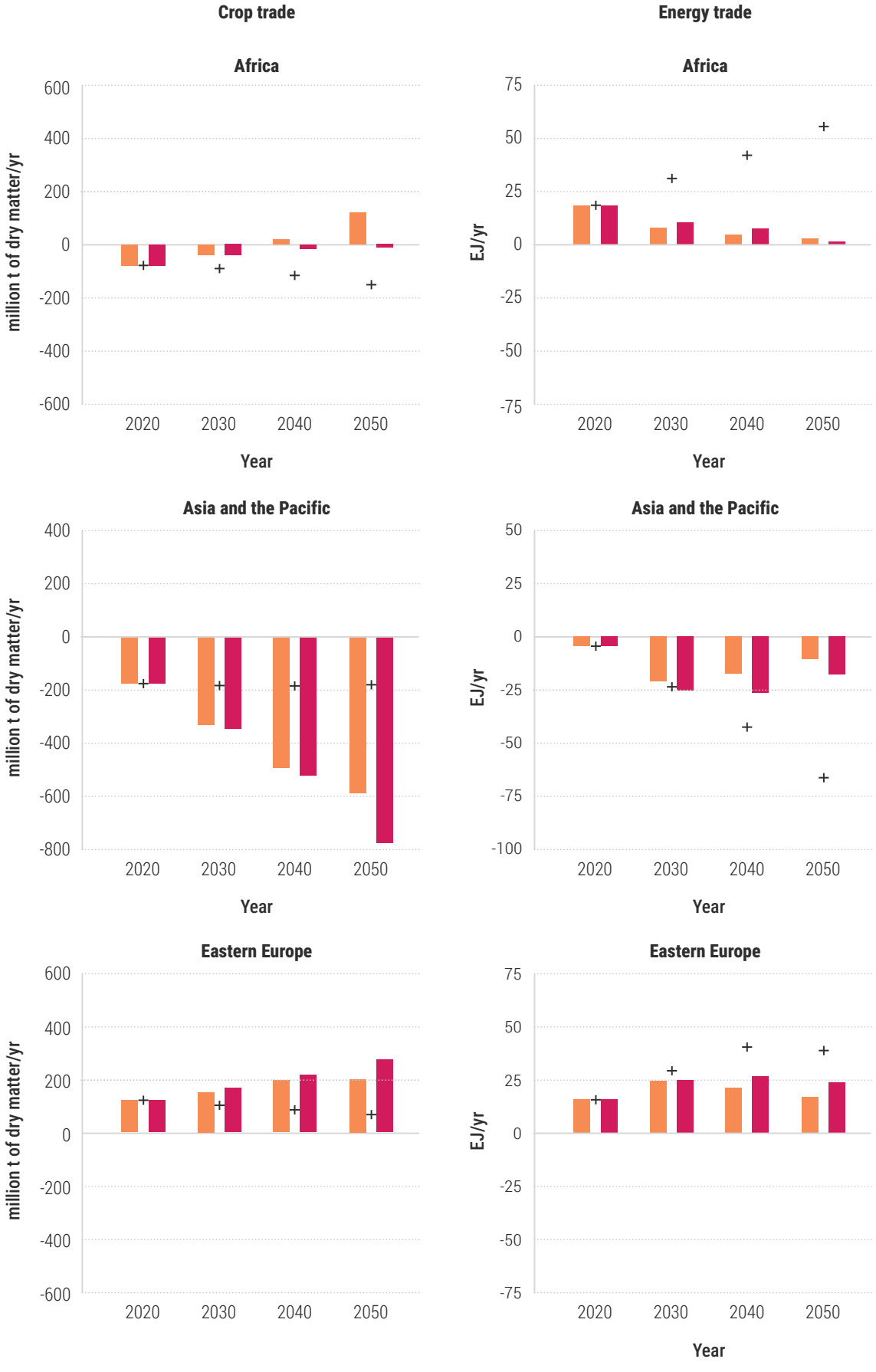
There are often synergies or trade-offs among regions – such as when one region increases net exports while other regions decrease proportionally – with the subsequent tele-coupling types showing similar or opposite dynamics. The results shown in **Figure 20.36** demonstrate different patterns of crop and energy exports under different transformation pathways. Each region has a different trajectory occurring at different speeds.

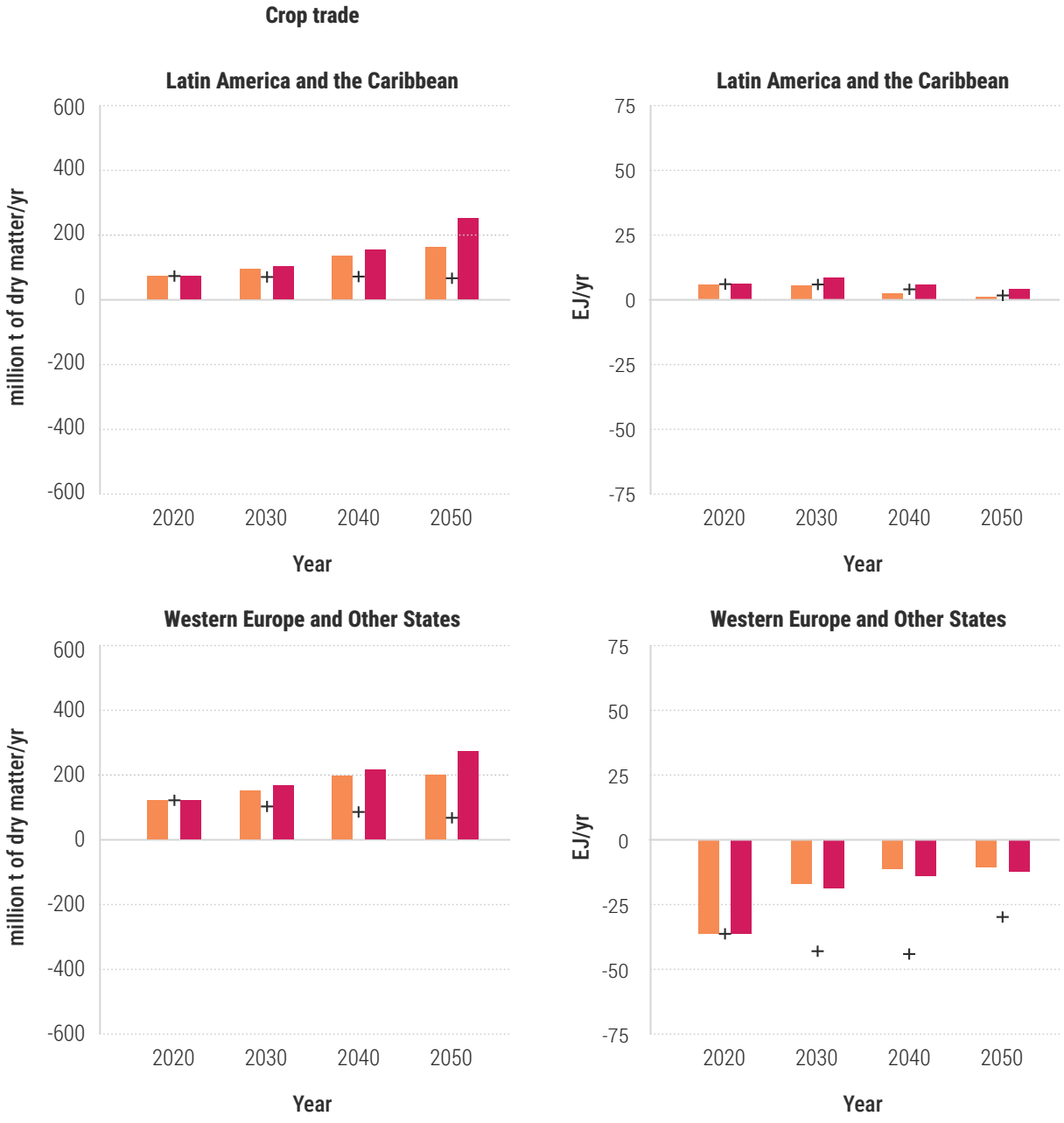
These changing tele-coupling dynamics may reshape the geographic distribution of environmental-socioeconomic impacts and have substantial implications for the global environmental crises. Increasing net exports requires more production and may increase biodiversity loss, pollution, CO_2 emissions, and land degradation in the production and exporting regions. Specifically, there may be elevated adverse effects in EE, LAC, and WEOG, due to increasing crop production and net exports under the behaviour-focused transformation and the technology-focused transformation. For Africa, this occurs with a behaviour-focused transformation only in 2040-2050. For energy crops, Africa, EE and LAC continue to export in the future, albeit at a reduced rate, depending on the different behavioural or technology-focused actions that are introduced. However, for all scenarios AP and WEOG continue to import energy.

In other words, AP may be the only region with continuously declining impacts because of continuously increasing net crop imports. The effects of increasing crop production in and export from Africa may be partially offset by its declining energy net exports. Consuming crops requires energy, thus emitting more CO_2 in the countries where they are consumed. Consuming energy for other purposes also emits CO_2 although different types of fossil fuel and other biomass energy sources emit different amounts of CO_2.

Furthermore, production, consumption, and associated transport of energy and crops generate various

Figure 20.36: **Projected dynamics of telecoupling in crop and energy trades under current trends, behavioural-focused transformation and technology-focused transformation**





consequences for spillover regions – regions affected by the interactions within and between sending and receiving regions. To minimize trade-offs under the transformative pathways, it is crucial to develop new policies and new transformative pathways to enhance synergies among different regions for global sustainability.

20.9.1.1 Future regional dynamics

Analysing the differences that can be observed across regions in each of the assessed systems highlights that under transformative pathways there are likely to be new transboundary, cross-border and interdependent relationships between and among regions and subregions in the future. How might interdependency and shared relationships build synergy in the future?

Energy: In both pathways all regions globally show an increasing trend in renewable energy production in the total energy mix. In Africa and Asia and the Pacific regions there is a steady and sustained increase in energy demand driven by both population growth and increasing access to renewable energy technology. This is different than other regions where trends are slow. In the future, if a behaviour-focused pathway alone is followed, all regions experience less energy

demand than if adopting the technology-focused pathway. Renewable energy is driven by a mix of wind, solar and biomass with associated carbon capture system technology. This has implications particularly in Africa and LAC, where agriculture land is being used for biofuel production creating food security issues. A more balanced approach is suggested by the Global Bioenergy Partnership in the Asia and the Pacific as it has a large potential for both solar and wind (including in the Pacific islands) energy. In the WEOG region fast-track measures to transition away from fossil fuels towards renewables are possible and can be supported by appropriate policy actions.

Food: Differential patterns are observed across the regions resulting from changes to the food system in the future. Both the Africa and LAC regions see a significant increase in land-use demands to support dietary shifts alongside the increase of energy crops, which is different than other regions. For example, Eastern Europe could support a move from livestock towards more energy crops. Again, WEOG clearly has a strong potential to transition to climate-resilient agriculture and a change in diet through behavioural changes making a significant positive contribution globally to a sustainable future.

Material: There are strong synergies across all the regions for this system transformation. This will require consistency across subregions and regions. Successful circularity can create green jobs and improve livelihood. However, there is a need for comprehensive and systematic disciplinary frameworks for future strategic planning and technological advancements in the field.

Economic and financial: The WEOG region is well placed to lead change in transforming financial systems to support transformation in the energy, food, and material-waste systems. Consequently, there is a clear imperative for this region to move swiftly for a sustainable future. Across all regions there is evidence that market-based mechanisms such as carbon emission trading and pricing can support sustainable transitions. All regions point to the need of strong and sustained political will to underwrite the transition to a green and sustainable future.

Environmental: Africa and Latin America and the Caribbean experience worsening biodiversity, water quality and increased water abstraction in the future. By employing behavioural change actions across the systems, water can be more optimally used in those regions. Conversely, across Asia and the Pacific, improvements to air quality are clear in both pathways as a result of the move away from fossil fuels. Across all regions the implications for the environment from the behaviour-focused pathway are much lower than the technology-focused pathway. This consistent message suggests that any future change should be led by behavioural change measures complimented by suitable technologies where needed, to nudge the globe towards sustainability and resiliency to avoid unintended consequences.

20.9.1.2 How are the socioeconomic effects distributed differently?

It is clear that, in all the five regions future transformation must address poverty, hunger alleviation and inequality at their heart. In achieving transformational change in Africa, the co-benefits of emission reduction include higher living standards, poverty reduction and positive health outcomes alongside higher GDP.

In Africa and Eastern Europe as part of the transformation, subregional differences in inequity remain. These inequities exist in WEOG too, due to higher upfront costs for citizens to drive change. LAC highlight the potential for job losses through technological transformation which could be mitigated through robust reskilling education. Such systemic challenges and vulnerabilities can drive migration choices. However, across all regions a general trend towards positive economic and health outcomes are noted under both transformational pathways. All regions, however, suggest that a combination of actions drawn from both pathways will be required to steer society to a positive and equitable future.

20.9.1.2.1 How does policy implementation in one region affect another?

Driving global energy production change with technological transitions can result in increasing pressure on land in both Africa and the LAC region to support energy crops for biofuel with CCS options for a net-zero transition. Similar pressures are felt in these regions because of a global push towards plant-based diets. In these transitions it is important to recognize that the result of global action could lead to regional pressures. Similarly, the telecoupling

section highlighted other challenges across regions due to changing trade relationships.

How can countries capitalize or counter effects: In the system transformation processes, the countries are likely to experience trade-offs, for example between biodiversity conservation and economic development or between clean energy transition and economic growth. However, there are examples where synergy building achieves such massive ecosystem restoration, afforestation and reforestation, green jobs can be created, and microeconomic activities can be expanded to maintain economic growth and social well-being. Such opportunities must be explored to develop global transformation, while recognizing that the transitions are specific to their region.

20.10 Conclusion

To effectively address the global environmental crises, the world can adopt deliberate, radical and tailored transformative pathways (IPBES 2025). Both the direct and the underlying drivers of existential challenges can be addressed holistically, maximizing synergies and minimizing trade-offs. Specific policies that seem to work are whole-of-government and whole-of-society approaches (Ortenzi et al. 2022). Negative synergistic interactions of these crises can be addressed by multipurpose transformative actions (Lawrence et al. 2023; IPBES 2025).

Achieving global goals and targets is possible by halting overexploitation of natural capital and gradually eliminating unsustainable practices such as overconsumption and food waste by implementing circularity principles in waste management. However, for these changes to occur, necessary and urgent economic and financial system reforms will be needed that reflect enabling policies and regulations. Therefore, effective implementation of hybrid transformative pathways, combining regionally specific solutions from both, can lead to a rapid transition towards a resilient development paradigm (IPBES 2024).

The findings therefore conclude that a combination of technological applications and behavioural solutions can help countries achieve the necessary transformations across all systems. Since there will be systemic feedback loops between and among different systems such as food-energy-waste interactions, countries should aim to reform those system structures and processes that create barriers or negative feedback loops (UNCCD 2024). In particular, the financial and economic system transformation has the power to incentivize integrative and transformative actions leading to changes in all systems. Thus, financial system reform is a priority in all regions. Improving and strengthening the role of institutional and governance mechanisms in facilitating system transformation is required to support these transitions (Tomalka et al. 2024).

Credit: vectorfusionart/Envato

Appendix 20.1 A Eastern Europe Key Trends Across the 2030-2040-2050 Milestones

1. Milestone 2030: Early Phase of Transition

- Technology-focused Transformation Pathway:

  a. Energy and Infrastructure: The focus is on scaling up technological solutions, including large-scale renewable energy projects, combating energy poverty and initial deployment of carbon capture and storage (CCS) technologies. The energy grid begins modernization to accommodate higher shares of renewables.

  b. Economic Growth: The globalized economy model emphasizes efficiency gains, digitalization, and urbanization. The region experiences increased investment in high-tech industries, particularly in manufacturing and digital infrastructure.

  c. Environmental Systems: Early improvements are seen in emission reductions and energy efficiency, but biodiversity loss continues at a slower pace. There is a greater focus on industrial efficiency rather than ecosystem health.

- Behaviour-focused Transformation Pathway:

  d. Behavioural and Lifestyle Changes: Early stages of promoting sustainable consumption patterns, plant-based diets, and low-impact living. Decentralized energy solutions begin gaining traction, particularly in rural communities.

  e. Local Economies: Community-driven projects, agroecology, and green job creation become more prevalent. Regional economies prioritize inclusivity and resilience, focusing on reducing socioeconomic disparities.

  f. Environmental Systems: Efforts begin in earnest to restore ecosystems and integrate biodiversity into land management. Initiatives like rewilding and regenerative agriculture take root, enhancing climate resilience and soil health.

Policy Implications for 2030:

- Governments should prioritize investments in both large-scale infrastructure projects as Technology-focused Transformation Pathways and community-driven sustainability initiatives as Behaviour-focused Transformation Pathways. Early policy alignment is critical to ensure that the benefits of high-tech solutions reach all communities while fostering inclusive, sustainable growth.

- Strengthening cross-border energy cooperation and initiating region-wide environmental restoration projects will lay the foundation for future resilience.

2. Milestone 2040: Mid-Transition Phase

- Technology-focused Transformation Pathway:

  g. Energy Systems: Significant progress is made in just energy transition – including energy poverty, decarbonization, with a majority share of energy coming from renewables. CCS technologies are fully operational in key sectors, helping manage emissions from heavy industry.

  h. Economic Disparities: While urban centres benefit from economic growth, rural areas face challenges from automation and the shift to high-tech industries. Regional disparities may widen if adequate support mechanisms are not in place.

  i. Environmental Impacts: Although emissions are reduced, there are potential trade-offs as large infrastructure projects could impact local ecosystems and land use.

- Behaviour-focused Transformation Pathway:

  j. Resilience and Adaptation: By 2040, lifestyle changes are deeply integrated into

society, leading to lower energy demand, more sustainable food systems, and greater regional self-sufficiency. Circular economy practices gain momentum, focusing on waste reduction, repair, and resource efficiency.

k. Social Cohesion: The behaviour-focused pathway's emphasis on local economies, community resilience, and shared resources ensures more equitable distribution of benefits. Green jobs in sectors like agroecology, sustainable forestry, and decentralized energy aiming also at combating energy poverty are widely available.

l. Environmental Benefits: Biodiversity and ecosystem health are notably improved, with widespread adoption of sustainable land management practices including organic certification. Nature-based solutions complement technological advances, enhancing regional climate adaptation.

Policy Implications for 2040:

- To manage disparities, poverty energy, governments need to implement robust just transition frameworks that bridge the gap between urban and rural areas. Policies should support upskilling and job creation in green sectors, ensuring that economic benefits are shared across regions.

- Integrated environmental strategies should align high-tech solutions (e.g., precision farming) with nature-based approaches like reforestation to maximize co-benefits in climate, nature, and pollution control.

3. Milestone 2050: Achieving Sustainability Goals

- Technology-focused Transformation Pathway:

m. Full Decarbonization: The energy system is nearly fully decarbonized, with renewables, smart grids, and CCS technologies playing central roles. Electrification of transport and industry is widespread, leading to significant reductions in greenhouse gas emission

n. Globalized Economy and Urbanization: The region's economies are highly integrated into global supply chains, with productivity gains driven by automation and digital technologies. However, social inequalities could persist if technological advancements are not accompanied by equitable access and social protections.

o. Environmental Sustainability: While emissions are under control, large-scale industrial activity may still pose challenges to biodiversity and resource management if not carefully managed.

- Behaviour-focused Transformation Pathway:

p. Low-Impact Lifestyles: By 2050, Eastern Europe has largely adopted circular economy principles, leading to minimal waste generation, high resource efficiency, and widespread sustainable consumption. Communities are self-reliant, with strong local economies based on low-impact practices.

q. Holistic Environmental Health: The behaviour-focused pathway achieves long-term environmental resilience through extensive rewilding, protected areas, and regenerative practices. Ecosystems are restored, contributing to climate stability, clean water, and healthy soils.

r. Social Equity and Well-being: The emphasis on inclusivity and community resilience results in high levels of social cohesion, health, and well-being. Poverty and inequality are minimized as green jobs, local ownership, and community-based solutions take centre stage.

Policy Implications for 2050:

- Governments should focus on sustaining and scaling up successful initiatives from both pathways. Policies should ensure that technological advancements remain accessible

to all while supporting decentralized and community-driven models that promote equity and resilience.

- Long-term governance frameworks must prioritize ecological restoration, cross-border environmental cooperation, and alignment between economic activities and planetary boundaries.

Conclusion: Key Trends and Strategic Recommendations for 2030-2040-2050

The three milestones highlight the evolving needs and opportunities as Eastern Europe progresses through its sustainability transition. By integrating the technology-focused pathway's high-tech efficiency with the behaviour-focused pathway's inclusive and low-impact approaches, governments can achieve a balanced strategy that delivers socioeconomic benefits while ensuring environmental sustainability.

Strategic Recommendations:

Hybrid Governance Models: Adopt policies that balance large-scale infrastructure investments with localized, community-driven solutions. Regional cooperation and policy harmonization will be critical to achieving shared goals.

Inclusive Growth Strategies: Support the creation of green jobs and equitable access to the benefits of technology, particularly in rural and marginalized areas. Just transition policies including within the area of combating energy poverty – an area of real concern for Eastern Europe, are essential to prevent widening disparities.

Environmental Integration: Align technological innovations with nature-based solutions, ensuring that climate, nature, and pollution goals are addressed holistically. Cross-border environmental projects should be a priority to maximize regional resilience.

Long-Term Resilience: Plan for resilience by investing in decentralized energy systems, sustainable agriculture, and regenerative land-use practices. These investments will ensure that the region can thrive even as global challenges evolve.

This comprehensive approach enables Eastern Europe to navigate the complexities of the 2030-2050 time frame, positioning the region as a leader in sustainable development while addressing the needs of all communities.

Credit: nastuffa/Envato

References

Introduction

Desai, B. H. (2022). Regulating Global Climate Change: From Common Concern to Planetary Concern. Environmental Policy and Law, 52(5-6), 331-347. https://doi.org/10.3233/EPL-219050

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Brondizio, E.S., Settele, J., Diaz, S. and Ngo, H.T. (eds.). Bonn: IPBES secretariat. https://doi.org/10.5281/zenodo.3831673

Intergovernmental Panel on Climate Change (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Lee, H.a.R., J. (eds.). Geneva: Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/syr/

United Nations Environment Programme (2023). Emissions Gap Report 2023. Nairobi: United Nations Environment Programme. https://www.unep.org/resources/emissions-gap-report-2023

United Nations Economic and Social Council (2024a). Progress towards the Sustainable Development Goals Report of the Secretary-General, 2 May 2024. https://unstats.un.org/sdgs/report/2024/

United Nations Development Programme (2022). Human Development Report 2021-22: Uncertain Times, Unsettled Lives: Shaping our Future in a Transforming World. New York. https://hdr.undp.org/content/human-development-report-2021-22

World Bank (2024). Transforming Education for Inclusive Growth. Africa's Pulse, No. 30, October 2024. World Bank, Washington, DC. https://openknowledge.worldbank.org/server/api/core/bitstreams/baea7aea-da11-45e8-82ec-101ac5f1e6ab/content

Africa Region

Africa Carbon Markets Initiative (2022). Roadmap report: Harnessing carbon markets for Africa. Africa Carbon Markets Initiative. Available at: https://www.seforall.org/system/files/2022-11/acmi_roadmap_report_2022.pdf

African Development Bank (2016). The PIDA Energy Vision. The Programme for Infrastructure Development in Africa of the African Development Bank. https://www.afdb.org/fileadmin/uploads/afdb/Documents/Generic-Documents/PIDA per cent20brief per cent20Energy.pdf

African Development Bank (2023). African Economic Outlook, 2023: Mobilizing Private Sector Financing for Climate and Green Growth in Africa. https://www.afdb.org/en/knowledge/publications/african-economic-outlook

African Development Bank (2023). The PIDA Energy Vision. The Programme for Infrastructure Development in Africa of the African Development Bank. https://www.afdb.org/fileadmin/uploads/afdb/Documents/Generic-Documents/PIDA%20brief%20Energy.pdf

African Development Bank (2023). African Economic Outlook, 2023: Mobilizing Private Sector Financing for Climate and Green Growth in Africa. African Development Bank. https://www.afdb.org/en/knowledge/publications/african-economic-outlook

African Development Bank Group (2022). African Economic Outlook 2022 Supporting Climate Resilience and a Just Energy Transition in Africa. Abidjan, Cote d'Ivoire. https://www.afdb.org/en/documents-publications-african-economic-outlook-2023-previous-african-economic-outlook/african-economic-outlook-2022

Agyekum, E.B., Adebayo, T.S., Ampah, J.D. et al. (2023). Transportation in Africa under Paris Agreement 2 °C goal—a review of electric vehicle potentials, cleaner alternative fuels for the sector, challenges, and opportunities. Environmental Science and Pollution Research, 1-36. https://doi.org/10.1007/s11356-023-30911-z

Amir, M. and Khan, S.Z. (2022). Assessment of renewable energy: Status, challenges, COVID-19 impacts, opportunities, and sustainable energy solutions in Africa. Energy and Built Environment, 3(3), 348–362. https://doi.org/10.1016/j.enbenv.2021.03.002

Akinbobola, S. O., Anyanwu, L., Galadima, Z. K., & Ereh, R. E. (2025). Innovations in Biomass and Bioenergy: Addressing Energy Poverty in Rural Africa. International Journal of Climate Change and Policy 11(2), 61–77. https://doi.org/10.56201/ijssmr.v8.no1.2022.pg32.40

Apeaning, R.W. and Thollander, P. (2013). Barriers to and driving forces for industrial energy efficiency improvements in African industries–a case study of Ghana's largest industrial area. Journal of Cleaner Production, 53, 204-213. https://core.ac.uk/download/pdf/190355641.pdf

Armani, M., Asefa, M., Sissou, Z. and Agyekum, E.O. (2022). Enhancing climate change adaptation and mitigation actions on land in Africa. Future Ecosystems for Africa (FEFA), University of the Witwatersrand. https://futureecosystemsafrica.org/report/Land-Evidence-Base.pdf

Ateba, B.B. and Prinsloo, J.J. (2018). The electricity security in South Africa: Analysing significant determinants to the grid reliability. International Journal of Energy Economics and Policy 8(6), 70–79. https://www.econjournals.com/index.php/ijeep/article/view/6864

Atteridge, A., Bhatpuria, D., Macura, B., Barquet, K. and Green, J. (2022). Assessing finance for nature-based solutions to climate change. Stockholm Environment Institute. https://www.sei.org/wp-content/uploads/2022/11/sei-wp-assessing-finance-nature-based-solutions-2022.pdf

Balgehshiri, S.K.M. and Zohuri, B. (2023). The impact of energy transition to net-zero emissions on the world economy and global strategies. Journal of Economics & Management Research 4, 185, 2-7. https://www.onlinescientificresearch.com/articles/the-impact-of-energy-transition-to-netzero-emissions-on-thenbspworld-economy-and-global-strategies.pdf

Bedasa, Y. (2023). Is Africa's food insecurity linked to land use coverage, irrigation adoption and water scarcity? Irrigation Drainage 73(1), 334-345. . https://doi.org/10.1002/ird.2873

Bjornlund, V., Bjornlund, H. and van Rooyen, A.F. (2020). Exploring the factors causing the poor performance of most irrigation schemes in post-independence sub-Saharan Africa. International Journal of Water Resources Development, 36(1), S54-S101. https://doi.org/10.1080/07900627.2020.1808448

Blimpo, M.P., Dato, P., Mukhaya, B. and Odarno, L. (2024). Climate change and economic development in Africa: A systematic review of energy transition modeling research. Energy Policy 187, 114044. https://doi.org/10.1016/j.enpol.2024.114044

Brears, R.C. (2022). Extended case studies of financing nature-based solutions. In: Financing Nature-Based Solutions: Exploring Public, Private, and Blended Finance Models and Case Studies, 241-263. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-93325-8_11

Cáceres, A.L., Jaramillo, P., Matthews, H.S., Samaras, C. and Nijssen, B. (2022). Potential hydropower contribution to mitigate climate risk and build resilience in Africa. Nature Climate Change, 12(8), 719-727. https://doi.org/10.1038/s41558-022-01413-6

Cattaneo, A., Sánchez, M.V., Torero, M. and Vos, R. (2021). Reducing food loss and waste: Five challenges for policy and research. Food Policy 98, 101974. https://doi.org/10.1016/j.foodpol.2020.101974

Cotterman, T., Small, M.J., Wilson, S., Abdulla, A. and Wong-Parodi, G. (2021). Applying risk tolerance and sociotechnical dynamics for more realistic energy transition pathways. Applied Energy 291, 116751. https://doi.org/10.1016/j.apenergy.2021.116751

DeClerck, F.A.J., Koziell, I., Benton, T., Garibaldi, L.A., Kremen, C., Maron, M. et al. (2023). A whole earth approach to nature-positive food: Biodiversity and agriculture. In: Science and Innovations for Food Systems Transformation. Cham: Springer. https://doi.org/10.1007/978-3-031-15703-5_25

Deutch, J. (2020). Is net-zero carbon 2050 possible? Joule 4, 2237-2242. https://doi.org/10.1016/j.joule.2020.09.002

Du Plessis, W. (2015). Energy efficiency and the law: A multidisciplinary approach. South African Journal of Science 111(1-2), 01-08. https://doi.org/10.17159/sajs.2015/20130302

Economic Commission for Africa (2020a). Greening Africa's Industrialization. Addis Ababa, Ethiopia. https://www.uneca.org/sites/default/files/fullpublicationfiles/era-2016_eng_rev6may.pdf

Economic Commission for Africa (2020b). Innovative Finance for Private Sector Development in Africa Development in Africa. Economic Report on Africa 2020. https://repository.uneca.org/handle/10855/43834

Economic Commission for Africa (2023). Circular economy: Slow transition by member states despite EU action. Special Report 2023. https://www.eca.europa.eu/ECAPublications/SR-2023-17/SR-2023-17_EN.pdf

Ezeh, E.M., Agu, P.C. (2025). Constructive evaluation of recent trends in bioenergy transition dynamics in Africa. Discover Energy 5, 29. https://doi.org/10.1007/s43937-025-00090-8

Fintech Global (2022). FinTech Funding in Africa is on track to decline in 2022. https://fintech.global/2022/06/17/fintech-funding-in-africa-is-on-track-to-decline-in-2022

Food and Agriculture Organization of the United Nations (2023). Agro informatics. "Digital in action" at WSIS forum 2023: FAO takes stock in agri-food systems transformation for SDGs achievement. https://www.fao.org/agroinformatics/news/news-detail/digital-in-action-at-wsis-forum-2023-fao-takes-stock-in-agrifood-systems-transformation-for-sdgs-achievement/en

Food and Agriculture Organization of the United Nations (2020). Global Forest Resources Assessment 2020: Main report. Rome, Italy: FAO. https://doi.org/10.4060/ca8753en

Forster, P., Huppmann, D., Kriegler, E., Mundaca, L., Smith, C., Rogelj, J., & Séférian, R. (2018). Mitigation pathways compatible with 1.5°C in the context of sustainable development supplementary material. In V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, & P. R. Shukla (Eds.), Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. https://www.ipcc.ch/sr15

Fredriksson, P.G. and Gupta, S.K. (2023). Irrigation and gender roles. Journal of Development Economics, 163, 103076. https://doi.org/10.1016/j.jdeveco.2023.103076

Galbert, J. and Olinga, O. (2023). Agricultural productivity and climate change: Evidence of a non-linear relationship in sub-Saharan Africa. https://mpra.ub.uni-muenchen.de/117669/1/agricultural per cent20productivity per cent20and per cent20climate per cent20change per cent20in per cent20Sub-Saharan per cent20Countries.pdf

Global Wind Energy Council (2019). Global wind report. Brussels, Belgium. Available at: https://gwec.net/wp-content/uploads/2020/08/Annual-Wind-Report_2019_digital_final_2r.pdf

Global Panel on Agriculture and Food Systems for Nutrition (GPAFSN) (2020). Future food systems: For people, our planet and prosperity. Global Panel on Agriculture and Food Systems for Nutrition. London, UK. https://foresight.glopan.org/

Hafner, S., Jones, A. and Anger-Kraavi, A. (2021). Economic impacts of achieving a net-zero emissions target in the power sector. Journal of Cleaner Production 312, 127610. https://doi.org/10.1016/j.jclepro.2021.127610

Haughey, E., Neogi, S., Portugal-Pereira, J., van Diemen, R. and Slade, R.B. (2023). Sustainable intensification and carbon sequestration research in agricultural systems: A systematic review. Environmental Science & Policy 143, 14-23. https://doi.org/10.1016/j.envsci.2023.02.018

Herrero, M., Hugas, M., Lele, U., Wirakartakusumah, A. and Torero, M. (2023). A shift to healthy and sustainable food systems. Nature Food 4(1), 1-8. https://doi.org/10.1038/s43016-022-00615-4

Intergovernmental Panel on Climate Change (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (eds.). Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009157896

Intergovernmental Panel on Climate Change (2023). Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. https://www.cambridge.org/core/product/161F238F406D530891AAAE1FC76651BD

International Energy Agency (2019). The future of hydrogen: Seizing the opportunities. International Energy Agency. Available at: https://www.iea.org/reports/the-future-of-hydrogen

International Energy Agency (2020). Climate Impacts on African Hydropower. Paris: Interantional Energy Agency. https://www.iea.org/reports/climate-impacts-on-african-hydropower

International Energy Agency (2020). Climate Impacts on African Hydropower. Paris: International Energy Agency. https://www.iea.org/reports/climate-impacts-on-african-hydropower

International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, World Bank, and World Health Organization (2020). 2020 Tracking SDG7 Report. https://trackingsdg7.esmap.org/downloads.

International Renewable Energy Agency (2021). World energy transitions outlook: 1.5 degrees pathway. https://irena.org/publications/2021/March/World-Energy-Transitions-Outlook

IPBES (2018). Summary for Policymakers of the Assessment Report on Biodiversity and Ecosystem Services for Africa. Archer, E., Dziba, L.E., Mulongoy, K.J., Maoela, M.A., Walters, M., Biggs, R. et al. (eds.). Bonn, Germany: IPBES Secretariat. https://doi.org/10.5281/zenodo.3236189

Kelemu, S., Niassy, S., Torto, B., Fiaboe, K., Affognon, H., Tonnang, H., Maniania, N.K. and Ekesi, S. (2015). African edible insects for food and feed: Inventory, diversity, commonalities and contribution to food security. Journal of Insects as Food and Feed 1(2), 103-119. https://doi.org/10.3920/JIFF2014.0016

Khanna, M., Rajagopal, D. and Zilberman, D. (2021). Lessons learnt from experience with biofuels: Comparing hype with evidence. Review of Environmental Economics and Policy 15(1), 92-112. https://doi.org/10.1086/713026

Kouton, J. (2021). The impact of renewable energy consumption on inclusive growth: Panel data analysis in 44 African countries. Economic Change and Restructuring 54(1), 145-165. https://doi.org/10.1007/s10644-020-09263-3

Lefèvre, B. and Mainbuy, G. (2009). Urban transport energy consumption: Determinants and strategies for its reduction. Surveys and Perspectives Integrating Environment and Society 2(3), 1-14. https://journals.openedition.org/sapiens/914

Lokotola, C.L., Mash, R., Naidoo, K., Mubangizi, V., Mofolo, N. and Schwerdtle, P.N. (2023). Climate change and primary health care in Africa: A scoping review. The Journal of Climate Change and Health 11, 100229. https://doi.org/10.1016/j.joclim.2023.100229

Ludwig, K. (2021). Financing nature-based solutions: Overview of relevant finance options. Adelphi. https://snrd-asia.org/wp-content/uploads/2021/11/Module-4_Financing-NbS.pdf

Manjong, N.B., Oyewo, A.S. and Breyer, C. (2021). Setting the pace for a sustainable energy transition in Central Africa: The case of Cameroon. IEEE Access 9, 145435-145453. https://doi.org/10.1109/ACCESS.2021.3121000

Matandirotya, N.R., Filho, W.L., Mahed, G., Maseko, B. and Murandu, C.V. (2022). Edible Insects Consumption in Africa towards Environmental Health

and Sustainable Food Systems: A Bibliometric Study. International Journal of Environmental Research and Public Health 19(22), 14823. https://doi.org/10.3390/ijerph192214823

Maupin, A. (2017). The SDG13 to combat climate change: An opportunity for Africa to become a trailblazer? African Geographical Review 36(2), 131-148. https://doi.org/10.1080/19376812.2016.1171156

McMillan, M. and Zeufack, A. (2022). Labor productivity growth and industrialization in Africa. Journal of Economic Perspectives 36(1), 3-32. https://doi.org/10.1257/jep.36.1.3

Mehra, D., Rael, T. and Bloem, M.W. (2024). A review of the intersection between climate change, agriculture, health, and nutrition in Africa: costs and programmatic options. Frontiers in Sustainable Food Systems 8. https://doi.org/10.3389/fsufs.2024.1389730

Mohammedshum, A.A., Mannaerts, C.M., Maathuis, B.H. and Teka, D. (2023). Integrating socioeconomic, biophysical, and institutional factors for evaluating small-scale irrigation schemes in Northern Ethiopia. Sustainability, 15(2), 1704. https://doi.org/10.3390/su15021704

Mrabet, R. and Moussadek, R. (2022). Climate smart agriculture development in Africa. In: Mkomwa, S. and Kassam, A. (eds.). Conservation Agriculture in Africa: Climate Smart Agricultural Development. CABI publisher, 17-65. https://doi.org/10.1079/9781789245745.0002

Mutezo, G. and Mulopo, J. (2021). A review of Africa's transition from fossil fuels to renewable energy using circular economy principles. Renewable and Sustainable Energy Reviews 137, 110609. https://doi.org/10.1016/j.rser.2020.110609

Mutumbi, U., Thondhlana, G. and Ruwanza, S. (2022). Co-designed interventions yield significant electricity savings among low-income households in Makhanda, South Africa. Energies 15(7), 2320. https://doi.org/10.3390/en15072320

Ngondjeb, D.Y., Atewamba, C. and Macalou, M. (2020). Insights on Africa's future in its transition to the green economy. In: Advances in African Economic, Social, and Political Development. https://doi.org/10.1007/978-3-030-44180-7_13

Nkuba, M., Chanda, R., Mmopelwa, G., Kato, E., Mangheni, M.N. and Lesolle, D. (2019). The effect of climate information in pastoralists' adaptation to climate change. International Journal of Climate Change Strategies and Management 11(4), 442-464. https://doi.org/10.1108/IJCCSM-10-2018-0073.

Nwokolo, S.C., Singh, R., Khan, S., Kumar, A. and Luthra, S. (2023). Africa's Path to Net-Zero: Exploring Scenarios for a Sustainable Energy Transition. Springer Cham. https://doi.org/10.1007/978-3-031-44514-9

Obiwulu, A.U., Erusiafe, N., Olopade, M.A. and Nwokolo, S.C. (2022). Modelling and estimation of the optimal tilt angle, maximum incident solar radiation, and global radiation index of the photovoltaic system. Heliyon 8(6), e09598. https://doi.org/10.1016/j.heliyon.2022.e09598

Organization for Economic Cooperation and Development (2023). Environment at a glance indicators: Circular economy - Waste and materials. https://www.oecd.org/environment/environment-at-a-glance/Environment per cent20at per cent20a per cent20Glance per cent20Indicators per cent20Circular per cent20economy per cent20waste per cent20and per cent20materials per cent20Q2.pdf

OECD, AUC and ATAF (2024). Revenue Statistics in Africa 2024: Facilitation and Trust as Drivers of Voluntary Tax Compliance in Selected African Tax Administrations. Paris: OECD Publishing. https://doi.org/10.1787/78e9af3a-en

Olson, K. and Omoyajowo, K. (2025). Africa's Hydropower Lifeline: The Congo River. Open Journal of Soil Science 15, 173-198. https://doi.org/10.4236/ojss.2025.153009

Peng, J., Shi, X. and Tong, X. (2023). Extended producer responsibility for low carbon transition in automobile industry. Circular Economy 2(2), 100036. https://doi.org/10.1016/j.cec.2023.100036

Peters, R., Berlekamp, J., Kabiri, C., Kaplin, B.A., Tockner, K. and Zarfl, C. (2024). Sustainable pathways towards universal renewable electricity access in Africa. Nature Reviews Earth & Environment 5(2), 137-151. https://doi.org/10.1038/s43017-023-00501-1

Popoola, J.O., Ojuederie, O.B., Aworunse, O.S., Adelekan, A., Oyelakin, A.S., Oyesola, O.L. et al. (2023). Nutritional, functional, and bioactive properties of African underutilized legumes. Frontiers in Plant Science 14. https://doi.org/10.3389/fpls.2023.1105364

Saba, C.S., Djemo, C.R.T., Eita, J.H. and Ngepah, N. (2023). Towards environmental sustainability path in Africa: The critical role of ICT, renewable energy sources, agriculturalization, industrialization and institutional quality. Energy Reports 10, 4025-4050. https://doi.org/10.1016/j.egyr.2023.10.039

Smith, P., Reay, D. and Smith, J. (2021). Agricultural methane emissions and the potential for mitigation. Philosophical Transactions of the Royal Society A 379(2210), 20200451. https://doi.org/10.1098/rsta.2020.0451

Toromade, A.S., E. Kupa, T. I. Ijomah and D. A. Soyombo. (2024). Technological innovations in agricultural bioenergy production: A concept paper on future pathways. Research Journal of Life Sciences 08(01), 001–008. https://doi.org/10.530

The African Union Commission (2015). Agenda 2063: The Africa we Want. Framework Document. https://au.int/sites/default/files/documents/33126-doc-framework_document_book.pdf

United Nations Environment Programme (2019). The role of packaging regulations and standards in driving the circular economy. https://www.unep.org/resources/report/role-packaging-regulations-and-standards-driving-circular-economy

United Nations Environment Programme (2022). Plastics Science. https://wedocs.unep.org/bitstream/handle/20.500.11822/41263/Plastic_Science_E.pdf

United Nations Environment Programme (2023). Africa Environment Outlook for Business. https://www.unep.org/resources/report/africa-environment-outlook-business

United Nations Environment Programme (2023). Global Sustainable Development Report 2023 Times of crisis, times of change: Science for accelerating transformations to sustainable development. United Nations, New York. https://sdgs.un.org/sites/default/files/2023-09/FINAL%20GSDR%202023-Digital%20-110923_1.pdf

Van Huis, A. (2015). Edible insects contributing to food security? Agriculture & Food Security 4, 1-9. https://doi.org/10.1186/s40066-015-0041-5

Van Huis, A. and Oonincx, D.G. (2017). The environmental sustainability of insects as food and feed: A review. Agronomy for Sustainable Development 37, 1-14. https://doi.org/10.1007/s13593-017-0452-8

Vogel, C., Steynor, A. and Manyuchi, A. (2019). Climate services in Africa: Re-imagining an inclusive, robust and sustainable service. Climate Services 15, 100107. https://doi.org/10.1016/j.cliser.2019.100107

World Economic Forum (2022). Growing Intra-African Trade through Digital Transformation of Border and Customs Services: Regional Action Group for Africa. World Economic Forum. https://www.weforum.org/publications/growing-intra-africa-trade-through-digital-transformation-of-customs-and-borders

Zhang, X. (2024). Sustainable development in African countries: evidence from the impacts of education and poverty ratio. Humanities and Social Sciences Communications 11(1), 1386. https://doi.org/10.1057/s41599-024-03912-7

Asia and the Pacific Region

Adebayo, T., Genç, S., Castanho, R. and Kırıkkaleli, D. (2021). Do Public–Private Partnership Investment in Energy and Technological Innovation Matter for Environmental Sustainability in the East Asia and Pacific Region? An Application of a Frequency Domain Causality Test. Sustainability 13(6), 3039. https://doi.org/10.3390/SU13063039

Andeobu, L., Wibowo, S. and Grandhi, S. (2021). A Systematic Review of E-Waste Generation and Environmental Management of Asia Pacific Countries. International Journal of Environmental Research and Public Health 18(17), 9051. https://doi.org/10.3390/ijerph18179051

Asian Development Bank (2017a). Meeting Asia's Infrastructure Needs. Mandaluyong, Philippines: Asian Development Bank. http://dx.doi.org/10.22617/FLS168388-2

Asian Development Bank (2017b). Sustainable Land Management in Asia: Introducing the Landscape Approach. Mandaluyong, Philippines: Asian Development Bank. https://www.adb.org/sites/default/files/publication/224336/landscape-land-mgt.pdf

Asian Development Bank (2020). Internal Migration, Urbanization, and Poverty in Asia: Dynamics and Interrelationships. Mandaluyong, Philippines: Asian Development Bank. https://doi.org/10.1007/978-981-13-1537-4

Asian Development Bank (2023a). ASEAN and Global Value Chains: Locking in Resilience and Sustainability. Mandaluyong, Philippines: Asian Development Bank. http://dx.doi.org/10.22617/SPR230100-2

Asian Development Bank (2023b). Asia in the Global Transition to Net Zero: Thematic Report of the Asian Development Outlook 2023. Mandaluyong, Philippines: Asian Development Bank. http://dx.doi.org/10.22617/SPR230100-2

Asian Development Bank (2024). Asia and the Pacific SDG Partnership Report. People and Planet: Addressing the Interlinked Challenges of Climate Change, Poverty and Hunger in Asia and the Pacific. Mandaluyong, Philippines: Asian Development Bank. http://dx.doi.org/10.22617/SPR240043-2

Asian Infrastructure Investment Bank (2022). The Seventh Annual Meeting of the Board of Governors: Summary of Proceedings. Beijing: Asian Infrastructure Investment Bank. https://www.aiib.org/en/about-aiib/governance/board-governors/.content/index/_download/Gov2023-003-Summary-of-Proceedings-of-the-Seventh-Annual-Meeting-of-AIIB-Board-of-Governors-2022.pdf

Asian Infrastructure Investment Bank (2023). The Eighth Annual Meeting of the Board of Governors: Summary of Proceedings. Beijing: Asian Infrastructure Investment Bank. https://www.aiib.org/en/about-aiib/governance/board-governors/.content/index/_download/Gov2023-025-Summary-of-Proceedings-of-the-Eighth-Annual-Meeting-of-the-AIIB-Board-of-Governors-2023.pdf

Asif, M., Khan, M.I. and Pandey, A. (2024). Navigating the inclusive and sustainable energy transitions in South Asia: Progress, priorities and stakeholder perspectives. Energy Conversion and Management 313, 118589. https://doi.org/10.1016/j.enconman.2024.118589

Association of Southeast Asian Nations (2023). Sixth ASEAN State of the Environment Report. Jakarta: Association of Southeast Asian Nations Secretariat. https://asean.org/wp-content/uploads/2023/09/SOER6_Layout_0920_ISSN_sent.pdf

Azhgaliyeva, D., Kapoor, A. and Liu, Y. (2019). Green bonds for financing renewable energy and energy efficiency in South-East Asia: a review of policies. Journal of Sustainable Finance & Investment 10(2), 113-140. https://doi.org/10.1080/20430795.2019.1704160

Azimov, U. and Avezova, N. (2022). Sustainable small-scale hydropower solutions in Central Asian countries for local and cross-border energy/water supply. Renewable and Sustainable Energy Reviews 167, 112726. https://doi.org/10.1016/j.rser.2022.112726

Bianco, C. (2021). Power play: Europe's climate diplomacy in the Gulf. European Council on Foreign Relations. https://ecfr.eu/publication/power-play-europes-climate-diplomacy-in-the-gulf

Congreves, K.A., Otchere, O., Ferland, D., Farzadfar, S., Williams, S. and Arcand, M.M. (2021). Nitrogen Use Efficiency Definitions of Today and Tomorrow. Frontiers in Plant Science 12, 637108. https://doi.org/10.3389/fpls.2021.637108

CIMMYT (2019). Conservation agriculture works for farmers and for sustainable intensification, May 30 2019; https://www.cimmyt.org/news/conservation-agriculture-works-for-farmers-and-for-sustainable-intensification/https://www.cimmyt.org/news/conservation-agriculture-works-for-farmers-and-for-sustainable-intensification/

Food Agriculture Organization of the United Nations (2021). The State of Food Security and Nutrition in the World 2021: Transforming Food Systems for Food Security, Improved Nutrition and Affordable Healthy Diets for All. Rome: Food and Agriculture Organization. https://doi.org/10.4060/cb4474en

Food Agriculture Organization of the United Nations (2022a). Asia and the Pacific roadmap for primary forest conservation. Rome: Food and Agriculture Organization. https://doi.org/10.17528/cifor/008539

Food Agriculture Organization of the United Nations (2022b). Record fisheries and aquaculture production makes critical contribution to global food security. https://www.fao.org/newsroom/detail/record-fisheries-aquaculture-production-contributes-food-security-290622/en

Food Agriculture Organization of the United Nations (2022c). The State of World Fisheries and Aquaculture 2022: Towards Blue Transformation. Rome: Food and Agriculture Organization. https://doi.org/10.4060/cc0461en

Food Agriculture Organization of the United Nations (2023a). Aquaculture Transformation – Innovation and Investment for Sustainable Intensification and Expansion of Aquaculture in Asia and the Pacific Region. Bangkok: Food and Agriculture Organization. https://doi.org/10.4060/cc4962en

Food Agriculture Organization of the United Nations (2023b). Forest and landscape restoration in Asia and the Pacific, Thirtieth Session. Sydney: Food and Agriculture Organization. https://www.fao.org/3/cc7012en/cc7012en.pdf

Francis, A.E. (2020). Plastic Waste Management in Asia Pacific Region: Issues and Challenges. Environment and Ecology 38(3). https://environmentandecology.com/wp-content/uploads/2024/09/MS6-8.pdf

Giller, K.E., Delaune, T., Silva, J.V., Descheemaeker, K., van de Ven, G. and Schut, A.G. (2021). The future of farming: Who will produce our food? Food Security 13, 1073-1099. https://doi.org/10.1007/s12571-021-01184-6

German Agency for International Cooperation (GIZ) (2024). Report on Ecosystem-based Adaptation (EbA) and Nature-based Insurance Solutions (NbIS) in the Philippines and Asia. https://www.giz.de/en/downloads_els/GIZ-report-EbA-NbIS-Philippines-Asia-2024.pdf

Gould, C.F., Hou, X., Richmond, J., Sharma, A. and Urpelainen, J. (2020). Jointly modeling the adoption and use of clean cooking fuels in rural India. Environmental Research Communications 2(8), 085004. https://doi.org/10.1088/2515-7620/abaca9

Hamelin, N. and Bhatti, I.M. (2023). Energy usage, health issues, and pro-environmental behaviour: Exploring the link and promoting energy change in Kyrgyzstan. Energies 16(19), 6858.. https://doi.org/10.3390/en16196858

Herat, S. (2021). E-Waste Management in Asia Pacific Region: Review of Issues, Challenges and Solutions. Nature Environment and Pollution Technology 20(1), 45-53.. https://doi.org/10.46488/NEPT.2021.v20i01.005

Intergovernmental Panel on Climate Change (2022). Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge University Press. 321-445. https://doi.org/10.1017/9781009157964.006

Intergovernmental Panel on Climate Change (2023). Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009325844

International Energy Agency (2021). Do we need to change our behaviour to reach net zero by 2050? International Energy Agency. https://www.iea.org/articles/do-we-need-to-change-our-behaviour-to-reach-net-zero-by-2050

International Energy Agency (2022a). Global EV Outlook 2022: Securing supplies for an electric future. Paris: International Energy Agency. https://iea.blob.core.windows.net/assets/ad8fb04c-4f75-42fc-973a-6e54c8a4449a/GlobalElectricVehicleOutlook2022.pdf

International Energy Agency (2022b). Southeast Asia Energy Outlook 2022. Paris: International Energy Agency. https://iea.blob.core.windows.net/assets/e5d9b7ff-559b-4dc3-8faa-42381f80ce2e/SoutheastAsiaEnergyOutlook2022.pdf

International Energy Agency (2022c). Special Report on Solar PV Global Supply Chains. Paris: International Energy Agency. https://iea.blob.core.windows.net/assets/d2ee601d-6b1a-4cd2-a0e8-db02dc64332c/SpecialReportonSolarPVGlobalSupplyChains.pdf

International Energy Agency (2023). The World Energy Outlook 2023. https://iea.blob.core.windows.net/assets/ed1e4c42-5726-4269-b801-97b3d32e117c/WorldEnergyOutlook2023.pdf

International Monetary Fund (2024). Unlocking climate finance in Asia and the Pacific: Transitioning to a sustainable future. https://www.imf.org/en/Publications/Departmental-Papers-Policy-Papers/Issues/2024/01/29/Unlocking-Climate-Finance-in-Asia and the Pacific-Transitioning-to-a-Sustainable-Future-541458

International Renewable Energy Agency (2022). Renewable Energy Outlook for ASEAN: Towards a Regional Energy Transition. Abu Dhabi: International

Renewable Energy Agency. https://www.irena.org//media/Files/IRENA/Agency/Publication/2022/Sep/IRENA_Renewable_energy_outlook_ASEAN_2022.pdf

International Renewable Energy Agency (2023). Socio-economic footprint of the energy transition: Southeast Asia. Abu Dhabi: International Renewable Energy Agency. https://www.irena.org//media/Files/IRENA/Agency/Publication/2023/Jul/IRENA_Socioeconomic-footprint_energy_transition_SE_Asia_2023.pdf

Kazimierczuk, K., Henderson, C., Duffy, K., Hanif, S., Bhattacharya, S., Biswas, S. et al. (2023). A socio-technical assessment of marine renewable energy potential in coastal communities. Energy Research & Social Science 100, 103098. https://doi.org/10.1016/j.erss.2023.103098

KPMG Asia Pacific (2022). Decarbonization through renewable energy: Understanding Asia Pacific's Corporate Power Purchase Agreement landscape. Beijing, China: KPMG Asia. https://assets.kpmg.com/content/dam/kpmg/xx/pdf/2022/10/decarbonization-through-renewable-energy.pdf

Malik, A.Q. (2021). Renewables for Fiji – Path for green power generation. Renewable and Sustainable Energy Reviews 149, 111374. https://doi.org/10.1016/j.rser.2021.111374

Nkonya, E., Mirzabaev, A. and Von Braun, J. (2016). Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development. Springer Nature. https://link.springer.com/book/10.1007/978-3-319-19168-3

Ofanoa, M., Percival, T., Huggard, P., & Buetow, S. (2015). Talanga: the Tongan way enquiry. Sociology Study 5(4), 334-340. https://doi.org/10.17265/2159-5526/2015.04.009

Organization for Economic Co-operation Development (2021). Towards a more resource-efficient and circular economy: the role of the G20. Italy: Organisation for Economic Co-operation and Development. https://www.oecd.org/environment/waste/OECD-G20-Towards-a-more-Resource-Efficient-and-Circular-Economy.pdf

Pandey, A. and Asif, M. (2022). Assessment of energy and environmental sustainability in South Asia in the perspective of the Sustainable Development Goals. Renewable and Sustainable Energy Reviews 165, 112492. https://doi.org/10.1016/j.rser.2022.112492.

Park, S., Owens, K., Summerfield-Ryan, O., Taylor, M., Ulloa, A.M. and Viney, G. (2023). How can pacific island countries meet their nationally determined contributions? NPJ Climate Action 2, 23. https://doi.org/10.1038/s44168-023-00059-0

Peng, J., Shi, X. and Tong, X. (2023). Extended producer responsibility for low carbon transition in automobile industry. Circular Economy 2(2), 100036. https://doi.org/10.1016/j.cec.2023.100036

Prasad, M. and Prasad, R. (2023). Bifacial vs monofacial grid-connected solar photovoltaic for small islands: A case study of Fiji. Renewable Energy 203, 686-702. https://doi.org/10.1016/j.renene.2022.12.068

Rieckmann, M. (2018). Key themes in education for sustainable development. In Issues and trends in education for sustainable development. United Nations Educational, Scientific and Cultural Organization. https://unesdoc.unesco.org/ark:/48223/pf0000261803

Sharma, A., Parikh, J. and Singh, C. (2019). Transition to LPG for cooking: A case study from two states of India. Energy for Sustainable Development 51, 63-72. https://doi.org/10.1016/j.esd.2019.06.001

Skalamera, M. (2024). The varying levels of contrasting adaptation in Central Asia's climate change politics. Central Asian Survey 44(1), 85-104. https://doi.org/10.1080/02634937.2024.2373086

Song, C., Wu, Z., Dong, R.K. and Dinçer, H. (2023). Greening South Asia: Investing in sustainability and innovation to preserve natural resources and combat environmental pollution. Resources Policy 86, 104239. https://doi.org/10.1016/j.resourpol.2023.104239

Taylor, M. and Taylor, S. (2022). Applying energy justice principles: a case study of solar energy in Vanuatu. The Journal of World Energy Law & Business 15(3), 193-211. https://doi.org/10.1093/jwelb/jwac003

Townsend, R., Lampietti, J., Treguer, D., Schroeder, K., Haile, M. and Juergenliemk, A. (2019). Future of Food: Harnessing Digital Technologies to Improve Food System Outcomes. Washington, DC: The World Bank. https://openknowledge.worldbank.org/server/api/core/bitstreams/fc90a957-badf-5071-8855-3ab596b884c7/content

United Nations (2022a). 2022 Review of Climate Ambition in Asia and the Pacific: Raising NDC targets with enhanced nature-based solutions. New York: United Nations. https://www.unicef.org/eap/media/12896/file/ESCAP-2022-RP-2022-Review-Climate-Ambition-Asia and the Pacific.pdf

United Nations (2022b). Long-term low-emission development strategies. Sharm el-Sheikh: United Nations. https://unfccc.int/sites/default/files/resource/cma_2022_08.pdf

United Nations (2022c). Opportunities for reaching carbon neutrality in the Asia and the Pacific region: Economic and Social Commission for Asia and the Pacific. Bangkok: United Nations. https://www.unescap.org/sites/default/d8files/event-documents/ESCAP_78_11_E_.pdf

United Nations (2022d). The Sustainable Development Goals Report 2022. New York: United Nations Statistics Division. https://unstats.un.org/sdgs/report/2022/The-Sustainable-Development-Goals-Report-2022.pdf

United Nations (2024). The Sustainable Development Goals Report 2024. New York: United Nations Statistics Division. https://unstats.un.org/sdgs/report/2024/The-Sustainable-Development-Goals-Report-2024.pdf

United Nations Convention to Combat Desertification (2022). Global Land Outlook, second edition. Bonn: United Nations Convention to Combat Desertification. https://www.unccd.int/sites/default/files/2022-04/UNCCD_GLO2_low-res_2.pdf

United Nations Development Programme (2022a). Human Development Reports 2021/2022. New York: United Nations Development Programme. https://hdr.undp.org/system/files/documents/global-report-document/hdr2021-22pdf_1.pdf

United Nations Economic and Social Commission for Asia and the Pacific (2018). Key environment issues, trends and challenges in the Asia and the Pacific region. Bangkok: United Nations Economic and Social Commission for Asia and the Pacific. https://www.unescap.org/sites/default/files/CED5_1E_0.pdf

United Nations Economic and Social Commission for Asia and the Pacific (2019). Circular economy – Making sustainability part of the solution in Asia and the Pacific. https://www.unescap.org/blog/circular-economy-making-sustainability-part-the-solution-Asia and the Pacific

United Nations Economic and Social Commission for Asia and the Pacific (2022). Asia and the Pacific Digital Transformation Report 2022: Shaping Our Digital Future. Bangkok: United Nations Economic and Social Commission for Asia and the Pacific. https://www.unescap.org/kp/2022/Asia and the Pacific-digital-transformation-report-2022-shaping-our-digital-future

United Nations Economic and Social Commission for Asia and the Pacific (2023). Asia and the Pacific SDG Progress Report 2023: Championing sustainability despite adversities. New York: United Nations Economic and Social Commission for Asia and the Pacific. https://repository.unescap.org/bitstream/handle/20.500.12870/5279/ESCAP-2023-FS-SDG-Progress-Report.pdf

United Nations Economic and Social Commission for Asia and the Pacific (2024). Asia and the Pacific SDG progress report 2024. United Nations Publication. https://www.sdgbrunei.gov.bn/media/t30fl2ph/escap-2024-fs-ap-sdg-progress.pdf

United Nations Economic and Social Commission for Western Asia (2022). SDG 7 in Arab region. https://www.unescwa.org/publications/advancing-sdg-7-arab-region

United Nations Economic Social Commission for Asia and the Pacific (2012). Low Carbon Green Growth Roadmap for Asia and the Pacific: Decentralized Energy System. Bangkok: United Nations Economic and Social Commission for Asia and the Pacific. https://www.unescap.org/sites/default/files/14. per cent20FS-Decentralized-energy-system.pdf

United Nations Educational, Scientific and Cultural Organization (2023). Asia and the Pacific Regional Synthesis: Climate Change, Displacement and the Right to Education. Paris: United Nations Educational, Scientific and Cultural Organization. https://unesdoc.unesco.org/ark:/48223/pf0000385187

United Nations Environment Programme (2022a). Action Plan for the UN Decade on Ecosystem Restoration, 2021-2030. United Nations Environment Programme and Food and Agriculture Organization. https://wedocs.unep.org/20.500.11822/40514

United Nations Environment Programme (2022b). Net-Zero Carbon Scenarios for the Energy Sector in West Asia. Nairobi: United Nations Environment Programme. https://wedocs.unep.org/20.500.11822/41153

United Nations Environment Programme (2023). 2050 Electronic and Electrical Waste Outlook in West Asia. Nairobi: United Nations Environment Programme. https://wedocs.unep.org/20.500.11822/42147

United Nations Framework Convention on Climate Change (2023). Summary of Global Climate Action at COP 28. New York: United Nations Framework Convention on Climate Change. https://unfccc.int/sites/default/files/resource/Summary_GCA_COP28.pdf

Yang, M., Chen, L., Wang, J., Msigwa, G., Osman, A.I. and Fawzy, S. (2023). Circular economy strategies for combating climate change and other environmental issues. Environmental Chemistry Letters 21, 55-80. https://doi.org/10.1007/s10311-022-01499-6

Zakeri, B., Hunt, J.D., Laldjebaev, M., Krey, V., Vinca, A., Parkinson, S. et al. (2022). Role of energy storage in energy and water security in Central Asia. Journal of Energy Storage 50, 104587. https://doi.org/10.1016/j.est.2022.104587

Eastern European Region

Barseghyan, A. (2023). Sustainable Development in Armenia: Learning From the EU. EVN Report. https://evnreport.com/economy/sustainable-development-in-armenia-learning-from-the-eu/

Bashmakov, I. (2023). Climate change: Russian myth and the global Science. CENEV-XXI. https://cenef-xxi.ru/uploads/Russia_LTS_933fc7e0df.pdf

Bitsadze, R. (2023). EBRD and EU promote circular economy in Azerbaijan. European Bank for Reconstruction and Development, https://www.ebrd.com/news/2023/ebrd-and-eu-promote-circular-economy-in-azerbaijan.html

Bockarjova, M., Botzen, W.J.W., Bulkeley, H.A. and Toxopeus, H. (2022). Estimating the social value of nature-based solutions in European cities. Scientific Reports 12(1), 19833. https://doi.org/10.1038/s41598-022-23983-3

Bun, R., Marland, G., Oda, T., See, L., Puliafito, E., Nahorski, Z. et al. (2024). Tracking unaccounted greenhouse gas emissions due to the war in Ukraine since 2022. Science of The Total Environment 914, 169879. https://doi.org/10.1016/j.scitotenv.2024.169879

Climate Action Network Europe (2024). Future-Proofing Central Eastern European Grids for Tomorrow's Energy System. https://caneurope.org/content/uploads/2024/02/CAN-Europe_Future-Proofing-Central-Eastern-European-Grids.pdf

Resolution of the Council of Ministers of the Republic of Belarus dated May 29, 2024 No. 393 On the National Strategy for the Development of the Closed-Cycle Economy (Circular Economy) of the Republic of Belarus for the Period until 2035, 2024. https://pravo.by/document/?guid=12551&p0=C22400393

Elias, V. (2021). Advancing conservation and protecting biodiversity in the Russian Arctic. The Circle. https://apiwwfarcticse.cdn.triggerfish.cloud/uploads/2022/04/19173902/thecircle0421_low_res.pdf

Energy Monitor (2024). Energy transition in Russia. Energy Monitor, https://www.energymonitor.ai/data-insights/energy-transition-in-russia/?cf-view

EU4Environment (2022). National Program for Waste Management and National Waste Action Plan in Azerbaijan. https://www.eu4environment.org/app/uploads/2023/02/EU4Environment-call-for-expressions-of-interest-on-Waste-Management-Program-in-Azerbaijan-Final.pdf

European Academics Science Advisory Council (2022). Regenerative agriculture in Europe A critical analysis of contributions to European Union Farm to Fork and Biodiversity Strategies. www.easac.eu. https://easac.eu/fileadmin/PDF_s/reports_statements/Regenerative_Agriculture/EASAC_RegAgri_Web_290422.pdf.

European Commission (2021). Green infrastructure: Promoting the use of green infrastructure in all EU policies, to help restore nature and boost biodiversity. https://environment.ec.europa.eu/topics/nature-and-biodiversity/green-infrastructure_en

European Commission (2023a). Albania 2023 Report Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 2023 Communication on EU Enlargement policy. Brussels. https://neighbourhood-enlargement.ec.europa.eu/system/files/2023-11/SWD_2023_690%20Albania%20report.pdf

European Commission (2023b). Bosnia and Herzegovina 2023 Report. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 2023 Communication on EU Enlargement policy. Brussels. https://neighbourhood-enlargement.ec.europa.eu/system/files/2023-11/SWD_2023_691%20Bosnia%20and%20Herzegovina%20report.pdf

European Commission (2023c). North Macedonia 2023 Report. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 2023 Communication on EU Enlargement policy. Brussels. https://neighbourhood-enlargement.ec.europa.eu/system/files/2023-11/SWD_2023_693%20North%20Macedonia%20report.pdf

European Commission (2023d). Republic of Moldova 2023 Report. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 2023 Communication on EU Enlargement policy. Brussels. https://neighbourhood-enlargement.ec.europa.eu/system/files/2023-11/SWD_2023_698%20Moldova%20report.pdf

European Commission (2023e). Montenegro 2023 Report. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 2023 Communication on EU Enlargement policy. Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023SC0694

European Commission (2023f). Georgia 2023 Report. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 2023 Communication on EU Enlargement policy. Brussels. https://neighbourhood-enlargement.ec.europa.eu/system/files/2023-11/SWD_2023_697%20Georgia%20report.pdf

European Commission (2023g). Serbia 2023 Report. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 2023 Communication on EU Enlargement policy. Brussels. https://neighbourhood-enlargement.ec.europa.eu/system/files/2023-11/SWD_2023_695_Serbia.pdf

European Commission (2023h). Ukraine 2023 Report. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 2023 Communication on EU Enlargement policy. Brussels. https://neighbourhood-enlargement.ec.europa.eu/system/files/2023-11/SWD_2023_699%20Ukraine%20report.pdf

Commission Regulation (EU) 2023/2055 of 25 September 2023 amending Annex XVII to Regulation (EC) No 1907/2006 of the European Parliament and of the Council concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as regards synthetic polymer microparticles (Text with EEA relevance), 2023. http://data.europa.eu/eli/reg/2023/2055/oj

Commission Recommendation (EU) 2023/2407 of 20 October 2023 on energy poverty, 2023 (Commission, E.). http://data.europa.eu/eli/reco/2023/2407/oj

European Commission: Directorate-General for Environment (2020). Attitudes of Europeans towards the environment – Report. European Commission. https://doi.org/10.2779/902489

European Court of Auditors (2023). Circular economy – Slow transition by member states despite EU action. Special report 17, 2023. Publications Office of the European Union. https://www.doi.org/10.2865/36180

European Economic and Social Committee (2022). Food security and sustainable food systems. d'ALISSAC, A.P. (ed.). https://www.eesc.europa.eu/en/our-work/opinions-information-reports/opinions/food-security-and-sustainable-food-systems

European Environment Agency (2022). Air quality in Europe 2022 https://www.eea.europa.eu/publications/air-quality-in-europe-2022

European Environment Agency (2024a). Circular material use rate in Europe. https://www.eea.europa.eu/en/analysis/indicators/circular-material-use-rate-in-europe?activeAccordion=546a7c35-9188-4d23-94ee-005d97c26f2b Accessed: March 2025

European Environment Agency (2024b). Europe is not prepared for rapidly growing climate risks, 11 March. https://www.eea.europa.eu/en/newsroom/news/europe-is-not-prepared-for

European Environmental Bureau (2024). Green Solidarity: Guiding Principles for a Truly Just Social Climate Fund. Policy Brief. Brussels, Belgium: European Environmental Bureau. https://eeb.org/library/green-solidarity-guiding-principles-for-a-truly-just-social-climate-fund/

Eurostat (2022). Farms and farmland in the European Union – statistics. https://ec.europa.eu/eurostat/statistics-explained/SEPDF/cache/73319.pdf

Eurostat (2024). Renewable energy statistics. https://ec.europa.eu/eurostat/statisticsexplained/index.php?title=Renewable_energy_statistics2024

Garazha, O., Cherneha, I., Ulanchuk, V., Skus, O. and Nepochatenko, O. (2023). Agricultural Production in Eastern Europe: History, Current Status, and Prospects of the Development for Innovation Science and Innovation 19(2), 83-98. https://doi.org/10.15407/scine19.02.083

Gassiy, V. and Novikov, A. (2023). Circular economy for urban sustainable development: Recycling issues in Russia. E3S Web of Conferences 435, 01005. https://doi.org/10.1051/e3sconf/202343501005

Guillaume, L., Grayson, F., Leslie Bermont, D., Adolf, K.-L., Phoebe, K. and Angelo, R. (2022). Achieving the SDGs: Europe's Compass in a Multipolar World: Europe Sustainable Development Report 2022. Athens University of Economics and Business. https://ideas.repec.org/p/aue/wpaper/2235.html

Chan, S., Weitz, N., Persson, Å. and Trimmer, C. (2018). SDG 12: Responsible Consumption and Production A review of research needs. Technical Annex to the Formas report Forskning för Agenda 2030:

Översikt av forskningsbehov och vägar framåt. Stockholm: Stockholm Environment Institute. https://www.sei.org/wp-content/uploads/2018/11/sdg-12-responsible-consumption-and-production-review-of-research-needs.pdf

Chwialkowska, A. and Flicinska-Turkiewicz, J. (2021). Overcoming perceived sacrifice as a barrier to the adoption of green non-purchase behaviours. International Journal of Consumer Studies 45(2), 205-220. https://doi.org/10.1111/ijcs.12615

Intergovernmental Panel on Climate Change (2023). Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. https://www.cambridge.org/core/product/161F238F406D530891AAAE1FC76651BD

International Energy Agency (2021). Azerbaijan 2021 Energy Policy Review. IEA Energy Policy Reviews. Paris. https://doi.org/10.1787/90fa056d-en

International Energy Agency (2025). Energy system of Belarus. IEA Energy Policy Reviews. Paris. https://www.iea.org/countries/belarus2025

International Renewable Energy Agency (2023a). Energy Profile, Azerbaijan. https://www.irena.org/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Eurasia/Azerbaijan_Eurasia_RE_SP.pdf

International Renewable Energy Agency (2023b). Energy Profile, Russian Federation. https://www.irena.org/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Eurasia/Russian-Federation_Eurasia_RE_SP.pdf

International Renewable Energy Agency (2023c). Energy Profile, Ukraine. https://www.irena.org/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Europe/Ukraine_Europe_RE_SP.pdf

International Renewable Energy Agency (2023d). Energy Profile, Belarus. https://www.irena.org/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Europe/Belarus_Europe_RE_SP.pdf

International Renewable Energy Agency (2023e). Energy Profile, Armenia. https://www.irena.org/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Eurasia/Armenia_Eurasia_RE_SP.pdf

Interreg Europe (2023). More ambitious EU Renewable Energy Targets agreed. https://www.interregeurope.eu/policy-learning-platform/news/more-ambitious-eu-renewable-energy-targets-agreed

Kadatskaya, O.V., Sanets, E.V., Bykova, N.K. and Ovcharova, E.P. (2010). The State of Environment in the Republic of Belarus. Ambrazhevich, M.L., Germenchuk, M.G., Dobritsky, A.V., Zharkina, A.I., Komosko, I.V., Kuzmenkov, S.K. et al. (eds.). Minsk, Belarus: The Ministry of Natural Resources and Environmental Protection of the Republic of Belarus. https://www.minpriroda.gov.by/printv/en/new_url_1244680181-en

Kantor, O.G., Rudneva, Y.R., Dunov, D.Y., Ergasheva, S.T. and Leybert, B.M. (2023). Green Finance: Analysis of Prospects of the Russian Market. In Food Security in the Economy of the Future: Transition from Digital Agriculture to Agriculture 4.0 Based on Deep Learning. Popkova, E.G. and Sergi, B.S. (eds.). Cham: Springer International Publishing. 45-56. https://doi.org/10.1007/978-3-031-23511-5_6

Kilinc-Ata, N. and Dolmatov, I. (2023). The Russian Federation's renewable energy development determinants: evidence from empirical research. International Journal of Energy Sector Management 17(4), 779-800. https://doi.org/10.1108/IJESM-04-2022-0018

Konfo, T.R.C., Djouhou, F.M.C., Hounhouigan, M.H., Dahouenon-Ahoussi, E., Avlessi, F. and Sohounhloue, C.K.D. (2023). Recent advances in the use of digital technologies in agri-food processing: A short review. Applied Food Research 3(2), 100329. https://doi.org/10.1016/j.afres.2023.100329

Kopalkina, E. and Arustamyan, M. (2024). The Russian market is assimilating key green financial instruments: bonds, corporate lending, and mortgages. However, there are other forms of sustainable finance that could also potentially take root in the market. Economic conversations, https://econs.online/en/articles/opinions/sustainable-finance-in-russia-present-and-future/

Kudełko, M. (2022). Are EU environmental regulations consistent with the concept of internalisation of externalities – the case of Polish electricity sector. Economics and Environment 81(2), 89-105. https://doi.org/10.34659/eis.2022.81.2.443

Liobikienė, G. and Poškus, M.S. (2019). The Importance of Environmental Knowledge for Private and Public Sphere Pro-Environmental Behaviour: Modifying the Value-Belief-Norm Theory. Sustainability 11(12), 3324. https://doi.org/10.3390/su11123324

Maalouf, A., Maryev, V.A., Smirnova, T.S. and Mavropoulos, A. (2020). Current Waste Management Status and Trends in Russian Federation: Case Study on Industrial Symbiosis. In Handbook of Solid Waste Management: Sustainability through Circular Economy. Baskar, C., Ramakrishna, S., Baskar, S., Sharma, R., Chinnappan, A. and Sehrawat, R. (eds.). Singapore: Springer Singapore. 1-27. https://doi.org/10.1007/978-981-15-7525-9_15-1

Martirosyan, A. and UNDP (2024). Innovative Financing for the SDGs: A View from Belarus. https://www.undp.org/belarus/blog/innovative-financing-sdgs-view-belarus

McKinsey and Company (2023). Digital Challengers in the next normal in Central and Eastern Europe. https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/digital-challengers-in-the-next-normal-in-central-and-eastern-europe#/

National Recovery Council (2022). Ukraine's National Recovery Plan. https://uploads-ssl.webflow.com/621f88db25fbf24758792dd8/62c166751fcf41105380a733_NRC%20Ukraine%27s%20Recovery%20Plan%20blueprint_ENG.pdf

Organization for Economic Cooperation and Development (2022). Green Economy Transition in Eastern Europe, the Caucasus and Central Asia: Progress and Ways Forward. Paris: OECD Green Growth Studies

Radovanović, M., Filipović, S., Vukadinović, S., Trbojević, M. and Podbregar, I. (2022). Decarbonisation of eastern European economies: monitoring, economic, social and security concerns. Energy, Sustainability and Society 12(1), 16. https://doi.org/10.1186/s13705-022-00342-8

Simionescu, M. and Gavurová, B. (2023). Pollution, income inequality and green finance in the new EU member states. Humanities and Social Sciences Communications 10(1), 677. https://doi.org/10.1057/s41599-023-02197-6

Statista (2024). Luxury Goods - Eastern Europe. September 2024. https://www.statista.com/outlook/cmo/luxury-goods/eastern-europe

Statista (2024). Total greenhouse gas (GHG) emissions during the Russia-Ukraine war from February 2022 to February 2024, by sector. https://www.statista.com/statistics/1473619/total-ghg-emissions-from-russia-ukraine-war-by-sector/

Stecenko, I., Reshina, G. and Stecenko, A. Promotion of Environmental Audit for Transport Companies in Latvia. Reliability and Statistics in Transportation and Communication. Cham, Springer International Publishing https://doi.org/10.1007/978-3-030-96196-1_50

The European Automobile Manufacturers' Association (2023). Average age of the EU vehicle fleet, by country. September 2024. https://www.acea.auto/figure/average-age-of-eu-vehicle-fleet-by-country/

Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives, 2008 (The European Parliament and the Council). http://data.europa.eu/eli/dir/2008/98/2018-07-05

The Global Economy (2023a). Armenia: GDP share of agriculture. https://www.theglobaleconomy.com/Armenia/share_of_agriculture/2024

The Global Economy (2023b). Azerbaijan: GDP share of agriculture. https://www.theglobaleconomy.com/Azerbaijan/Share_of_agriculture/2024

The Global Economy (2023c). Russia: Employment in agriculture. https://www.theglobaleconomy.com/Russia/Employment_in_agriculture/202

The Global Economy (2023d). Belarus: GDP share of agriculture. https://www.theglobaleconomy.com/Belarus/Share_of_agriculture/2024

Todasca, B. (2023). Moldova gets 5.6 mln euro waste management grant through EBRD. SeeNews, https://seenews.com/news/moldova-gets-5-6-mln-euro-waste-management-grant-through-ebrd-1227130

United Nations Conference on Trade and Development (2022). Intersessional Panel of the United Nations Commission on Science and Technology for Development Contribution by Belarus to the CSTD 2022-2023 priority theme on "Technology and innovation for cleaner and more productive and competitive production". https://unctad.org/system/files/non-official-document/CSTD2022-23_c02_C_Belarus_en.pdf

United Nations Development Programme (2024). Planetary pressures–adjusted Human Development Index (PHDI). https://hdr.undp.org/planetary-pressures-adjusted-human-development index#/indicies/PHDI,%20statistical%20annex2024

United Nations Environment Programme (2023). Rapid Environmental Assessment of Kakhovka Dam Breach Ukraine, 2023. Nairobi, Kenya. https://wedocs.unep.org/20.500.11822/43696

United Nations Global Crisis Response Group (2022). Global Impact of war in Ukraine on food, energy and finance systems. https://news.un.org/pages/wp-content/uploads/2022/04/UN-GCRG-Brief-1.pdf

Widuto, A. (2023). Energy poverty in the EU. European Parliamentary Research Service. https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/733583/EPRS_BRI(2022)733583_EN.pdf

Yakovlev, V.A. and Alexseev, S.P. (2022). Development of the food system in Russia and its role in the global food system. IOP Conference Series: Earth and Environmental Science 1112(1), 012064. https://doi.org/10.1088/1755-1315/1112/1/012064

Yakusheva, N. (2019). Managing protected areas in Central Eastern Europe: Between path-dependence and Europeanisation. Land Use Policy 87, 104036. https://doi.org/10.1016/j.landusepol.2019.104036

Żuk, P. and Żuk, P. (2022). Prosumers in Action: The Analysis of Social Determinants of Photovoltaic Development and Prosumer Strategies in Poland. International Journal of Energy Economics and Policy 12, 294-306. https://doi.org/10.32479/ijeep.13124

Latin America and the Caribbean (LAC) Region

Aguilar, M.G., Jaramillo, J.F., Ddiba, D., Páez, D.C., Rueda, H., Andersson, K. et al. (2022). Governance challenges and opportunities for implementing resource recovery from organic waste streams in urban areas of Latin America: insights from Chía, Colombia. Sustainable Production and Consumption 30, 53-63. https://doi.org/10.1016/j.spc.2021.11.025

Aguilera Bravo, M. (2023). Environmental human rights : new thinking from Latin America and the Caribbean. Theory and Practice of Public International Law: Brill Nijhoff, Leiden. https://doi.org/10.1163/9789004543775

Alexandre, G., Rodriguez, L., Arece, J., Delgadillo, J., Garcia, G.W., Habermeier, K. et al. (2021). Agroecological practices to support tropical livestock farming systems: a Caribbean and Latin American perspective. Tropical Animal Health and Production 53(1), 111. https://doi.org/10.1007/s11250-020-02537-7

Allub, L., Álvarez, F., Cont, W., Juncosa, F., Odriozola, J. (2024). Report on Economic Development (RED) 2024. Renewed energies: A just energy transition for sustainable development. Caracas: Development Bank of Latin America and the Caribbean (CAF). https://scioteca.caf.com/handle/123456789/2250

Batista, C., Knipper, M., Sedas, A.C., Farante, S.V., Wainstock, D., Borjas-Cavero, D.B. et al. (2024). Climate change, migration, and health: perspectives from Latin America and the Caribbean. The Lancet Regional Health – Americas 40. https://doi.org/10.1016/j.lana.2024.100926

Battistello Espíndola, I. and and Batista da Silva, L.P. (2023). Data-sharing and decision support system to improve governance in transboundary waters in the La Plata River basin. Water International 48(8), 1000-1013. https://doi.org/10.1080/02508060.2023.2295663

Berkhout, P. and Warner, J. (2023). Transboundary water relations of the Itaipu Dam: Unveiling Brazilian consensual hydro-hegemony. Regions and Cohesion 13(3), 1-28. https://doi.org/10.3167/reco.2023.130302

Breyer, C., Oyewo, A.S., Kunkar, A. and Satymov, R. (2023). Role of Solar Photovoltaics for a Sustainable Energy System in Puerto Rico in the Context of the Entire Caribbean Featuring the Value of Offshore Floating Systems. IEEE Journal of Photovoltaics 13(6), 842-848. https://doi.org/10.1109/JPHOTOV.2023.3319022

Cabieses, B. and Huerta, C. (2024). Effects of climate change on migration in Latin America and Caribbean: a scoping review. Frontiers in Climate 6, 1412285. https://doi.org/10.3389/fclim.2024.1412285

Caron, P., Loma-Osorio, G.F.y.d., Nabarro, D., Hainzelin, E., Guillou, M., Andersen, I. et al. (2018). Food systems for sustainable development: proposals for a profound four-part transformation. Agronomy for sustainable development 38. https://doi.org/10.1007/s13593-018-0519-1

Camargo-Bertel, A.A., Lizarazo, C., Corredor, L., Campillo, J., Gonzalez-Quiroga, A. and Pupo-Roncallo, O. (2024). Analyzing trends in energy modelling tools in Latin America: A comprehensive review. Energy Reports 12, 3075-3095. https://doi.org/10.1016/j.egyr.2024.08.080

Cerri, C.E.P., Cherubin, M.R., Villela, J.M., Locatelli, J.L., Carvalho, M.L., Villarreal, F. et al. (2024). Carbon farming in the Living Soils of the Americas. Frontiers in Sustainable Food Systems 8, 1481005. https://doi.org/10.3389/fsufs.2024.1481005

Cindrella, J. and Renjith, K.R. (2025). Understanding the Role of Oceans in Global Sustainability: Biogeochemistry and Challenges in the Anthropocene. In Radiation Status in the Marine World. Jindal, M.K., David, A. and Khandaker, M.U. (eds.). Cham: Springer Nature Switzerland. 1-29. https://doi.org/10.1007/978-3-031-82403-6_1

De Marco, P., de Souza, R.A., F. A. Andrade, A., Villén-Pérez, S., Nóbrega, C.C., Campello, L.M. et al. (2023). The value of private properties for the conservation of biodiversity in the Brazilian Cerrado. Science 380(6642), 298-301. https://doi.org/10.51594/estj.v5i1.731doi:10.1126/science.abq7768

Díaz-Bonilla, E. and Piñeiro, V. (2024) 'Latin America and the Caribbean', in Global Food Policy Report 2024: Food Systems for Healthy Diets and Nutrition. Washington, DC: IFPRI, pp. 541–553. https://cgspace.cgiar.org/server/api/core/bitstreams/2a4099eb-631b-49f7-9229-44553be58a21/content#page=34

Economic Commission for Latin America and Caribbean (ECLAC). (2023). Natural Resources Outlook in Latin America and the Caribbean. Executive summary (LC/PUB.2023/7). Santiago. https://hdl.handle.net/11362/48997

Echebarria Fernández, J. (2021). Maritime Governance and Small Island Developing States of the Wider Caribbean Region in the Era of Climate Change Adaptation. In Sustainability in the Maritime Domain: Towards Ocean Governance and Beyond. Carpenter, A., Johansson, T.M. and Skinner, J.A. (eds.). Cham: Springer International Publishing. 355-402. https://doi.org/10.1007/978-3-030-69325-1_18

Esteves, F., Molina-Perez, E., Kalra, N., Syme, J. and Vogt-Schilb, A. (2024) 'Job creation and decarbonization synergies in Latin America: a simulation-based exploratory modelling analysis'. Frontiers in Climate, 6. https://doi.org/10.3389/fclim.2024.1339877

Eguino, H., Delgado, R., Buttazzoni, M., Alvarenga, M., Palomo, L., Cartes, F. et al. (2024). Rumbo a una inversión pública resiliente y descarbonizada: prácticas de integración de la acción climática en la gestión de la inversión pública. https://doi.org/10.18235/0005663

FAO, IFAD, PAHO, UNICEF and WFP (2024) Latin America and the Caribbean Regional Overview of Food Security and Nutrition 2024: Building resilience to climate variability and extremes for food security and nutrition. Rome: FAO. https://doi.org/10.4060/cd3877en

Fernandes, S., Athayde, S., Harrison, I. and Perry, D. (2024). Connectivity and policy confluences: a multi-scalar conservation approach for protecting Amazon riverine ecosystems. Perspectives in Ecology and Conservation 22(2), 129-136. https://doi.org/10.1016/j.pecon.2024.02.002

Ganase, A., Kanhai, A., Lochan, H. and Gooding, N. (2023). A Guide to Coral Reef and Seagrass Restoration in Tobago: Marine Resilience Initiative, Tobago. Tobago. https://www.ima.gov.tt/wpcontent/uploads/2023/09/IMA_RestorationGuide_Tobago-MARIN_Sept13.pdf

Gallego-Schmid, A., López-Eccher, C., Muñoz, E., Salvador, R., Cano-Londoño, N.A., Barros, M.V. et al. (2024). Circular economy in Latin America and the Caribbean: Drivers, opportunities, barriers and strategies. Sustainable Production and Consumption 51, 118-136. https://doi.org/10.1016/j.spc.2024.09.006

Gallego-Schmid, A., Vásquez-Ibarra, L., Guerrero, A.B., Henninger, C.E. and Rebolledo-Leiva, R. (2025). Circular economy in a recently transitioned high-income country in Latin America and the Caribbean: Barriers, drivers, strengths, opportunities, key stakeholders and priorities in Chile. Journal of Cleaner Production 486, 144429. https://doi.org/10.1016/j.jclepro.2024.144429

Galvez, D. P. and Revinova, S. Y. (2025) 'Energy transition as a path to sustainable development in Latin American countries', Unconventional Resources, 6, p. 100157. https://doi.org/10.1016/j.uncres.2025.100157

Hampl, N. (2024). Energy systems for Brazil's Amazon: Could renewable energy improve Indigenous livelihoods and save forest ecosystems? Energy Research & Social Science 112, 103491. https://doi.org/10.1016/j.erss.2024.103491

Hernández-Blanco, M., Costanza, R., Anderson, S., Kubiszewski, I. and Sutton, P. (2020). Future scenarios for the value of ecosystem services in Latin America and the Caribbean to 2050. Current Research in Environmental Sustainability 2, 100008. https://doi.org/10.1016/j.crsust.2020.100008

Holechek, J.L., Geli, H.M.E., Sawalhah, M.N. and Valdez, R. (2022). A Global Assessment: Can Renewable Energy Replace Fossil Fuels by 2050? Sustainability 14(8), 4792 https://doi.org/10.3390/su14084792

International Energy Agency (2023). Latin America Energy Outlook 2023. Paris: International Energy Agency. https://www.iea.org/reports/latin-america-energy-outlook-2023

International Resource Panel (IRP). (2019). Global Resources Outlook 2019: Natural Resources for the Future We Want. Oberle, B., Bringezu, S., Hatfield-Dodds, S., Hellweg, S., Schandl, H., Clement, J. et al. (eds.). Nairobi: United Nations Environment Programme. https://wedocs.unep.org/20.500.11822/27517

Icaza-Alvarez, D., Jurado, F. and Tostado-Véliz, M. (2024). Smart energy planning for the decarbonization of Latin America and the Caribbean in 2050. Energy Reports 11, 6160-6185. https://doi.org/10.1016/j.egyr.2024.05.067

Jaax, A., Zwicker, S., Fujitani, M., Pohle, A., Palmer Cantillo, S., Mancera Pineda, J.E. et al. (2024). Tracing nitrogen pollution from wastewater on an oceanic, touristic island: Integrating local knowledge and uncertainty into a mass balance modelling approach. Ocean & Coastal Management 253, 107135. https://doi.org/10.1016/j.ocecoaman.2024.107135

IPBES (2024). Summary for Policymakers of the Thematic Assessment Report on the Interlinkages among Biodiversity, Water, Food and Health of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. McElwee, P. D., Harrison, P. A., van Huysen, T. L., Alonso Roldán, V., Barrios, E., Dasgupta, P., DeClerck, F., Harmáčková, Z. V., Hayman, D. T. S., Herrero, M., Kumar, R., Ley, D., Mangalagiu, D., McFarlane, R. A., Paukert, C., Pengue, W. A., Prist, P. R., Ricketts, T. H., Rounsevell, M. D. A., Saito, O., Selomane, O., Seppelt, R., Singh, P. K., Sitas, N., Smith, P., Vause, J., Molua, E. L., Zambrana-Torrelio, C., and Obura, D. (eds.). IPBES secretariat, Bonn, Germany. DOI: https://doi.org/10.5281/zenodo.13850289

Kalra, N., Rodríguez Caballero, K., Monge, M. and Rodríguez Tornquist, S., 2023. The Benefits and Costs of Reaching Net-Zero Emissions in Latin America and the Caribbean. Washington, D.C.: Inter-American Development Bank. Available at: https://publications.iadb.org/en/benefits-and-costs-reaching-net-zero-emissions-latin-america-and-caribbean

Kariuki, J.M. (2024). Nuevo Clima: Energy in Transition—The Role of Smart Conventional Energy Systems, Hydrogen, and Lithium-ion Batteries in Latin America and the Caribbean's (LAC) Energy Future. In Energia Progresiva: An Intertemporal Analysis of Latin America and the Caribbean's Energy Landscape in the Industrial Age. Kariuki, J.M. (ed.). Cham: Springer Nature Switzerland. 575-611. https://doi.org/10.1007/978-3-031-68846-1_23

Kraak, V.I. and Aschemann-Witzel, J. (2024). The Future of Plant-Based Diets: Aligning Healthy Marketplace Choices with Equitable, Resilient, and Sustainable Food Systems. Annual Review of Public Health 45, 253-275. https://doi.org/10.1146/annurev-publhealth-060722-032021

Lentini, E. (2022). Building a water security agenda for Latin America and the Caribbean 2030. Contributions from the Conference on Water Finance and Governance in Latin America and the Caribbean: Towards Dakar 2022. Caracas: Development Bank of Latin America (CAF). https://scioteca.caf.com/handle/123456789/1882

Levy, A., Messina, D., Salgado, R. and Contreras Lisperguer, R. (2023). Pathways to sustainable planning for a just energy transition in Latin America and the Caribbean: an analysis of best practices in selected countries. Natural Resources and Development series, No. 216 (LC/TS.2023/4). Santiago: Economic Commission for Latin America and the Caribbean (ECLAC). https://repositorio.cepal.org/server/api/core/bitstreams/f82109e1-f017-4ba3-ac7d-43b79c7530f9/content

Lino, G.a.S., M. La Saeta Universitaria Académica y de Investigación (2023). ENERGÍAS RENOVABLES EN AMERICA LATINA Y EL CARIBE PARA LA MITIGACIÓN DEL CAMBIO CLIMÁTICO. La Saeta Universitaria Académica y de Investigación 11, 43-71. https://doi.org/10.56067/saetauniversitaria.v11i2.354

Martynov, B., Borzova, A. and Nekrasov, B. (2020). Amazon cooperation treaty organization in the context of Sustainable Development Goals. International Trends / Mezhdunarodnye protsessy 18(4), 108-126. https://doi.org/10.17994/IT.2020.18.4.63.3

Mahadeo, S. and Del Savio, L. (2023). Transboundary maritime cooperation: the case of the Eastern Caribbean Region. Frontiers in Marine Science 10, 1251911. https://doi.org/10.3389/fmars.2023.1251911

Oyewo, A.S., Kunkar, A., Bogdanov, D. and Breyer, C. (2024). Defossilising Caribbean's energy system: Highlighting on e-fuel imports, grid integration, and accelerated transition. IET Renewable Power Generation 18(S1), 4650-4678. https://doi.org/10.1049/rpg2.13173

Palacios, A., Koon Koon, R., Castro-Olivera, P.M., Miranda-Flores, G., Taylor, L. and Córdova-Lizama, A. (2024). Pathways to hydrogen production through variable renewable energy capacity: A study of Mexico and Jamaica. Energy Conversion and Management 311. https://doi.org/10.1016/j.enconman.2024.118483

Reyes-García, V., Fernández-Llamazares, Á., Aumeeruddy-Thomas, Y., Benyei, P., Bussmann, R.W., Diamond, S.K. et al. (2022). Recognizing Indigenous peoples' and local communities' rights and agency in the post-2020 Biodiversity Agenda. Ambio 51(1), 84-92. https://doi.org/10.1007/s13280-021-01561-7

Robinson, G.M. (2024). Global sustainable agriculture and land management systems. Geography and Sustainability 5(4), 637-646. https://doi.org/10.1016/j.geosus.2024.09.001

Rodríguez, C., García, B., Pinto, C., Sánchez, R., Serrano, J. and Leiva, E. (2022). Water Context in Latin America and the Caribbean: Distribution, Regulations and Prospects for Water Reuse and Reclamation. Water 14(21), 3589. https://doi.org/10.3390/w14213589

Rodríguez-Arce, M., Angulo-Paniagua, J., Victor-Gallardo, L., Roccard, J., Quirós-Tortós, J., Alexander, K. et al. (2024). Integrated climate, land, energy, and water framework to support the Nationally Determined Contribution updating process. Energy Strategy Reviews 51. https://doi.org/10.1016/j.esr.2024.101316

Santos, T. and Colgan, C.S. (2023). Regionalism Beyond Land Borders: Strengthening regional integration in Latin America and the Caribbean through blue economy policies. Revista Brasileira de Política Internacional 66, e018. https://doi.org/10.1590/0034-7329202300218

Salazar, L., González, M. and Alvarez, L. (2024). Climate Change Vulnerability and Food Insecurity: Empirical Evidence for Countries in Latin America and the Caribbean. Inter-American Development Bank https://doi.org/10.18235/0013311

Sandoval Yate, D.F., Triana Ángel, N. and Burkart, S. (2024). Pathways towards sustainability: A capacity needs assessment for the implementation *of*

the Colombian Policy for Sustainable Cattle 2022–2050. Journal of Rural Studies 112, 103472. https://doi.org/10.1016/j.jrurstud.2024.103472

Seijger, C., Urfels, A., Christoforidou, M., Hellegers, P., Borghuis, G., Langan, S. et al. (2025). More food, but less land and water for nature: Why agricultural productivity gains did not materialize. Agricultural Water Management 307, 109229. https://doi.org/10.1016/j.agwat.2024.109229

Tundys, B. and Bretyn, A. (2023). Energy Transition Scenarios for Energy Poverty Alleviation: Analysis of the Delphi Study. Energies 16(4), 1870. https://doi.org/10.3390/en16041870

United Nations Environment Programme (2021). El Peso de las Ciudades en América Latina y el Caribe: Requerimientos Futuros de Recursos y Potenciales Rutas de Actuación.. Nairobi: United Nations Environment Programme. https://wedocs.unep.org/20.500.11822/37655

Vélez-Henao, J.A. and Pauliuk, S. (2025). Pathways to a net-zero building sector in Colombia: Insights from a circular economy perspective. Resources, Conservation and Recycling 212, 107971. https://doi.org/10.1016/j.resconrec.2024.107971

Wang, K.C.M., Lee, K.E. and Mokhtar, M. (2021). Solid Waste Management in Small Tourism Islands: An Evolutionary Governance Approach. Sustainability 13(11), 5896. https://doi.org/doi:10.3390/su13115896

Yalew, S., van Vliet, M., Gernaat, D., Ludwig, F., Miara, A., Park, C. et al. (2020). Impacts of climate change on energy systems in global and regional scenarios. Nature Energy 5. https://doi.org/10.1038/s41560-020-0664-z

Yarlagadda, B., Wild, T., Zhao, X., Clarke, L., Cui, R., Khan, Z. et al. (2023). Trade and climate mitigation interactions create agro-economic opportunities with social and environmental trade-offs in Latin America and the caribbean. Earth's Future 11(4), e2022EF003063. https://doi.org/10.1029/2022EF003063

Yépez-García, A. and Jimenez Mori, R.A. (2024). Economía de las pérdidas de electricidad en América Latina y El Caribe. https://doi.org/10.18235/0012971

Western Europe and Other Group (WEOG) Region

Agamuthu, P. and Babel, S. (2023). Waste management developments in the last five decades: Asian perspective. Waste Management & Research 41(12), 1699-1716. https://doi.org/10.1177/0734242X231199938

Aguilar-Hernandez, G.A., Dias Rodrigues, J.F. and Tukker, A. (2021). Macroeconomic, social and environmental impacts of a circular economy up to 2050: A meta-analysis of prospective studies. Journal of Cleaner Production 278, 123421. https://doi.org/10.1016/j.jclepro.2020.123421

Alaska Arctic Observatory and Knowledge Hub (AAOKH) (2024). Trails to the Whale: A 20-yr record of Utqiagvik's spring whaling trails. Report for the Barrow Whaling Captain's Association. M. Drukenmiller, J.J., R. Tururraq Glenn-Borade, K. Kivaaq Pikok, and D.D.W. Hauser (ed.). https://arctic-aok.org/

Alaska Eskimo Whaling Commission (AEWC) (2024). Co-management. https://www.aewc-alaska.org/co-management

Alberti, F. (2023). Regenerative Streets: Pathways towards the Post-Automobile City. Sustainability 15(13), 10266. https://doi.org/10.3390/su151310266

Arctic Monitoring and Assessment Programme (AMAP) (2024). Working Group of the Artic Council. https://www.amap.no/

Bassi, F. (2023). European Consumers' Attitudes towards the Environment and Sustainable Behaviour in the Market. Sustainability 15(2), 2071-1050. https://doi.org/10.3390/su15021666

Berkes, F. (2010). Sacred Ecology. Routledge: Taylor & Francis. https://doi.org/10.4324/9780203123843

Bourke, P.M., Evers, J.B., Bijma, P., van Apeldoorn, D.F., Smulders, M.J.M., Kuyper, T.W. et al. (2021). Breeding Beyond Monoculture: Putting the "Intercrop" Into Crops. Frontiers in Plant Science 12, 734167. https://doi.org/10.3389/fpls.2021.734167

BurnSilver, S., Magdanz, J., Stotts, R., Berman, M. and Kofinas, G. (2016). Are mixed economies persistent or transitional? Evidence using social networks from Arctic Alaska. American Anthropologist, 118(1), pp.121-129. https://doi.org/10.1111/aman.12447

Camarasa, C., Kalahasthi, L.K. and Rosado, L. (2021). Drivers and barriers to energy-efficient technologies (EETs) in EU residential buildings. Energy and Built Environment 2(3), 290-301. https://doi.org/10.1016/j.enbenv.2020.08.002

Chen, X., Mcelroy, M.B., Wu, Q., Shu, Y. and Xue, Y. (2019). Transition towards higher penetration of renewables: an overview of interlinked technical, environmental and socioeconomic challenges. Journal of Modern Power Systems and Clean Energy 7(1), 1-8. https://doi.org/10.1007/s40565-018-0438-9

Costanza, R. (2023). To build a better world, stop chasing economic growth. Nature 624(7992), 519-521. https://doi.org/10.1038/d41586-023-04029-8

CIMMYT (2019). Conservation agriculture works for farmers and for sustainable intensification. https://www.cimmyt.org/news/conservation-agriculture-works-for-farmers-and-for-sustainable-intensification/https://www.cimmyt.org/news/conservation-agriculture-works-for-farmers-and-for-sustainable-intensification/

H.R.5376 — 117th Congress (2021-2022). (2022). H.R.5376 - Inflation Reduction Act of 2022. U.S. Congress. Congress.gov, Library of Congress, https://www.congress.gov/bill/117th-congress/house-bill/5376

Department of Climate Change Energy the Environment and Water (DCCEEW) (2023). Powering Australia. Commonwealth of Australia, https://www.dcceew.gov.au/energy/strategies-and-frameworks/powering-australia#:~:text=A%20Powering%20Australia%20Industry%20Growth,Program%20to%20bolster%20Australian%20manufacturing

Dodd, T. and Nelson, T. (2022). Australian household adoption of solar photovoltaics: A comparative study of hardship and non-hardship customers. Energy Policy 160, 112674 https://research-repository.griffith.edu.au/server/api/core/bitstreams/f45f36e4-76e5-4006-b907-3eaa8ba56fd6/content

European Commission (2016). A European Agenda for the Collaborative Economy. https://ec.europa.eu/commission/presscorner/detail/en/IP_16_2001

European Commission (2022). Communication from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions: REPowerEU Plan COM/2022/230 final. Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM per cent3A2022 per cent3A230 per cent3AFIN

European Court of Auditors (2023). Special Report 17/2023: Circular economy – Slow transition by member states despite EU action. Luxembourg. https://www.eca.europa.eu/en/publications/SR-2023-17

Galán-Martín, Á., Vázquez, D., Cobo, S., Mac Dowell, N., Caballero, J.A. and Guillén-Gosálbez, G. (2021). Delaying carbon dioxide removal in the European Union puts climate targets at risk. Nature Communications 12(1), 6490. https://doi.org/10.1038/s41467-021-26680-3

Gielen, D., Boshell, F., Saygin, D., Bazilian, M.D., Wagner, N. and Gorini, R. (2019). The role of renewable energy in the global energy transformation. Energy Strategy Reviews 24, 38-50. https://doi.org/10.1016/j.esr.2019.01.006

Global Panel on Agriculture and Food Systems for Nutrition (2020). Future Food Systems: For people, our planet, and prosperity. Foresight 2.0 London, UK. https://www.glopan.org/foresight2/

Guo, Y., Tan, H., Zhang, L., Liu, G., Zhou, M., Vira, J. et al. (2023). Global food loss and waste embodies unrecognized harms to air quality and biodiversity hotspots. Nature Food 4(8), 686-698. https://doi.org/10.1038/s43016-023-00810-0

Huntington, H.P., Sakakibara, C., Noongwook, G., Kanayurak, N., Skhauge, V., Zdor, E. et al. (2021). Chapter 31 - Whale hunting in Indigenous Arctic cultures. In The Bowhead Whale. George, J.C. and Thewissen, J.G.M. (eds.). Academic Press. 501-517. https://www.sciencedirect.com/science/article/pii/B9780128189696000315

Intergovernmental Panel on Climate Change (IPCC) (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S.

et al. (eds.) (ed.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://doi.org/110.1017/9781009157896

Intergovernmental Panel on Climate Change (IPCC) (2022). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. H.-O. Pörtner, D.C.R., M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.) https://doi.org/10.1017/9781009325844

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://doi.org/10.5281/zenodo.3553458

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2022). Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Balvanera, P., Pascual, U., Christie, M., Baptiste, B., and González-Jiménez, D. (eds.). IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.6522522

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2024). Thematic Assessment Report on the Interlinkages among Biodiversity, Water, Food and Health of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Harrison, P. A., McElwee, P. D., and van Huysen, T. L. (eds.). IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.13850054

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2025) Thematic assessment of the underlying causes of biodiversity loss and the determinants of transformative change and options for achieving the 2050 Vision for Biodiversity; Summay for Policy Makers; IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.11382230.

Internal Revenue Service (IRS). (2022). Inflation Reduction Act of 2022. U.S. Department of the Treasury. https://www.irs.gov/inflation-reduction-act-of-2022, Accessed September 2025

Lawrence, M., Homer-Dixon, T., Janzwood, S., Rockstrom, J., Renn, O. and Donges, J.F. (2023). Global polycrisis: The causal mechanisms of crisis entanglement. http://dx.doi.org/10.2139/ssrn.4483556

Lecocq, F., H. Winkler, J.P. Daka, S. Fu, J.S. Gerber, S. Kartha, V. Krey. et al. (2022). Mitigation and development pathways in the near- to mid-term. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. P.R. Shukla, J.S., R. Slade, A. Al, Khourdajie, R.v.D., D. McCollum, M. Pathak, S. Some. et al.(eds.). Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.006

Maduta, C., D'Agostino, D., Tsemekidi-Tzeiranaki, S., Castellazzi, L., Melica, G. and Bertoldi, P. (2023). Towards climate neutrality within the European Union: assessment of the Energy Performance of Buildings Directive implementation in Member States. Energy and Buildings, 113716. https://doi.org/10.1016/j.enbuild.2023.113716

McIntyre, O. (2025). Towards sustainability in transboundary water resources: The role of inter-state solidarity. Environmental Policy and Law, 0(0). https://doi.org/10.1177/18785395241309705

McGinty, D.B. (2021). '5 Opportunities of a Circular Economy'. https://www.wri.org/insights/5-opportunities-circular-economy

Ministry of Business Innovation and Employment (MBIE) (2023). New Zealand Energy Strategy. https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-strategies-for-new-zealand/new-zealand-energy-strategy/#:~:text=It per cent20has per cent20committed per cent20to per cent20reaching,100 per cent25 per cent20renewable per cent20electricity per cent20by per cent202030

Ortenzi, F., Marten, R., Valentine, N.B., Kwamie, A. and Rasanathan, K. (2022). Whole of government and whole of society approaches: call for further research to improve population health and health equity. BMJ Global Health 7(7), e009972. https://doi.org/10.1136/bmjgh-2022-009972

Panniello, U., Ardito, L. and Petruzzelli, A.M. (2022). Scoping the state of the sharing economy and its antecedents at the country level: Cross-country differences in Europe. Geoforum 133, 140-152. https://doi.org/10.1016/j.geoforum.2022.05.013

Parra-Domínguez, J., Sánchez, E. and Ordóñez, Á. (2023). The prosumer: A systematic review of the new paradigm in energy and sustainable development. Sustainability 15(13), 10552. https://doi.org/10.3390/su151310552

Pereira, H.M. and Navarro, L.M. (2015). Rewilding European landscapes. Springer Nature. https://doi.org/10.1007/s10021-012-9558-7

Piketty, T. (2014). Capital in the twenty-first century. Harvard University Press. https://doi.org/10.4159/9780674369542

Raneng, J., Howes, M. and Pickering, C.M. (2023). Current and future directions in research on community gardens. Urban Forestry & Urban Greening 79, 127814. https://doi.org/10.1016/j.ufug.2022.127814

Rodrigues, P., Alvim-Ferraz, M., Martins, F., Saldiva, P., Sá, T. and Sousa, S. (2020). Health economic assessment of a shift to active transport. Environmental pollution 258, 113745. https://doi.org/10.1016/j.envpol.2019.113745

Sachdeva, S., Jordan, J. and Mazar, N. (2015). Green consumerism: moral motivations to a sustainable future. Current Opinion in Psychology 6, 60-65. https://doi.org/10.1016/j.copsyc.2015.03.029

Stechemesser, A., Koch, N., Mark, E., Dilger, E., Klösel, P., Menicacci, L. et al. (2024). Climate policies that achieved major emission reductions: Global evidence from two decades. Science 385(6711), 884-892. https://doi.org/10.1126/science.adl6547

Tomalka, J., Hunecke, C., Murken, L., Heckmann, T., Cronauer, C., Becker, R. et al. (2024). Stepping back from the precipice: Transforming land management to stay within planetary boundaries. Potsdam, Germany: Potsdam Institute for Climate Impact Research. https://doi.org/10.48485/pik.2024.018

Turner, W.R., Nakamura, T. and Dinetti, M. (2004). Global urbanization and the separation of humans from nature. Bioscience 54(6), 585-590. https://doi.org/10.1641/0006-3568(2004)054[0585:GUATSO]2.0.CO;2

Turnhout, E., McElwee, P., Chiroleu-Assouline, M., Clapp, J., Isenhour, C., Kelemen, E. et al. (2021). Enabling transformative economic change in the post-2020 biodiversity agenda. Conservation Letters 14(4), e12805. https://doi.org/10.1111/conl.12805

United Nations Convention to Combat Desertification (2024). Planetary boundaries: Confronting the global crisis of land degradation; 1 December, Press Release; Planetary boundaries: Confronting the global crisis of land degradation | UNCCD Secretariat, Bonn, Germany. https://www.unccd.int/news-stories/press-releases/planetary-boundaries-confronting-global-crisis-land-degradation

United Nations Environment Programme (2019). The role of packaging regulations and standards in driving the circular economy. https://www.unep.org/resources/report/role-packaging-regulations-and-standards-driving-circular-economy

United Nations Environment Programme (2023). Emissions Gap Report 2023. Nairobi: United Nations Environment Programme. https://www.unep.org/resources/emissions-gap-report-2023

United Nations Framework Convention on Climate Change (UNFCCC) (2023). Summary of Global Climate Action at COP28. https://unfccc.int/sites/default/files/resource/Summary_GCA_COP28.pdf

United States Environmental Protection Agency (2022). Building a circular economy for all: Progress Toward Transformative Change. Washington DC. https://www.epa.gov/system/files/documents/2022-09/EPA_Circular_Economy_Progress_Report_Sept_2022.pdf.

United Nations Environment Programme Copenhagen Climate Centre (UNEP-CCC) and Climate Technology Centre and Network (CTCN). Climate Technology Progress Report 2024: Unleashing Renewable Energy for Ambitious NDCs., Copenhagen, Denmark https://unepccc.org/wp-content/uploads/2025/01/the-climate-technology-progress-report-2024.pdf

United States Environmental Protection Agency (2024). Inventory of US Greenhouse Gas Emissions and Sinks 1990-2022. Washington DC 004. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022

Watkins, E. and Meysner, A. (2022). European Circular Economy policy landscape overview. Institute for European Environmental Policy. https://ieep.eu/publications/european-circular-economy-policy-overview/

White, K., Habib, R. and Hardisty, D.J. (2019). How to SHIFT consumer behaviours to be more sustainable: A literature review and guiding framework. Journal of Marketing 83(3), 22-49. https://doi.org/10.1177/0022242919825649

Winkler, H., Lecocq, F., Lofgren, H., Vilariño, M.V., Kartha, S. et al. (2022). Examples of shifting development pathways: lessons on how to enable broader, deeper, and faster climate action. Climate Action 1(1), 1-20. https://doi.org/10.1007/s44168-022-00026-1

World Wide Fund for Nature (WWF) (2022). Living Planet Report 2022 – Building a nature-positive society. Almond, R.E.A., Grooten, M., Juffe Bignoli, D. & Petersen, T. (ed.). WWF, Gland, Switzerland https://www.wwf.org.uk/our-reports/living-planet-report-2022

Vijayan, D., Ludwig, D., Rybak, C., Kaechele, H., Hoffmann, H., Schönfeldt, H. C. (2022). et al. Indigenous knowledge in food system transformations. Communications Earth & Environment 3(1), 1-3. https://doi.org/10.1038/s43247-022-00543-1

Zapata-Diomedi, B., Knibbs, L.D., Ware, R.S., Heesch, K.C., Tainio, M., Woodcock, J. et al. (2017). A shift from motorized travel to active transport: What are the potential health gains for an Australian city?. PLoS One 12(10), e0184799. https://doi.org/10.1371/journal.pone.0184799

21 Driving the Transformations

Co-ordinating Lead Authors: Catalina Turcu (University College London), Eric Zusman (Institute for Global Environmental Strategies), Medani Bhandari (Atlantic States Legal Foundation)

Lead Authors: Simone Lucatello (Instituto Mora – SECHITI), Valerie Nelson (University of Greenwich), Sandra Torrusio (National University of La Plata)

Fellows: Martina Rotolo (University College London)

Contributing Authors: Sibel Eker (Radboud University/ International Institute for Applied Systems Analysis), Paul Lucas (PBL Netherlands Environmental Assessment Agency), Audrone Telesiene (Kaunas University of Technology)

Credit: YouraPechkin/Envato

Chapter summary

Credit: Naypongstudio/Envato

Achieving internationally agreed environmental, social and economic goals requires whole-of-government and whole-of-society approaches (*established but incomplete*). These approaches can transform interconnected economic and financial, energy, food systems, materials/waste and environmental systems. Such a transformation, in turn, requires identifying and implementing solutions that leverage synergies, such as nature-based solutions, while limiting trade-offs, such as job losses, across systems. These approaches also necessitate putting circular economy principles into practice; changing entrenched values and behaviours; accounting for diverse worldviews and knowledge systems; committing to just and equitable principles; facilitating co-production in scenario modelling; and strengthening capacities to manage increasingly ambitious multidimensional changes {21.5}.

A whole-of-government approach necessitates breaking down silos and engage in new forms of multilateralism (*established but incomplete*). Internationally agreed goals require aligning national policies with international goals while recognizing that no single ministry or department can transform the economics and finance, energy, materials, environment and food systems alone. Inter-agency committees, staffing rotations, innovative cross-agency budgeting practices and harmonized reporting protocols can help forge these connections. Though shifting power dynamics, rising nationalism and institutional weaknesses threaten international cooperation, new forms of multilateralism that capitalize on adaptive, forward-looking policies and build bridges across diverse national and subnational interests offer a way forward {21.5}.

A whole-of-society approach requires enabling the meaningful participation of all agents of change (*unresolved*). It is essential that governance reforms promote the inclusion of all agents of change to achieve sustainable solutions and just transitions. Boosting accountability, transparency and addressing the underlying causes of unsustainability are also critical. The growing role of actors beyond government, such as corporations, financial institutions, labour groups, civil society and local communities can contribute to positive outcomes

Table 21.1: Actor categories and their roles

Actors	Roles
Governments	Establish policies, legislation, and financing. Transform economic, financial, energy and agricultural systems, repurpose subsidies, internalize externalities, and develop policies and technologies to reduce GHG emissions, improve energy efficiency, minimize food loss and waste, enhance climate resilience in food and water systems, and integrate natural capital in decision-making.
Intergovernmental organizations	Coordinate efforts, set global standards, and finance global public goods, such as a stable climate. Support economic and financial transformation through policy guidance and risk monitoring; advance energy transformation by promoting renewable energy and clean technology; and promote climate-resilient agriculture.
The public	Consumers, voters, workers, investors, activists, and community members. Drive system transformation by, for example, supporting green businesses, ethical finance, and greater local resilience in energy and food systems.
Civil society	Connect people to power, hold institutions accountable and advocate for justice, sustainability and inclusivity. Transforms systems through advocacy, public awareness and expose corruption and harmful practices.
Private sector	Align profit with purpose, makes market goods and invests. Transform the economic and financial system by channelling investment in green products; shifting away from fossil fuels in the energy system; and committing to fair trade, no deforestation and ethical labour in supply chains.
Academia	Generate knowledge, educate leaders and shapes policy and innovation. Transforms all systems by training future leaders, informing policy with independent research, and advancing the development of clean technology, biotechnology, and data science.
Nature	Provide resources and shapes the stability, productivity and sustainability of systems. Drive system transformation by promoting natural capital approaches, supporting renewables, sustaining agriculture through ecosystem services, and regulating climate, carbon, airsheds, and water systems. Nature is foundational to the long-term sustainability of all human and ecological systems.

across contexts, scales and sectors. Their participation must be embedded within governance systems to ensure sustainable transformation and effective implementation {21.5}.

Unpacking the roles and actions of agents of change – individual actors, networks of actors, and communities of interest and social movements – can help accelerate transformation (*well-established*). Actors refer to governments, intergovernmental organizations, the public, civil society, the private sector, academia, professional organizations, and nature. Networks of actors include the UN regions, the EU, and cities. Communities of interest refer to spiritual and faith groups, Indigenous Peoples as well as local communities that coalesce around common interests or values, and social movements that work together to shift dominant societal practices, such as climate, youth, or educational movements. This categorization suggests actors can be human or non-human, individual or collective, formal or informal, material or immaterial {21.41} (Table 21.1)..

Networks of actors: Clubs of like-minded countries and actor constellations offer promising avenues for plurilateral cooperation, enabling solutions by reducing gridlock and facilitating joint action. One example is the Coalition of the Willing on Pollinators, with over 32 countries and four observers, including the United Nation's Food and Agriculture Organization and Biodiversity and Ecosystem Services Network, promoting country-led policy and innovative action to protect pollinators. Another example is the Covenant of Mayors, a political network of urban leaders committed to climate and energy action {21.4.9}.

Communities of interest and social movements: Actors and networks united by shared values – such as religious beliefs, environmental protection, and rights – form a collective force for change. They

transcend geography and individual interests to influence decisions and drive system transformation. Examples include slow-food communities, food councils, India's Chipko and Niyamgiri movements, the Chico Mendes movement in Brazil, and Buen Vivir in Latin America {21.4.1.10}.

Nature is a powerful actor that deserves greater representation in decision-making processes (*established but incomplete*). Rooted in the understanding of life's interdependence, many Indigenous worldviews and legal systems see nature as intertwined with human systems, carrying mutual responsibilities. Nature should therefore not be treated as an externality, but as a foundational actor and provider of services whose health underpins the health of all human systems. This can be achieved through integrating ecological values, natural capital accounting, ecosystem-based approaches and prioritizing ecosystem health in system transformations {21.4}

Agents of change are often motivated to act in their self-interest in health and well-being, economic and financial stimuli, regulatory frameworks, and culture, imaginaries, norms, common values and beliefs (*established but incomplete*). Examples of how these motivators can stimulate action include the following:

- **Health:** a recognition that human and planetary health are interconnected, for example, concerns over a population's raising rates of obesity, diabetes and heart disease – all linked to poor diets, air pollution and sedentary lifestyles – can become the catalyst for transformative change by driving reforms to food, energy, urban, transport and other systems, even redefining economic prosperity {21.4.2.1}.

- **Economic and financial:** actions can be stimulated by economic incentives that make transformation profitable, or by a recognition that nature underpins the long-term sustainability of their business, for example, nature-positive economic and bioeconomy approaches {21.4.2.2}

- **Regulatory frameworks:** legislation and regulations that incentivize or penalize businesses can motivate action, for example, legislation that embodies the Polluter Pays Principle {21.4..2.3}.

- **Culture, imaginaries, norms, common values and beliefs**: these can motivate action by shaping perceptions, fostering identity and solidarity, and providing a moral compass to guide actions, for example, Indigenous leadership in sustainable land governance and biodiversity conservation {21.4.2.4}.

Changing power-interest dynamics to prevent vested interests from capturing environmental regulatory and related policymaking processes is essential (*well-established*). Prospects for transformation can be enhanced by understanding an agent's interest in and power over food security, energy access, social equity and related policy issues. In many countries, large multinational corporations possess the power and/or interest to prevent change, while NGOs and community-based organizations have the interest but not the power to promote change, and the public may lack both the interest and power to drive change. All agents of change must feel empowered and develop an interest in transformations. Empowering Indigenous Peoples, local communities, and other marginalized groups can alter inequitable power dynamics. Strengthening public integrity and accountability can accelerate sustainable transformations {21.4.1.11}.

Comprehensive packages of policy and enabling reforms are needed to break systemic lock-ins (*unresolved*). Breaking interrelated barriers and lock-ins across systems requires a mix of strategies – big plans, small wins and systemic rule changes. For example, phasing out coal, ending fossil-fuel subsidies, reskilling workers, and highlighting adverse health effects can make energy systems more sustainable. Reforming subsidies, ensuring fair market access, securing land rights, and shifting diets can transform food systems. These approaches can gain momentum during environmental crises, such as past pollution events that drove environmental reforms in the United States of America and China, and through deeper value shifts, such as embracing care, reciprocity, and rethinking human–nature relationships {21.5}.

Ultimately, strengthening global cooperation and adopting bold policies are essential for driving a transformation that is not only swift but also just

Credit: ©UNEP

and sustainable (*unresolved*). This is achievable but will require unprecedented action to address geopolitical tensions, stabilize the climate, restore ecosystems, build zero-waste economies, and ensure equity, and may require new forms of multilateralism that are more target-focused and agile. Countries at different development levels will need tailored approaches, with low-income countries focusing on technology and infrastructure to boost yields and cut energy use, while high-income countries prioritize decarbonization, electrification, sustainable diets, and food systems. Crucially, all actions must centre on the rights and resilience of the most marginalized to ensure a just and inclusive transformation {21.5}.

21.1 Introduction

The evidence is clear: resource-intensive development patterns have given rise to climate change, biodiversity loss, land degradation and desertification and pollution and waste crises. Chapters 3–6 covered these crises, demonstrating that they are attributable to human activity. Previous chapters also demonstrate that these crises are part of the reason the world is not on track to achieve the Sustainable Development Goals (SDGs), the Paris Agreement, or the 2050 Vision for Biodiversity (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES] 2019; United Nations 2023; Intergovernmental Panel on Climate Change [IPCC] 2023).

The evidence suggests the world is running out of time to live within planetary boundaries and maintain safe operating spaces (Rockström *et al.* 2009; Rockström *et al.* 2013; Gupta *et al.* 2024; van Vuuren *et al.* 2025). A course change is needed to alter the direction and character of development. Such a change requires working across scales, inducing deep shifts in values and behaviours, and engaging a diverse range of agents of change in a concerted effort to transform unsustainable systems. In short, existing transformations must be accelerated if we are to achieve internationally agreed targets. The focus on accelerating transformation builds on developments in previous chapters. Chapters 10–11 outline the global implications of continuing current trends and explore possible transformative pathways. Chapters 19 and 20 describe such pathways for different income groups and regions. Chapters 12 and 13 define six principles of transformation and outline seven steps to develop solution pathways in five systems, covered in Chapters 14–18.

While transformation is not new to this Global Environment Outlook, Chapter 21 is unique in that it aims to explain how a sustainable transformation can be accelerated. Much of the answer to the acceleration question lies in three processes (**Figure 21.1**). The first process involves enabling the participation of different agents of change in the co-production of transformative pathways. The second process consists of combining targeted interventions and promoting shifts in values and beliefs to break lock-ins that run across systems. The third process involves empowering agents of change to rebalance power-interest dynamics and form joined-up agendas that help drive forward the other two processes.

Although the chapter presents the three processes separately, they often overlap and feed into each other in practice. For instance, co-production involves engaging with different agents of change to break systemic lock-ins and open opportunities for leveraging motivators. These processes are also complex, non-linear and characterized by feedback loops and uncertainties, mirroring the broader political-economic context in which they operate. Hence, a discussion of governance arrangements that bring together the processes and agents of change as part of whole-of-government and whole-of-society approaches concludes the chapter.

21.2 Co-producing transformations across systems and regions

21.2.1 The scale and pace of change

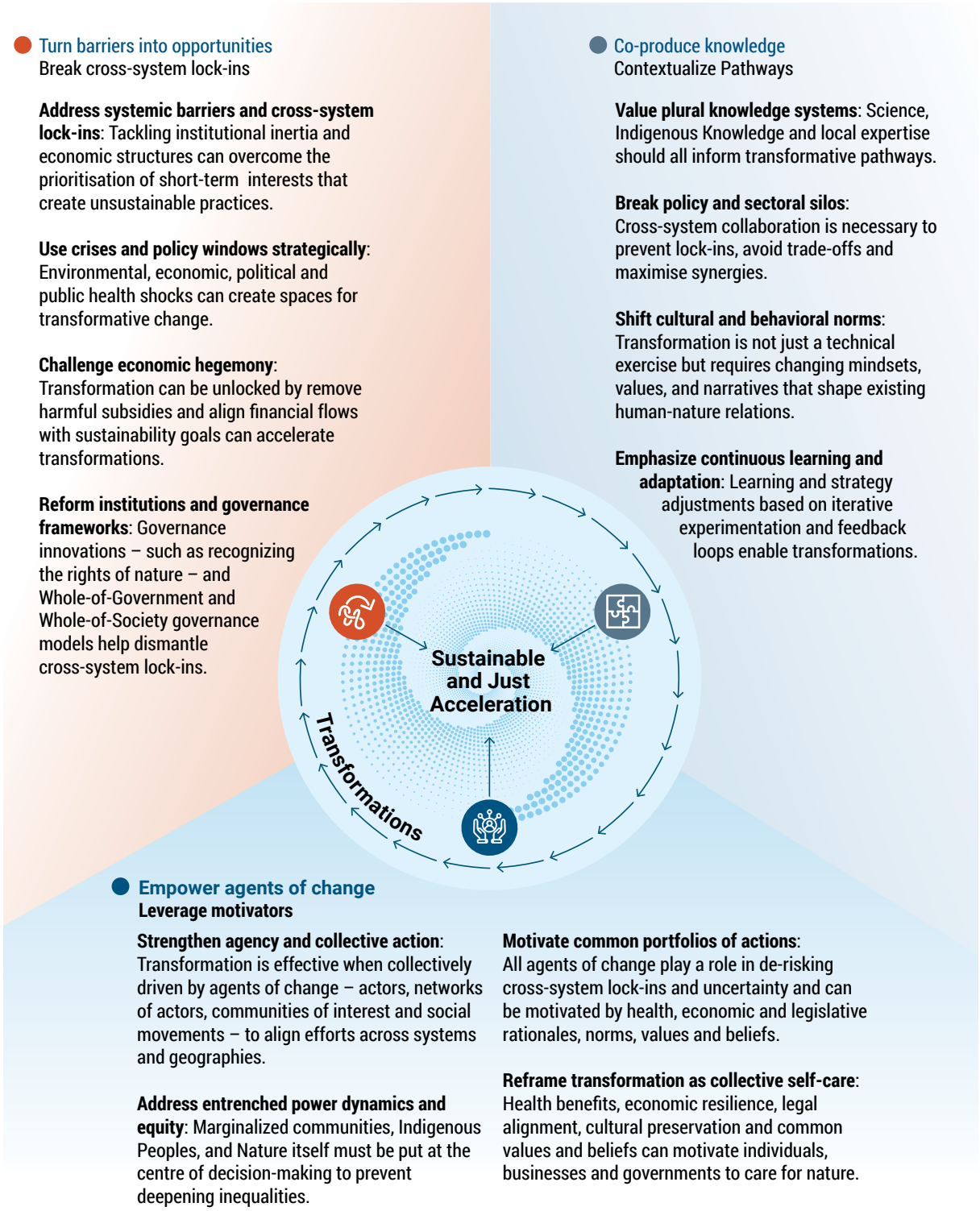
This section begins with a brief review of modelling results on the scale and pace of change, setting the stage for discussion of the co-production process that can help contextualize key insights from the exercise. One of the most important insights from the modelling is that the world needs to dramatically increase the speed and scale of changes to achieve internationally agreed environmental goals. For instance, the modelling shows a need for significant increases in agricultural yields, decarbonization and electrification rates, energy intensity, and dietary shifts between 2020 and 2050. Results related to energy and food systems indicate similar trends.

However, the modelling also underlines options within and across systems and regions that can help make those changes possible. One way to accelerate this large-scale transformation is to capitalize on synergies across energy, food, and other systems. For instance, decarbonizing the energy system can reduce water use for cooling in thermal power plants. This, in turn, can reduce both energy demand and the amount of land used to grow bioenergy products. The spared land could be used for installing large-scale solar installations, while improving agricultural productivity, saving water and preserving biodiversity. Adaptation strategies that build resilience can also complement synergies among energy, food and other systems (**Box 21.1**).

Another way to accelerate transformation is to tailor pathways to countries and regions at different development levels, as shown in 19.6 with a discussion of different approaches to transforming food systems. To illustrate, the modelling shows that low-income countries would benefit from concentrating on technological and infrastructure investments that increase crop yields and reduce energy intensity. At the same time, high-income countries would benefit from focusing on decarbonization

Figure 21.1: How to accelerate a sustainable transformation

A sustainable and just acceleration for all requires systems to transform faster, and at a greater scale, and higher level of cross-system integration and depth.



and electrification, while reducing meat consumption and improving food system sustainability. These tailored approaches can also generate wide-ranging synergies not only across systems but also across regions. For example, decarbonization efforts in high-income countries can lead to positive technological changes, such as the development of more efficient solar panels, that spill over into other sectors and regions (Ndicu *et al.* 2023).

Box 21.1: Adaptation can strengthen integration and acceleration across systems

While transformative pathways require changes in energy and food systems, climate adaptation strategies could enhance resilience within these systems and strengthen synergies between them. For example, in the energy sector, adaptation measures might upgrade infrastructure to withstand extreme weather events while delivering additional benefits for food security. Meanwhile, climate adaptation in food systems can improve water use efficiency to cope with changing rainfall patterns, while also yielding additional energy savings (Nenkov 2024). Further, adaptation can facilitate transformative pathways by reducing risks associated with rapid changes – for instance, in low-income countries where agricultural productivity needs to increase significantly, adaptation measures could include developing early warning systems and crop insurance schemes. These systems could not only protect farmers from climate-related losses but would also help stabilize energy and food systems as they too undergo changes (Ivanova et al. 2020).

21.2.2 Co-producing pathways and sustainable futures

One of the keys to a synergistic and tailored approach to accelerating sustainable transformations is the co-production of pathways. Co-production is a process that enables the participation of diverse agents of change in the creation and application of context-specific, inclusive and plural solutions to complex challenges (Djenontin and Meadow 2018; Moallemi *et al.* 2023). These solutions combine different forms of local knowledge, including post-colonial, feminist and intersectional perspectives, with scientific expertise, including data-driven modelling (Djenontin and Meadow 2018), which can accelerate transformation by increasing the likelihood of acceptance and implementation across diverse communities and systems.

Co-production has several strengths that can facilitate the integration of these different forms of knowledge and ensure that pathways align with the needs of diverse agents of change. For instance, co-production can help build collective ownership while encouraging innovative thinking about sustainable solutions (Polk 2015). It can further forge different interests and place greater emphasis on the governance reforms that could help articulate those interests (Sorrentino, Sicilia and Howlett 2018). Co-production also allows for contestation, empowering marginalized voices that might otherwise be left out of decisions over pathways and futures (Scoones *et al.* 2020).

Many tools can facilitate participation in co-production processes, including foresight tools such as horizon scanning and scenario planning. These tools have proved useful in helping different agents of change consider emerging issues, and multiple outcomes and futures (United Nations Environment Programme [UNEP] and International Science Council [ISC] 2024). Some co-production tools have a less technical orientation; arts-based methods can contribute to modelling by creating inclusive spaces for dialogue and collaboration, encouraging plurality and catalysing new ways of approaching sustainability (Heras *et al.* 2021; van Beek 2025). Importantly, these approaches can transcend hegemonies by creating new imaginary worlds through artistic and experiential methods that enable participants to reflect on sustainable futures (Bendor *et al.* 2017) and inspire local transformations (Bentz *et al.* 2022).

It is nonetheless important to recognize that co-production has limitations and can slow down acceleration. For instance, co-production is often dominated by depoliticized discourses that employ scientific arguments to evoke universalized ideas (Turnhout *et al.* 2020, p. 16). In these cases, scientific knowledge can be ascribed a stronger authority compared to other knowledge systems, including Indigenous ones, due to colonial modernities (Arora and Stirling 2023). Co-production can also be both a knowledge-making and political practice, which can fail without sufficient attention to power imbalances and political structures (Turnhout *et al.* 2020; Chambers *et al.* 2022). Because equality among participants is not guaranteed, elite participants can use their resources to manipulate processes to advance their own interests.

Making co-production sustainable and inclusive requires efforts to recognize and work around these limitations. This can entail ensuring that co-production is intentional and embraces pluralism in the production of knowledge. It can also involve amplifying marginalized perspectives so that they can challenge existing hegemonic perspectives and formations (Scoones *et al.* 2020; Hamilton and

Ramcilovic-Suominen 2022; UNEP and ISC 2024). Finally, co-production can be guided by ethics of care (UNEP and ISC 2024) and include representations of nature in decision-making (Puig de la Bellacasa 2017), drawing on relational philosophies and practices that are familiar to different Indigenous Peoples (**Box 21.2**). These approaches can ensure co-production helps to contextualize transformative pathways and futures, speeding up the pace of transformation.

21.3 Overcoming barriers and breaking lock-ins

This section focuses on two key challenges in transforming systems: system-level barriers and cross-system or systemic lock-ins. It begins by organizing barriers at the system level and progresses to breaking the lock-ins that form across systems due to the interconnections between them.

21.3.1 Identifying and organizing barriers

Barriers are deeply embedded obstacles that prevent change in key systems and reinforce status quo decisions and development patterns. While there are many ways to classify barriers, this section organizes them into economic and financial, social, environmental, institutional or political, and technical categories. This classification is helpful as barriers tend to be context- and system-specific (**Table 21.2**). Their specificity makes it relatively straightforward to determine ways in which they can be overcome.

While it can seem relatively straightforward to remove a barrier on paper, it is important to recognize the underlying reasons barriers exist. These range from sunk costs in existing infrastructure to institutional processes embedded in laws, policies, and bureaucracy to established markets with high entry costs. Other sources include easy access to capital for business-as-usual investments and elites that control resources and power. Yet another set of reasons for barriers are environmental values favouring established practices, irreversible biophysical changes such as land use, knowledge shaped by inequalities and hegemonic perspectives, and established consumptionpatterns (Goldstein *et al.* 2023).

21.3.2 Cross-cutting lock-ins

Lock-ins are systemic inertias that arise from mutually reinforcing collections of barriers that make their combined effects greater than the sum of their individual parts (Elliot 2011; Stoddard *et al.* 2021). These combinations can lead to self-reinforcing dynamics that promote overconsumption, perpetuate inequities, and prioritize profits over

Box 21.2: Aspects of desired futures according to Indigenous Peoples

- Spiritual reconnection and respect for the values of "good living" as embodied in concepts of care, for example, Sumak Kawsay of the Quechua Peoples.
- Territories of life cared for and managed by Indigenous communities and guided by Indigenous Knowledge, organization, and spirituality, and recognizing Indigenous human rights.
- Strengthening food sovereignty based on the rescue of traditional agriculture and fishing, and the promotion of agroecological practices.
- Sustainable, social and solidarity economy, not the exploitation and commodification of natural resources.
- Financing and accountability whereby Indigenous Peoples can manage funds, and enhanced accountability for the effects of funding extractive and polluting practices.
- Generating climate forecasts with farmers, pastoralists and national meteorological systems through on-farm rainfall data production through stakeholder engagement processes.

Sources: UNEP and ISC (2024, p. 34-37) and Figure 2.2, IK&LK Chapeau D.

Table 21.2: Illustrative examples of different types of barriers across the five key systems

Barriers	Economic System	Materials/waste System	Energy System
Economic and financial	• Resource-intensive development models • Pricing structures that fail to internalize externalities • Subsidies for unsustainable products/practices • Limited access to green financing	• Market dominance of virgin materials • Low costs of single use products • Fragmented supply chains • Trade barriers to recyclable materials	• High initial costs – sometimes perceived – of low carbon technologies • Fossil fuel subsidies • Lack of finance for energy efficiency • Grid connection costs • Energy dependency • Monopoly of large-scale energy providers
Social	• Cultural norms of overconsumption • Workforce skill gaps • Short-term thinking • Social stigmas around alternative economies • Economic inequality and injustice • Promotion of extraction and exploitation of nature	• Lack of awareness and education of lifecycle effects • Consumer preference for new products • Norms around disposability and recycle-reuse-repair • Social stigma around alternatives modes of production and consumption.	• Perceived high costs of renewable energy • Not in my backyard (NIMBY) • Lack of customer demand for low-carbon energy • Energy poverty and inequality • Identity issues
Environmental	• Land and resource scarcity • Unaccounted environmental risks and costs • Environmental externalities	• Inefficient recycling systems • Natural resources depletion • Poor waste-to-energy practice • Microplastics	• Water use and pollution • Environmental impact of mining • E-waste from renewable-energy technologies
Institutional or political	• Corruption and lack of transparency • Political polarization • Institutional inertia and silos • Limited institutional capacity • Regulations and legislation that support unsustainable practices	• Lack of regulations and legislation • Waste management systems • Lack of institutional collaboration • Lack ofCorruption and lack of transparency • Political polarization • Institutional inertia and silos • Limited institutional capacity • Regulations and legislation that support unsustainable practices multi-level multi-scale coordination	• Fossil fuels' political and lobbying groups • Centralized large-scale energy providers • Energy market structure/ governance
Technical	• Outdated infrastructure • Lack of skills • Dependence on foreign markets and access to markets • Weak digital economy	• Materials contamination • Availability of close-loop systems • Limited technology and processes for material disassembly/ recovery/ upcycling/ reuse/ remanufacturing	• Intermittency of renewable energy • Availability of energy-storage technologies • Energy conversion efficiency and transmission losses • Grid capacity

Barriers	Food System	Environmental System	Cross-cutting
Economic and financial	• High costs of sustainable foods • Subsidies for industrial agriculture • Cost of land and water • Import dependency • Limited demand for organic or sustainable produce	• High costs/lack of investment in pollution-control technologies • Short-term economic priorities • Lack of investment in conservation • Profit-driven resource exploitation. • The true cost of our production systems and their products	• Dominance of anthropocentric worldviews • Growth-oriented development • Market competition and short-termism • Inequality • Vested interests, regulatory capture and corporate controls • Lack of policy integration • Lack of whole-of-government and whole-of-society governance models • Unsustainable habits, behaviours and social norms • Resistance to change • Lack of awareness and education • Lack of whole-of-government and whole-of-society governance models • Unsustainable habits, behaviours and social norms • Resistance to change • Lack of awareness and education
Social	• Cultural food preferences • Food deserts • Food insecurity • Resistance to change in diets and food habits • Limited awareness of environmental impacts of dietary choices • Unhealthy food behaviours	• Attitudes towards nature and human-nature relationships • Environmental inequality and injustice • Limited acceptance of pollution control technologies and clean fuels. • Perceptions of environmentalism as a luxury	
Environmental	• Water scarcity • Soil degradation • Use of fertilizers and pesticides • Match between crops and climate	• Geography • Climate conditions • Climate change • Invasive species • Deforestation	
Institutional or political	• Dominance/ influence of market/ corporate forces • Globalized food chains • Agricultural policy • Lack of support for small farmers/ agroecological practices	• Lobbying by polluting industries • Lack of environmental legislation and regulation • Prioritizing development over conservation • Lack of political will for climate action • Climate deniers	
Technical	• Crop yields • Irrigation systems • Pest and disease control • Outdated farming technology/ infrastructure • Food processing/ storing/ transportation technology	• Availability of pollution control and clean technologies • Lack of biodiversity/ climate change monitoring models/ tools • Water purification/ desalinization technology	

people (Béné 2022; Beery *et al*. 2023). Such dynamics are partially attributable to the fact that lock-ins tend to work across systems (Seto *et al*. 2016; Unruh 2000; Unruh 2002).

For example, a carbon lock-in occurs when centralized fossil-fuel energy systems create self-reinforcing inertia, hindering alternative technologies. This is driven by economic and policy disincentives, public acceptance, and energy-dependent lifestyles (Rydin and Turcu 2019; Goldstein *et al.* 2023). It can also be driven by high sunk costs and long capital lifetimes that can, for instance, make it challenging to decommission coal-fired power plants. Such lock-ins can occur in cities where structural political and economic drivers reinforce unequal and environmentallyunsustainable development practices. Additionally, business-as-usual urban planning and complex urban governance networks further entrench thesebarriers (UNEP and UN-Habitat 2021, p. 26).

Food systems are locked into industrial farming by multinational corporations, driven by high-yield monocultures, intensive use of chemicals and large-scale mechanization (Béné 2022). High-tech farming is seen as the key to success, discouraging sustainable practices due to economic and social barriers. Global factors such as corporate dominance, financial markets, deregulation, privatization, and austerity further channel capital into unsustainable commodity agriculture, making food systems less sustainable and healthy.

Similar lock-ins can be found in the forestry sector, where commodity-driven deforestation is fuelled by institutional and corporate interests, disproportionately affecting lower-income regions. At the same time, high-income countries drive demand for products like palm oil and cocoa (Santika *et al.* 2023). Corporate zero-deforestation pledges face economic and institutional barriers, including low market adoption, loopholes, weak compliance, and limited scope, yielding minimal results (Lambin and Furomo 2023). Modest progress has been made with region- and commodity-specific zero-deforestation commitments, but scaling requires broader corporate adoption and market coverage (Lambin and Furumo 2023).

Lock-ins are mostly problematic because they interact across systems, such as those involving energy, food, and materials/waste. Such cross-system lock-in occurs in industrial agriculture, which relies on fossil-fuel-based fertilizers, mechanization and global supply chains. This dependence reinforces high energy consumption and waste generation, while limiting the adoption of regenerative farming, local food systems, and circular practices such as composting and bioenergy production. Interconnected lock-ins perpetuate resource inefficiencies and environmental degradation and pose significant challenges for resource management and sustainable development (Horlings 2018). They can lead to stranded assets, where abandoned infrastructure investments cause environmental harm in countries unable to afford transformation (Heras and Gupta 2023).

21.3.3 Overcoming multiple barriers to break cross-system lock-ins

To drive transformation, systemic lock-ins must be understood and turned into opportunities, with interventions focused on removing specific barriers or system-specific lock-ins that reinforce each other. Interventions may include reducing initial investment costs or removing harmful subsidies to address economic barriers. Social barriers can be tackled through programmes that raise public awareness and promote the public acceptability of sustainable alternatives. Legal reforms aimed at enhancing transparency in budgeting and contracting can help reduce corruption and overcome institutional or political barriers. Advances in data and management technologies may also remove barriers to creating pathways for sustainable change (**Box 21.3**).

The most effective approach is often when multiple interventions are combined to build public support for reforms. For example, the city of Rosario in Argentina successfully navigated systemic lock-ins by fostering democratic decision-making over resources at the district level. The Rosario Habitat programme improved informal settlements, living standards, and tenure security, while the Rosario Urban Agriculture programme integrated urban farming into land-use planning and enabled participatory budgeting to redistribute resources and strengthen community capacity building (UNEP and UN Habitat 2021, p. 177).

Cities can utilize various entry points to transform system-level barriers into opportunities and overcome

Box 21.3: Data, barriers and lock-ins

Transformative change relies on access to, management of, and analysis of high-quality environmental data. From in situ measurements to satellite remote sensing, this data forms the foundation for informed decisions (ITU News Magazine 2020). Advances in artificial intelligence, machine learning, and big data can also help overcome these barriers (Duporge et al. 2021; Robinson et al. 2021). Open data access, open science, citizen science (Landman et al. 2020; Nyadzi et al. 2022; Nkuba et al. 2023), and scientific diplomacy can help extract and share the data necessary for sustainable transformation. Key questions moving forward include how to clear barriers to data sharing and how technological and social changes, such as big data and citizen science, can make more data accessible to accelerate transformations.

cross-system lock-ins. In some Latin American and African cities, vulnerable communities have improved their quality of life by recycling waste while promoting circularity. Local governments have played a key role by providing legal frameworks, economic support, and formalizing these efforts. Some argue that these local urban initiatives – in Bogotá, Buenos Aires, Lima, Quito, São Paulo or Durban – can be scaled by aligning with international processes such as the 2030 Agenda (de Miguel *et al.* 2021).

In the food and agriculture sector, several strategies are employed to promote sustainable agriculture, including land care in Australia, community forest management in India, Nepal, and Viet Nam, and farmer field schools and irrigation user groups in Asia, Africa, and Latin America (Pretty *et al.* 2018). A transformative policy-led redesign of agrifood systems is underway in Andhra Pradesh, India (Bharucha, Mitjans, and Pretty 2020). Similarly, agroecology movements in Brazil show how to create collective spaces for sustainable food alternatives that extend beyond the local scale (van den Bergh *et al.* 2022). Scientific evidence shows that clear, ambitious policies, adequate financing, institutional support, and multi-faceted capacity building can reduce farmers' costs, increase yields, improve farm health with locally sourced inputs, and provide additional co-benefits, making the transformation of the food system more feasible (Bharucha, Mitjans, and Pretty 2020).

Efforts to turn barriers into opportunities should not only focus on new approaches. Many agroecological transformations are supported by Indigenous Peoples who have practised sustainable farming for generations (UNEP and ISC 2024) – Mayan communities in Central America use traditional milpa agroecological and spiritual farming systems that enhance ecosystems (Pretty *et al.* 2018; Bharucha, Mitjans, and Pretty 2020; UNEP and ISC 2024). Other examples demonstrate that recovering and expanding Indigenous foodways – rooted in autonomy, self-determination, care, spirituality, and justice – can support sustainable agroecological practices (Huambachano 2024; Nkuba *et al.* 2021; Nkuba *et al.* 2023).

In some cases, combining science and traditional practices can clear barriers. For example, in the Appalachian Mountains, integrating scientific and local knowledge showed that ancestral apple varieties are more resilient to climate change, suggesting they should be promoted (Veteto and Carlson 2014). Breaking cross-system lock-ins also requires changes to global food system rules, such as reforming financial systems to prevent funding unsustainable food production and promote commons-based, regional food systems (Béné 2022). These efforts can be supported by a clear narrative that challenges unsustainable discourses and highlights why transformation is necessary and achievable (Vaara and Whittle 2021).

Breaking cross-system lock-ins may require leveraging opportunities created by environmental, social, political, or economic crises that disrupt unsustainable systems. For example, air and water pollution crises have sparked major reforms in environmental regulation in countries, such as the United States in the 1970s and China in the 2010s. These kinds of environmental crises can catalyse change and break lock-ins, for instance, leading to the expanded use of solar energy to reduce import dependency, improve the environment, create jobs, and foster innovation (Kussul and Drozd 2023). Similarly, large-scale events like the Olympics, FIFA World Cup, or G7 summits can create opportunities for policy shifts, prompting politicians to propose sustainability initiatives.

In addition to seizing some of these opportunities, deeper shifts in values, such as ethics of care and reciprocity for life, are crucial. Such shifts should focus on deconstructing imaginaries, power structures, and human-non-human relations (Feola, Vincent, and Moore 2021). Goldstein *et al.* (2023) argue that comprehensive analyses of lock-in phenomena can help identify which challenges to overcome and which explanations to prioritize.

There is no one-size-fits-all approach to turning cross-system lock-ins into opportunities. Overcoming multiple interrelated barriers to break cross-system lock-ins benefits from a mix of strategies, including big plans, small wins, and systemic rule changes (Termeer *et al.* 2024). These approaches can gain traction when crises or major events disrupt incumbent interests and existing institutions. Sustainable transformation is also more likely when supported by ongoing efforts to address the underlying causes of cross-system barriers and lock-ins.

21.4 Leveraging motivation

This section focuses on the agents of change who can overcome the interrelated barriers and cross-system lock-ins discussed in the previous section, through common portfolios and joined-up agendas. It also sets out several motivators that can balance power-interest dynamics and strengthen collective action towards cross-cutting system transformation.

21.4.1 Agents of change

Agents of change are entities that perceive a problem as salient or dominant and act in a goal-directed manner to resolve it (Liefferink and Wurzel 2017; Birchall and Bonnett 2021). They enact agency, which can be human – in the form of will, rational deliberation or control over actions and subsequent consequences (Liefferink and Wurzel 2017; Birchall and Bonnett 2021) – and non-human – such as natural forces but also things, plants and animals in Indigenous cultures that drive earthly responses (Duerbeck, Schaumann and Sullivan 2015). Such agents are also material or immaterial, formal or informal, and can form networks and coalesce around a common interest or problem.

Systems exist and co-exist with and within multiple types of agents. Interactions within and across systems among agents can lead to system-wide behavioural shifts, influencing and affecting each other in potentially transformative ways (Arnold and Wade 2015). This is discussed at length in Chapters 14–18. The agents of change are grouped into three categories for ease of understanding (**Figure 21.2**):

- Actors
- Networks of actors
- Communities of interest and social movements

21.4.1.1 Actors

Actors were introduced in 12.4.5 and include individuals, groups, or entities affecting or affected by crises. They hold a stake in outcomes and can intentionally or unintentionally influence, shape, or initiate processes positively or negatively (Chinyioand Olomolaiye 2009). This chapter distinguishes actors from stakeholders to move discussions beyond rights holder debates and human-centred classifications.

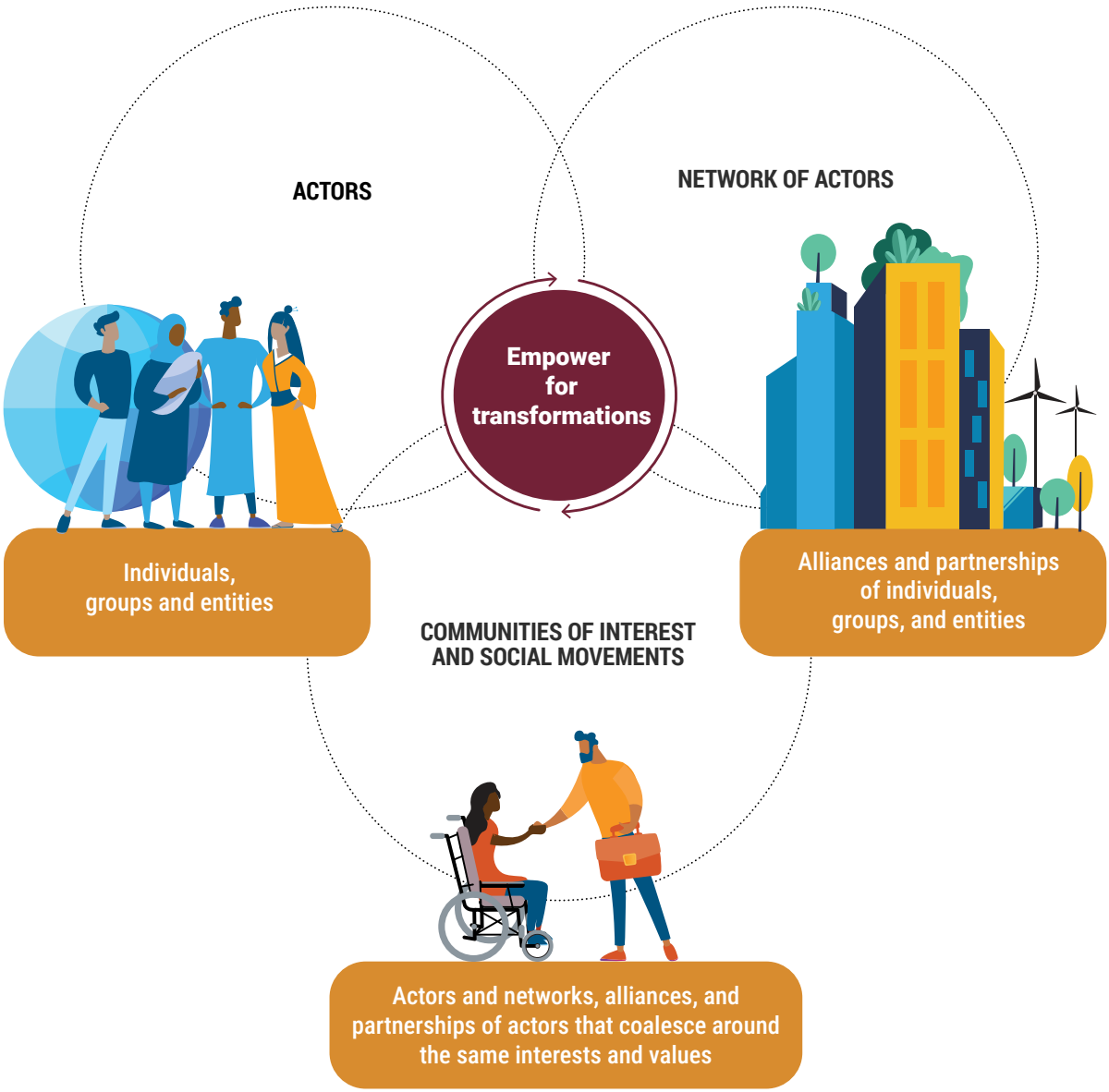
The seven main categories of actors are as follows: governments; intergovernmental organizations; the public including Indigenous Peoples; civil society; the private sector; academia and professional associations; and nature. **Table 21.3** briefly defines and summarizes these actors and their roles. This chapter argues that nature is an actor and must be viewed as an equal partner at the decision-making table. This view builds on IPBES (2019), the EEA's narratives for change series (Benini and Viaud 2020) and UNEP's report on Nature in the Boardroom (2024), but also relational thinking from Eastern philosophy and Indigenous cultures, emphasizing unity between people and nature (Strand *et al.* 2023; UNEP 2024).

21.4.1.1.1 Governments

Governments at the national, regional and local levels can play a pivotal role in transforming systems. They are integral to transformation because they formulate the policies, regulations and strategies that influence a system's direction and priorities. For example, they are typically responsible for formulating and implementing agriculture, trade, nutrition, and overall sustainable agriculture policies that can influence key outcomes and the overall structure of a food system.

National governments are viewed as actors with high powers and interests. For instance, national

Figure 21.2: Three categories of agents of change actors



governments can determine whether to employ market-based or command-control instruments to curb pollution. They can also decide whether to support international programmes such as Energy for All and play a key role in driving both environmentally sustainable and socially just transformations. Local governments vary in power depending on a country's political system and governance structure, such as centralized or decentralized systems. Scandinavian countries have strong national and local governments, while Switzerland, China, and the United States of America have stronger national governments. In Sweden, local governments have significant autonomy in areas like education, healthcare and public transportation – this is strengthened through constitutional guarantees and financial independence (Lidström and Madell 2021).

21.4.1.1.2 Intergovernmental organizations

Intergovernmental organizations play a coordinating and norm-setting role in system transformations at the global level, often with low powers and interests at the national level. They provide guidelines, frameworks, programmes and platforms for global collaboration. Examples include the EU Green Deal driving global sustainability efforts through policy alignment (Oberthür and Dupont 2021; Cordella and Sala 2022) and the UN's

Table 21.3: Categories of actors, their definitions and roles

Actors	Definition	Role
Governments States, federations, ministries, regions, municipalities.	Governance, regulatory, and administrative structures shape national or jurisdiction-wide decisions.	Governs, protects rights, enforces laws, and mediates interests across levels within nation states/ national jurisdictions.
Intergovernmental organizations United Nations, World Bank, European Union, World Health Organization.	Formed by multiple countries through treaties or agreements to collaborate on common issues, such as security, trade, or environmental protection.	Makes international policy, lobbies international laws and regulations, coordinates nations, provides aid, and safeguards planetary health.
The public Laypersons, citizens, voters, local communities, Indigenous Peoples	The collective population of a society or community, including individuals and groups.	Acts on rights, consumes, owns, experiences transformations, and produces citizen science.
Civil society NGOs, Oxfam, Greenpeace, WWF, foodbanks.	The sum of non-governmental organizations and voluntary groups that operate independently from the government at various levels.	Advocates for marginalized groups, lobbies for change, takes a participatory approach, and promotes public interest, social welfare, and community engagement.
Private sector Corporations, multinationals, SMEs, start-ups, banks.	Owned and operated by private individuals or businesses who aim to generate profit.	Delivers goods/services, makes profits, provides investment, and has fiduciary duties to shareholders.
Academia and professional associations Universities, research institutes, engineering/ medical associations	Undertakes education, research, and the advancement of knowledge in specific fields.	Provides education, research, develops standards, and co-produces evidence-based solutions.
Nature Ecosystems, plants, animals, air, water, soil, natural resources.	The physical world exists independently of human 'creation', including living organisms, landscapes, and natural processes, and subsequent resources and services provided.	Contributes intrinsic, instrumental, and relational values, provides ecosystem services, absorbs environmental impacts, and causes unpredictable events like tides, eruptions, and extinctions. It is foundational to the stability, productivity, and long-term sustainability of all human and ecological systems.

Source: Adapted from Ginige, Amaratunga, and Haigh 2018

Global Framework for Climate Services that facilitates the delivery of climate services for Member States (United Nations 2016). Intergovernmental organizations can also set laws for environmental protection, such as the EU's Nature Restoration Law, or put pressure on nature rights under the ICC Legal Framework Concerning Victims (Lostal 2024).

21.4.1.1.3 The public

The public includes individuals as well as communities or groups of people who may not have a formal affiliation (Tsingou 2015). The public can influence system transformation by exercising preferences and choices: changing consumer demand for healthier, sustainably sourced and ethically produced food can drive transformation in the food system (17.2). The public can also influence outcomes by mobilizing to counter environmentally harmful practices. Examples include protests against fracking in the United States of America, leading to policy changes and moratoriums in states such as New York (Negro 2021; Graham and Rupp 2022; Young 2023), or community-led pressures around environmental and health concerns in United

Republic of Tanzania that led the government to re-evaluate its uranium mining policies in the Selous Game Reserve (Kileo *et al.* 2019; Muhanga 2019). The public also drives transformations through citizen science, shaping pathways based on local knowledge and goals for meaningful, measurable change.

21.4.1.1.4 Civil society

Civil society organizations play an active role in driving systemic transformations (Mohr, Raman and Gibbs 2013). While some non-governmental organizations face criticism for imposing their views (Büscher and Fletcher 2019), they can drive transformation and advocate for reducing ecological footprints and improving health and well-being. To illustrate, the Centre for Science and Environment in India campaigned for stricter air pollution standards, leading to the Bharat Stage VI vehicle emissions standards in 2020 (Roychowdhury *et al.* 2019; Khodke, Watabe and Mehdi 2021). The Kenya Climate Justice Women Champions, to highlight another example, have advocated for gender-sensitive climate adaptation and mitigation strategies (Esipisu 2013; Gicheru, Mwenda and Omwami 2024).

21.4.1.1.5 Private sector

Some private sector actors hold significant power and interest in sustainability, particularly in driving transformations in materials/waste (15.2) and energy systems (16.2). With clear policy direction, such actors can play a pivotal role in enabling change. For example, in Germany, Siemens and Volkswagen have supported renewable energy and electric vehicles in line with Energiewende (Pons-Seres de Brauwer 2022). At the same time, private sector choices can also slow transitions, as in Australia, where BHP Group, formerly Broken Hill Proprietary Company, was criticized for fossil-fuel investments that conflicted with renewable energy goals (McDonald *et al.* 2023). Large agribusinesses and food retailers influence food systems by shaping production, supply chains, and marketing, and making food decisions that can drive changes in the types of foods available and their effect on health and the environment. In Brazil, for example, JBS multinational has been linked to deforestation through large-scale cattle ranching (Rajão and Soares-Filho 2015), while in Indonesia, Wilmar International's palm oil production has had impacts on biodiversity (Brandi *et al.* 2015). Small-scale farmers' and food producers' can strengthen resilience in the food system through agroecological practices and socially inclusive approaches, though their influence may be more locally situated. Across regions, private sector actors are sometimes challenged for market-driven interests and greenwashing, however, their remain key to sustainable transformations. Environmental regulations and public education are important strategies to counteract this tendency (Flores and Rodríguez 2013).

21.4.1.1.6 Academia and professional organizations

Academic institutions and professional organizations drive system transformation through research, innovation, knowledge sharing, and educating future generations for societal change. Academic research informs policy- and decision-making processes and provides support for evidence-based projects and initiatives. Research-based organizations continuously experiment and seek alternatives by, for example, using art to unpack ontologies and values. Moreover, the academics that work in these organizations are often using feminist-, intersectional-, Indigenous- and decolonial-based perspectives to challenge the existing understanding of the environment (Arora and Stirling 2023).

21.4.1.1.7 Nature

Nature encompasses all living and non-living things that occur naturally without human intervention, including flora, fauna, resources, soil, water, and air. Some regard humans as part of nature, with Indigenous Peoples, Shintoists, and Buddhists perceiving nature as a complex web of life, where humans are integral to nature in a 'vital complementarity' that entails associated obligations and responsibilities for care (UNEP and ISC 2024, p. 18). Recognizing the perspectives and associated practices in which humans coexist with nature (IPBES 2022) is central to sustainability transformations. This requires shifting from anthropocentric to biocentric, ecocentric, and pluriversal approaches, and viewing nature as having intrinsic value and holding the knowledge and agency that drive transformation. Nature's agency is shown through unpredictable events that can either benefit or devastate ecosystems, such as the Permian-Triassic Extinction – which wiped out 90 per cent of marine species and 70 per cent of terrestrial species

– and volcanic eruptions and tsunamis that have been the cause of death over many millennia (NCEI/WDS 2024).

21.4.1.2 Network of actors

Actors seldom act in isolation. They form alliances or partnerships called networks of actors that not only help to break different kinds of lock-ins, but also determine system, societal and geographical conditions. **Figure 21.3** shows the complexity of networks of actors involved in the decarbonization of Romanian housing. Six networks of actors, forming constellations of interests and powers and linked by feedback loops, span multiple sectors and scales in the energy and housing systems (Turcu 2017).

Other networks of actors include UN regions, development categories such as high-income countries (HICs), least developed countries (LDCs), and small island developing states (SIDS), and cities. Cities are at the forefront of fighting multiple crises and are seen as instrumental in implementing solutions that can drive systemic transformations, overcoming barriers and lock-ins. They often lead from the front by rejecting coal and promoting clean energy, as well as advancing circularity by promoting zero-waste policies (Turcu 2023; Pincetl 2017). Cities play a growing role in climate negotiations over issues such as nationally determined contributions, the global goal for adaptation, and the loss and damage fund, with the Intergovernmental Panel on Climate Change planning a dedicated report on cities for the seventh assessment cycle.

21.4.1.3 Communities of interest and social movements

Communities of interest are actors or networks of actors united by shared values or goals, often collaborating to address issues such as rights, environmental protection and social justice (Turcu 2010). Communities of interest, also known as alliances, partnerships or assemblages, tend to transcend geographical boundaries and can unite activists, scientists, policymakers, governmental bodies, private businesses, their networks and associated resources. Examples include slow-food communities and food councils that advocate for sustainable agriculture and food localization, Zapatista groups for Indigenous justice in southern Mexico, and the International Land Coalition supporting Indigenous land rights and management. Communities of religious or spiritual interest can also drive system transformations by leveraging their moral authority, organizational capacity and influence to change social values, norms, behaviours and practices. The Catholic Church's 'Laudate Deum' and Interfaith Power & Light advocate for climate action and reducing carbon footprints (Northcott 2015).

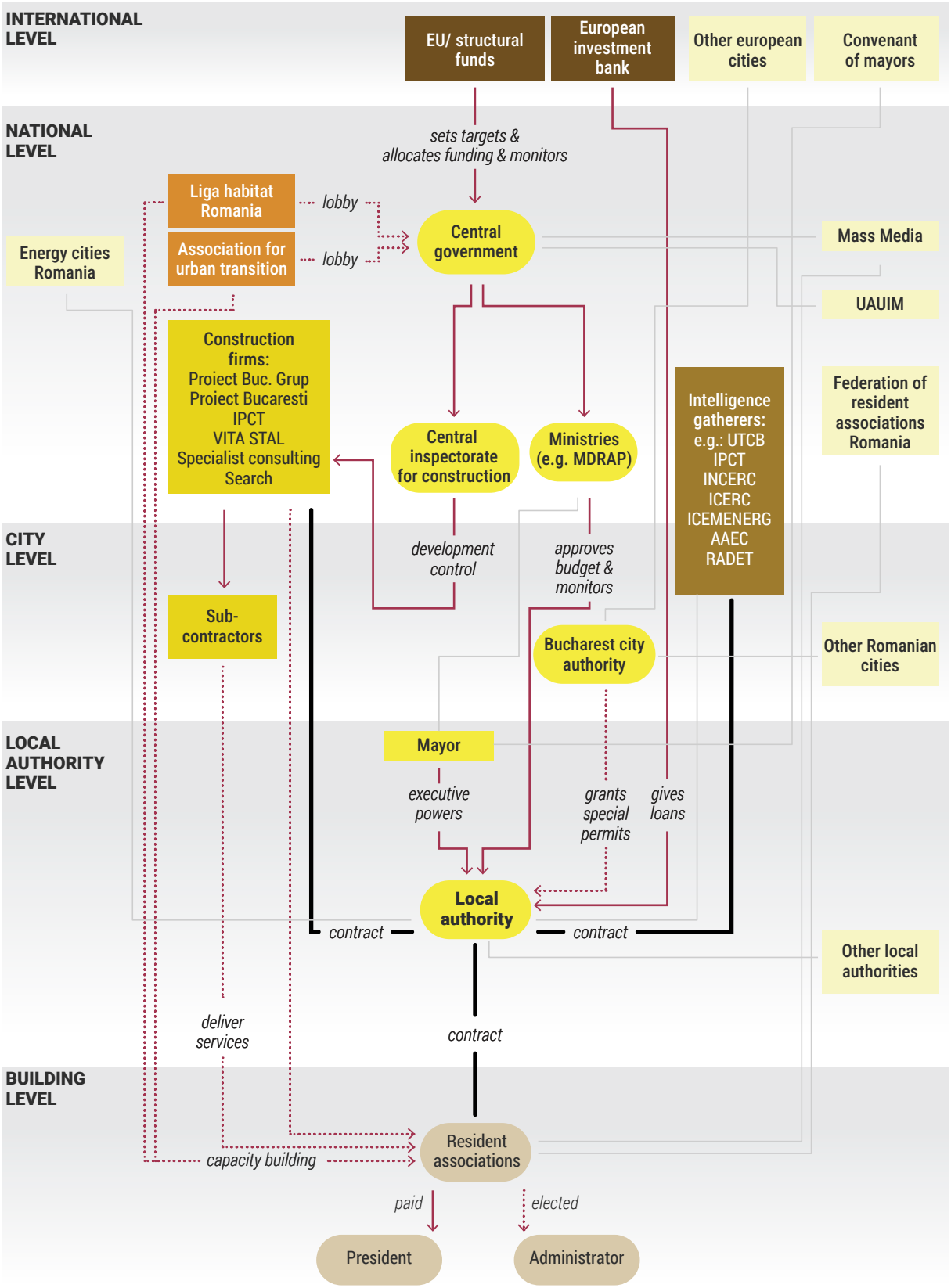
Social movements are collective actions by actors or networks of actors aiming to shift values and practices, for example, climate, youth, or educational movements. They campaign for environmental justice, engage grassroots communities, build shared identities, expand political opportunities, and mobilize resources to drive sustainability (McAdam 2017). For instance, Fridays for Future, led by Greta Thunberg, mobilizes youth worldwide for climate action, influencing policy reforms in Sweden, France, the UK and Germany (Thunberg 2021). Other examples include India's Chipko and Niyamgiri movements, the Chico Mendes movement in Brazil, Buen Vivir in Latin America, West Harlem Environmental Action in the United States of America, and Africa's Alliance for Food Sovereignty (Arora and Stirling 2023).

21.4.1.4 Power-interest dynamics

Agents of change are framed by power-interest dynamics. Power is the ability to act and create change, while interests involve holding a stake in outcomes through authority, responsibility, ownership and influence (Chinyio and Olomolaiye 2009). Power-interest dynamics shape change by influencing voices and solutions. For example, in the energy system, corporations and governments drive transformation through financial and regulatory power (Sovacool 2016), while in the materials/waste system, power-interest dynamics among agents of change shape circular practice development and implementation (Turcu and Gillie 2020).

The two-by-two Mendelow's Matrix (1981) provides a useful tool to map, categorize and manage agents based on their power and interests. **Figure 21.4** highlights how some agents are marginalized in decisions that shape their future due to their perceived low power or interest in environmental transformation. Traditionally, multinational corporations hold high power and interests, while the public and individuals have low power and interest. Non-governmental organizations and grassroots organizations have high interest but low power. Driving transformations requires empowering all agents, addressing power imbalances, and increasing engagement. **Figure 21.4** suggests strategies to achieve this.

Figure 21.3: **Six networks of actors in housing decarbonization in Romania: handlers, controllers, intelligence gatherers, deliverers, non-governmental, clients**



Source: Adapted from Turcu (2017)

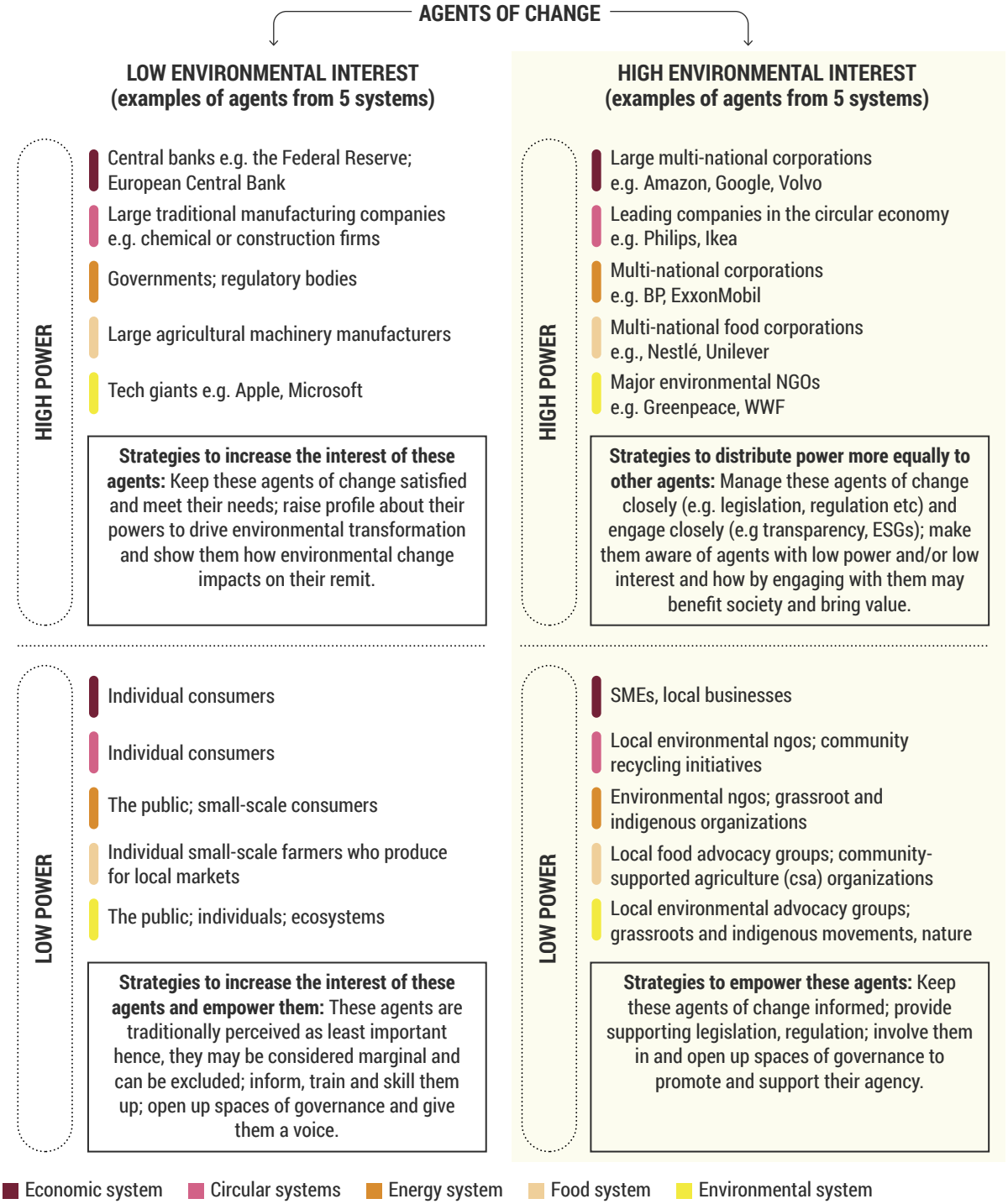
21.4.1.5 Common portfolios and joined-up agendas

Collaboration among agents of change helps overcome barriers and lock-ins, turning them into opportunities. This often entails developing common portfolios to drive transformation. A common portfolio approach mitigates risks, cross-system lock-ins, and uncertainties by fostering collective action and aligned agendas (Pereverza, Dierks, and Järvelä 2022).

Figure 21.5 shows how agents collaborated during the COVID-19 pandemic in London to create a common portfolio of actions in response to disruptions to access to food, highlighting the need for a more resilient urban food system (Turcu and Rotolo 2022).

The ban on single-use plastics across the world shows multi-agent partnerships driving significant environmental change through common portfolios of shared initiatives. Over 91 countries, including over

Figure 21.4: The power-interest matrix with examples from the five GEO-7 systems



30 in Africa, have banned single-use plastic bags, with Kenya enforcing the world's strictest ban in 2017 (UNEP 2018) and the EU's 2021 ban on single-use plastics like straws, cutlery, and cotton buds marked a major shift in its environmental and waste policies (European Commission 2021).

21.4.2 Key motivators

Accelerating a sustainable transformation often requires motivating agents of change into action. Motivations reach beyond domains of intentional action – such as levers, defined in 12.5 – to the ontological claims underpinning such action. Motivators are sets of constructs that induce agents of change to take action. Motivators stem from external and internal factors – including economic, technological, regulatory, and psychological factors – and can be explained in various ways (**Figure 21.6**). These motivators influence agents of change and systems, shaping perceptions of right and wrong, feasibility, legality, and ethical responsibility beyond individual actions (Turcu 2018).

Four categories of motivators are identified in this chapter:

- Health and well-being
- Economic and financial stimuli
- Regulatory frameworks
- Culture, imaginaries, social norms, common values and beliefs

Table 21.4 shows how the four motivator categories frame agency and drive action from agents of change based on different theoretical perspectives from **Figure 21.6**.

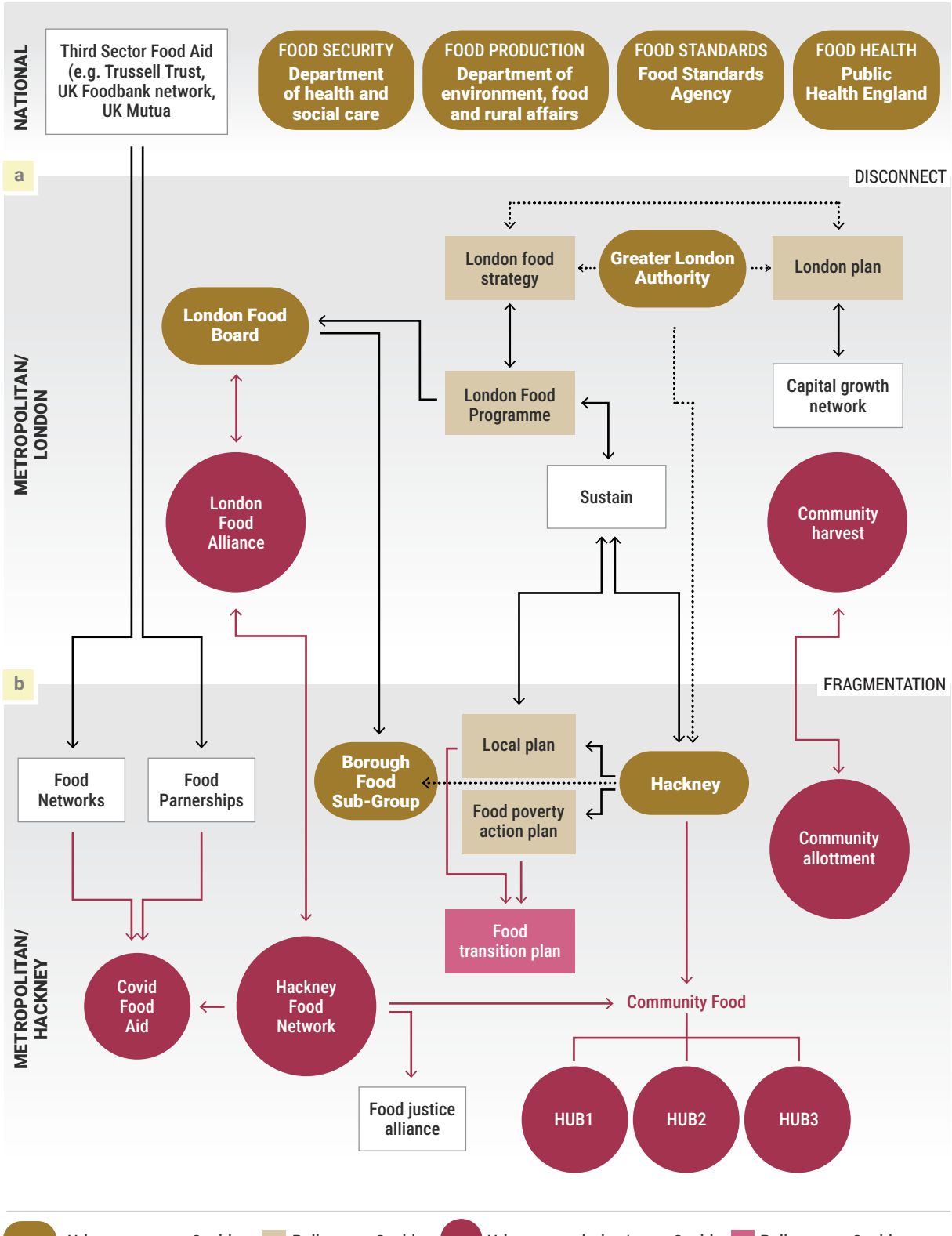
21.4.2.1 Health and well-being

A fundamental motivator for agents of change is ensuring their survival, health and well-being, which in ecological terms means preserving the vitality of ecosystems for human life. This has gained attention in environmental policy due to evidence linking planetary and human health, with studies showing that climate change, biodiversity loss, pollution and

Table 21.4: Explaining how agents of change are motivated to action through the various theoretical 'lenses described in Figure 21.6

Motivators	Understanding motivators through different theoretical lenses
Health and well-being	• Agents of change are motivated by scientific evidence about environmental crises and their measurable threats and implications on health and well-being (positivism) • Agents of change are motivated by their interpretation of health risks, drawing on dominant cultural norms, social understandings, their experiences and social interactions. (interpretivism and phenomenology)
Economic and financial stimuli	• Agents of change are motivated by economic incentives, such as subsidies and profit margins, that make transformation financially viable. (pragmatism) • Agents of change are motivated by economic policies and market forces; however, they are co-creators of these forces, capable of resisting, reinventing or innovating on the basis of their interests. (critical realism)
Regulatory frameworks	• Agents of change are motivated by laws and regulations, and when their actions are incentivized or penalized. (structuralism) • Agents of change are motivated by legislative or regulatory incentives and sanctions, but they interpret, resist or creatively adapt to restrictions. (critical realism)
Culture, imaginaries, social norms, common values and beliefs	• Agents of change are motivated by societal imaginaries and common values and enabled or deterred from action by cultural and social norms. Transformation is driven by changing imaginaries, cultures, social norms, values and beliefs. (Interpretivism and constructivism) • Agents of change are motivated by changes in cultural narratives and power dynamics, determined by the inclusion of marginalized groups and Indigenous Peoples. (Post-structuralism)

Figure 21.5: Agents of change in the food system



a There is no unitary national food policy in the United Kingdom of Great Britain and Northern Ireland. Most cities do not have food policy strategies, London is an exception.

b Local strategies/policies. Take direction from the Greater London Authority/ Mayor of London strategies/ policies but are not legally bound by them.

Source: Modified from Turcu and Rotolo (2022)

Box 21.4: Definitions of health

Health and well-being – The World Health Organization defines health as "complete physical, mental and social well-being and not merely the absence of disease or infirmity", recognizing the interconnections between social, psychological, and medical factors.

Planetary health – Emphasizes the interconnectedness of human and planetary health, using a holistic approach to promote health, equity, and sustainability amid global environmental challenges.

One Health – Acknowledges the interconnectedness of human, animal, and environmental health, offering a framework for evidence-based policies and solutions to protect all three.

land degradation harm both human and planetary health (Crane *et al.* 2021). The recognition that human and planetary health are interconnected has led to efforts to better assess the health effects of environmental policies and vice versa, with current research documenting, for example, the health co-benefits of climate action (Turcu 2025). This need for integration is highlighted in the 2023 Lancet Countdown Report, which stresses the "imperative for a health-centred response to irreversible environmental harms" (Romanello *et al.* 2023).

Scientific evidence highlights the strong link between climate change and health, emphasizing direct and indirect effects, health inequalities, economic costs, and the health co-benefits of climate action. These arguments can motivate or induce change by demonstrating how climate policies save lives and reduce healthcare costs (Romanello *et al.* 2023; Turcu 2025). Costa Rica, for example, has been successful in integrating its economic model with health, education and environmental development (**Box 21.5**).

Agents of change are increasingly using health and well-being as a justification for accelerating transformation, and there is a growing interest in how nature and health reinforce each other (**Box 21.6**). Nature-based solutions, nature restoration, and rewilding policies can boost biodiversity, promote physical activity, improve health, reduce environmental stress, and enhance cooperation among agents of change. Indigenous Peoples and relational philosophies and ways of living teach us that humans are part of a living whole, emphasizing harmony on nature (**Box 21.7**).

21.4.2.2 Economic and financial stimuli

Driving transformations often involves shifting away from dominant economic paradigms and market values. Arguments about the limits to growth are not new, and evidence shows that green growth is too slow, small-scale, and short-lived, suggesting a need to shift toward 'beyond-GDP' models. However, some agents of change may initially require economic

Box 21.5: Costa Rica's government makes bold investments in public health, education, and environmental protection

Costa Rica outperforms its Central American neighbours in quality of life and is among the world's happiest and most sustainable countries according to The Happy Planet Index (The Hot or Cool Institute 2021). Since abolishing its army in 1949, Costa Rica has prioritized social investment through tax reforms, funding public health, education, and environmental protection (Oviedo et al. 2015). This approach has led to universal healthcare, pensions, and primary education, resulting in high literacy, low infant mortality, long life expectancy, and relatively low poverty by Latin American standards. Costa Rica has set up the world-renowned Green Trademark, a payments for environmental services programme, and a thriving ecotourism industry by prioritizing biodiversity. Further, over 99 per cent of Costa Rica's electricity comes from renewables, with fossil fuel taxes helping to fund forest protection (Bertelsmann Stiftung 2013). Achieved with a fraction of Western resources, these efforts have led to well-being indicators comparable to or above the OECD average (OECD 2017).

Figure 21.6: How varying theoretical lenses describe motivations or motivators

Positivism

External factors - economic, technological, and regulatory - drive human agency and shape collective action (Riley, Emigh and Ahmed 2021; Verbeek 2023).

Critical Realism

Behaviour is shaped by both societal structures and agent agency and, action influenced by constraints and choice (Dreyer et al. 2022).

Post-positivism & Structuralism

Psychological structures - cognitive bias, values, norms, and perceptions - shape human behaviour (Sussman & Giffort 2019; Falcone et al. 2024; etc.), and influenced by social and cultural factors - such as norms, language, stereotypes, and power hierarchies - followed by individuals subconsciously.

Human action is guided by societal rules and structures, and agents of change act in alignment with their cultural context and values.

Poststructuralism & Relationism

Challenge universal structures in language and culture, emphasizing the politics of knowledge, role of institutions, and the agency of non-humans (Puig de la Bellacasa 2017; Haraway 2016).

Pragmatism

Human agency is driven by practical outcomes - such as impact, competence - and their ability to shape desired futures (Emirbayer & Mische 1998; Goller 2017).

Interpretivism, Constructivism & Phenomenology

Build on the post-positivist and structuralist construction of psychological structures and view human agency as dynamic and subjective, emphasizing that actions stem from personal interpretations of surrounding contexts (Blumer 1969; Franzese & Seigler 2020).

and financial incentives to align their interests and recognize the benefits of their actions. An increasing number of businesses recognize the need for profound changes in resource-intensive systems to sustain their ventures, as reflected in several prominent economic forums. For example, the World Economic Forum (2022) recognizes the need for systemic transformation for and by business, while the World Business Council for Sustainable Development (2020) advocates for transformative changes in sustainable systems.

In addition to more conventional economic and financial stimuli, nature-positive economic approaches are also gaining traction globally, recognizing a dependence on nature. For instance,

Box 21.6: The multiple benefits of nature

Growing evidence highlights that forging connections with nature has multiple benefits – sometimes referred to as the health benefits of nature connectedness. Natural elements such as parks, urban forests, and wetlands enhance biodiversity and water quality while promoting physical activity, relaxation, and social connections. These elements improve health and well-being while helping communities adapt to climate change by cooling temperatures, improving air quality, managing floods, supporting groundwater, and sequestering carbon (Turcu 2025). Many frameworks and resources help agents of change leverage the benefits of nature to enhance sustainability, health, and quality of life. Examples include ICLEI's BiodiverCities, C40's Urban Nature Accelerator and the UK's National Biodiversity Network.

the UK, in partnership with the UNDP's Biodiversity Finance Initiative and Financial Sector Deepening Africa (FSD-Africa), launched the Nature-Positive Economy programme to help less-developed countries transition to nature-positive economies. The programme supports the management of nature-related financial risks, the integration of nature into decision-making, the development of Action Plans for Nature, and the enhancement of evidence sharing (Dasgupta 2021).

21.4.2.3 Regulatory frameworks

Legislation and regulations aim to protect the common good and public interest, primarily from a human-centric perspective. Regulatory frameworks ensure resource distribution, sanction non-compliance, and limit harm to health and well-being. They define agents of change roles and responsibilities for the environment and support transparency and accountability.

Scientific evidence shows that environmental legislation and regulations often far outweigh their costs and can drive innovation and transformation across systems, with economy-wide benefits. This contrasts with the common belief that regulatory frameworks hinder market function, productivity, employment, and international competitiveness (Dechezleprêtre and Sato 2017). In reality, developed countries tend to have stronger environmental regulatory frameworks (Li and Ramanathan 2018; Stef and Ashta 2023), while evidence shows that in countries with a weak rule of law, corruption, injustice, inequality are associated with higher environmental degradation: and socioeconomic disparities.

Legislation and regulation can motivate agents to act and are viewed as key drivers in UNEP's Environmental Rule of Law. This report stresses that, amid multiple environmental crises, the environmental rule of law is more crucial than ever (UNEP 2023). It further finds that the COVID-19 pandemic positively influenced environmental legislation, with greater recognition of environmental rights, improved enforcement, and increased accountability. The report also highlights women's role in environmental reform, and the opportunities technology presents. However, it notes that the focus on climate change legislation often overshadows other environmental challenges.

Some countries have grounded their development and democracy in environmental legislation and regulation. Sweden's Environmental Code, established in 1998, consolidates 15 laws to ensure a healthy environment for current and future generations. It includes the polluter pays and precautionary principles, as well as advocating for product choice, resource management, recycling, and rules for appropriate site selection for activities. In 2017, this was complemented by a climate policy framework featuring a climate act, climate targets, and a climate policy council to help achieve net-zero GHG emissions by 2045 (Matti, Petersson, and Söderberg 2021).

Recently, there has been growing recognition that human-centric environmental laws can be complemented by those acknowledging nature as a rights holder. Earth jurisprudence is a legal philosophy that views humans as part of a broader community, where the welfare of each member depends on the well-being of the Earth as a whole (Cullinan 2011). It is closely linked to the legal concept of granting

Box 21.7 Nature-positive economy and the Aymara people

A nature-positive economy prioritizes ecosystem well-being and biodiversity, aiming for sustainable development that benefits both the environment and society. It includes practices such as conservation, restoration, and regenerative agriculture, promoting harmony between human activities and nature for long-term resilience. The Aymara people of the Andes have developed a worldview called "living well", where their needs – food, water, work, and care for the vulnerable – are met in harmony with the environment. This earth-centred philosophy has allowed them to thrive for millennia in harsh conditions without harming their natural surroundings.

natural entities legal personality and recognizing them as subjects of rights.

In 2018, Colombia's Supreme Court ruled in favour of a group of Indigenous Peoples, granting the Colombian Amazon rights to protect it from deforestation. This ruling is consistent with rights of nature, a legal and philosophical framework that has been recognized as helping to conserve biodiversity in many contexts by underlining that nature has rights comparable to humans (IPBES 2022). In fact, several countries, including Bolivia, Colombia, Ecuador, India and New Zealand, have adopted legal mechanisms granting rights of nature or legal personhood to non-human entities (Garver 2020; Darpö 2021).

21.4.2.4 Culture, imaginaries, social norms, common values and beliefs

Cultural and social norms, common values and beliefs can strongly motivate agents of change with action by shaping perceptions, fostering identity and solidarity, and providing a moral compass to guide actions.

Cultural narratives can mobilize social movements by aligning collective action and historical identity, and cultural norms can influence the implementation of policies. Sweden's love for nature is deeply rooted in Swedish culture and frames much of its environmental and sustainable spatial development policies (Turcu 2018).

Social imaginaries – defined as framings that are collectively held in a culture or social group – shape identities, notions of place and relations to others (Castoriadis 1994; Taylor 2004; Jasanoff and Kim 2015). They can be transformative by advancing pluralist and democratic ideas that challenge dominant and unsustainable hegemonies.

Social norms – the unwritten rules governing behaviour – can either support or hinder transformational change. Norms that value innovation, environmental stewardship, or justice can help agents of change by offering social approval, reducing risks, shifting behaviours, and creating tipping points for broader societal change (Bicchieri 2017).

Common values and beliefs from faith, religion, or Indigenous groups form the ethical foundation of society, guiding actions and shaping the aspirations of agents of change. When these agents align their actions with widely shared values, they are more likely to gain broad support and legitimacy. Values-driven transformation can inspire long-term commitments, as demonstrated by Indigenous leadership in sustainable land governance and biodiversity conservation.

About 80 per cent of the global population belongs to a religious or spiritual group (Hackett *et al.* 2012). Emerging evidence notes how religious teachings contribute to environmental protection debates and motivate transformational change by offering moral frameworks and fostering community mobilization.

Initiatives such as the Interfaith Rainforest Initiative, WWF's Sacred Earth: Faiths for Conservation, and UNEP's Faith for Earth: A Call for Action use faith-based principles to inspire environmental stewardship. WWF's Sacred Earth project works with religious communities to integrate conservation into their practices and promote environmental care. Many religions also embrace relational philosophies that connect humans to nature and emphasize ethics of care, which are vital for sustainability transformations.

It is important to note that rarely will all four categories of motivators be equally effective for all agents of change or across different systems, regions, or countries. However, a combination of motivators is more likely to inspire and drive action in sustaining and accelerating transformations. For example, **Table 21.5** illustrates how motivators can be used to align the interests of governments, the public, and the private sector in driving transformations.

Credit: NaturesCharm/Envato

Table 21.5: Using motivators to align the interests of governments, the public, and the private sector to drive transformations

Agents of change	Examples of interests	Examples of motivators for transformation
Governments	• Sustain economic growth, attract investment and improve the country's competitiveness • Comply with international standards • Protect public health • Ensure political legacy • Prevent future crises	• Use EF to support a nature-positive economy, such as Costa Rica's Payment for Environmental Services (PES) • Use RF to define roles and responsibilities for the environment, such as European Green Deal • Use HW to support 'Health-in-All Policies' (HiAP), UK's Ultra Low Emissions Zones (ULEZ), EU's Farm to Fork Strategy • Use SN to maintain political stability and support environmental decisions: New Zealand's legal personhood for nature; Bhutan's Gross National Happiness Policy • Use combinations of HW, EF, RF, and SN to manage risks and develop recovery plans
The public	• Personal and community health and well-being • Access to economic opportunities • Cost savings • Comply with social norms	• Use HW to demonstrate the benefits of unsustainable actions, e.g. smoking bans, sugar and fat taxes, congestion charges • Use EF to create new jobs in the 'green sector', and RF to ensure fairness and inclusion • Use SN and/or EF to reduce consumption or support alternative economic systems and barter communities • Use RF and/or SN to redefine acceptable behaviours, expectations, and sanctions
Private sector	• Reduce costs, increase profit margins; market expansion and competition (EF) • Brand reputation • Customer health and safety • Comply with regulations and legislation	• Use EF to support alternative market models, e.g. circular economy, eco-design, resource efficiency, renewable energy, carbon pricing • Use SN to reframe corporate social and environmental responsibilities, such as IKEA's re-use strategy, Patagonia's eco-friendly fashion • Use HW and/or RF to showcase or regulate health benefits and trade-offs of market choices • Use RF to enforce environmental actions and choices

21.5 Accelerating a sustainable transformation

The previous sections outlined three often related processes needed to drive a sustainable transformation: enabling participation in the co-production of futures and pathways, turning barriers of the existing development patterns into opportunities for change, and encouraging agents of change, including non-human agents, to work with motivators – health, economics, legislation, and norms – to expand these opportunities. This section reflects on not only how these processes can move forward to drive transformation, but also on how a multidimensional sustainable transformation can be accelerated.

21.5.1 What is acceleration and why do we need it?

This section, building on the definition and principles of transformation presented in 12.4 and

12.5, defines and discusses the need for acceleration. While there is no universal blueprint, at the most fundamental level, acceleration requires continually expediting the speed of change to build momentum behind shifts within or across systems. It also entails reorienting those systems around new goals, informed by knowledge of common policy, technology, behavioural feedback and governance system dynamics (Allen and Malekpour 2024).

These rapid changes are necessary because the world is not progressing quickly enough on the sustainability agenda to live within planetary boundaries (Rockström *et al.* 2009; Rockström *et al.* 2013; Rockström *et al.* 2023; Gupta *et al.* 2024). Several reasons exist for why accelerating transformative change is itself urgent, beginning with the fact, as demonstrated throughout the report, that rates of change in key systems are too slow. To illustrate, the rate of decoupling economic development from energy consumption needs to more than double (Marques *et al.* 2018).

A related reason for acceleration is the increasing costs of maintaining the status quo. Delays in altering GHG emission trajectories increase the likelihood of temperature increases, intense storms and other effects that can cross tipping points and jeopardize the achievement of targets in the SDGs Framework, the Paris Agreement or the Kunming-Montreal Global Biodiversity Framework (United Nations 2023). By expediting transformative changes, the world will not only reduce the magnitude of potential adverse effects but also save resources and build resilience to the global environmental crises (Jaffee *et al.* 2018). Simply stated, a sustainable future requires a swift and sustainable transformation of systems.

21.5.2 Toward a multidimensional transformation

While there is a need to transform quickly, a sustainable transformation is likely to fail if it focuses on speed only. Rather, efforts are required to accelerate change, increasing the pace of progress on multiple dimensions of sustainability (Pattberg and Bäckstrand 2023). A narrow focus on rapid change may lead to hasty decisions with unintended consequences that undermine support for the changes across different scales, social segments and agents of change (Rosa 2003; Bardin *et al.* 2008; Colvile 2016; Beck and Rosa 2022). This subsection examines these additional dimensions, starting with space and scale.

Transformation must operate at multiple scales: local, regional, and global. Focusing on scale will help anchor sustainability initiatives in the surrounding context and offer opportunities for spreading success. As underlined in the co-production discussion in this chapter, considering context is imperative because what constitutes a sustainable transformation is relative (Rockström *et al.* 2013). Different parts of the world will have varying starting, entry, and end points, as well as different priorities, resources, and enabling environments (Southern and Jones 2004; Gerk and Qassim 2008).

A second dimension of transformation involves working across sectors and systems. Much like working across levels and scales, a deliberate effort is required to align the interests in key sectors such as economy, energy, and food. Sectoral integration is necessary to avoid fragmented efforts that give rise to inefficiencies, trade-offs or bureaucratic conflicts (Berg 2022).

A third dimension of a sustainable transformation involves different social segments and agents of change. In this context, political and social inclusion merit attention as a policy that accelerates renewable energy adoption could have adverse impacts on communities dependent on fossil fuels. Including distinct segments of society and agents of change as part of a just transition is thus essential, as the notion of transformation might mean different things to different agents of change (Trask 2009; Kuschel *et al.* 2017).

A fourth dimension of transformation pertains to the depth of change. Many of the challenges to a sustainable transformation are not related to deeply held values and ontologies. Changes to these values, goals and paradigms (IPBES 2022), as well as the expansion and spread of participatory, emancipatory and pluralist processes, are needed for a transformation to be sustainable (Scoones *et al.* 2020).

In sum, accelerating transformation is not equivalent to accelerating a sustainable transformation. The latter suggests a more nuanced, multidimensional

Box 21.8: Participatory and inclusive governance reforms that can support a multidimensional transformation

Rapid technological, economic, or societal transformations may generate trade-offs. For example, globalization has resulted in the homogenization of cultural practices, eroding local traditions and languages (Yoo and Yi 2022; Allen et al. 2024). This can lead to identity crises, especially for communities whose heritage is endangered. Societal norms may also be destabilized, as the swift adoption of new technologies and ideas may outpace societal readiness.

Acceleration can result in generational divides, where younger people adopt change more rapidly than older generations, creating tensions within families and communities (Beck and Rosa 2022). Furthermore, rapid shifts in social expectations, such as changes in gender roles or family structures, can cause confusion and resistance among certain groups, leading to social fragmentation and polarization.

It is, however, possible that more inclusive and participatory forms of governance could help limit those trade-offs. For example, public consultations and transparent budgeting processes may be able to address those concerns. Additionally, public-private partnerships in clean energy may help raise revenues, but they also elicit questions about which vendors are being used and at what cost. Here again, efforts to open decision-making processes over vendor selection criteria may help allay those concerns and lower costs or boost product quality.

Finally, disruptive changes to prevailing social structures may lead to social displacement – for instance, the creation of formal waste-management systems may undermine the informal gathering and recycling of materials. In this instance, it will be critical to recognize the role of the informal economy and identify pathways to participate in its steady improvement.

view that is not only about how rapidly or efficiently systems change but also how effectively and equitably they transform. This multidimensional view suggests that the shift may not happen instantaneously or seamlessly but rather entails continuous, nonlinear efforts to restructure systems in line with the six principles of transformation in 12.4. Furthermore, this restructuring needs to occur across multiple scales, spaces, sectors, systems, social segments, and agents of change within a compressed time frame.

21.5.3 Governance for accelerating a sustainable transformation

A question arising from the previous section is how to capitalize on the multidimensionality of that transformation while also driving rapid change. Several disciplines have offered insights into this question. Some branches of economics, for instance, hold that the interplay between socioeconomic and technological advances can contribute to productivity surges or spark swift exponential growth that feeds off itself and builds wider changes in areas such as computing power. The theory of disruptive innovation suggests a process that also builds on itself when new technologies start as niche products but evolve to supplant outdated industries and markets (Christensen *et al.* 2018). Meanwhile, organizational studies contend that institutional agility and forward-thinking leadership are critical to expediting these processes.

Although there is significant potential to catalyse a virtuous cycle of change that supports accelerating a sustainable transformation, political ecology emphasizes that these optimistic narratives often underplay the critical role of power relations and economic structures that shape and drive environmental transformations. This political ecology view suggests that environmental degradation and the uneven distribution of resources are not simply technical challenges but are deeply embedded in broader political and economic processes. Such processes prioritize short-term economic growth over long-term environmental and social sustainability, perpetuating inequalities in resource access and environmental risks (Robbins 2019; Buzarovski 2022).

Credit: Image-Source/Envato

Given these constraints, governance and institutional reforms can serve as crucial components in fostering and sustaining momentum for change. Some governance reforms will be needed to strengthen integration across the processes highlighted in this chapter. For example, governance reforms that enhance connections between participatory forms of co-production, efforts to overcome lock-ins and empower agents of change to leverage motivators can arguably give rise to changes within and across systems. This may entail making stronger links between co-production, barriers analyses, and empowerment of key agents in climate, biodiversity, pollution and other planning processes. Strengthening the interface between these three processes can create self-reinforcing loops, mirroring what political ecology describes as the recursive relationship between environmental degradation and sociopolitical processes. As pathways become more aligned with the context, lock-ins will break faster, and motivators will achieve greater results. This cyclical interaction accelerates the pace of transformation, creating opportunities for faster yet sustainable progress across various dimensions of change.

While greater integration across processes is essential, governance reforms can also help alter the structures that entrench political-economic systems. More specifically, the multisectoral and multilevel forms of governance that break down the siloed structures and related thinking, preventing transformative processes from moving forward. Silos and sectoral divisions often mirror deeper power dynamics that hinder coordinated responses to environmental challenges (Peet and Watts 2004). To a significant extent, this necessitates reforms that generate opportunities for agencies with different remits to work together as part of a whole-of-government approach. For instance, economic, social welfare and environmental ministries can be motivated to find synergies and enhance coherence across portfolios or interests in healthcare, land use and climate policies (Zusman and Amanuma 2018).

At the same time, there is also a critical vertical or multilevel dimension to reforming governance structures. Enhancing vertical integration in governance and policy implementation can involve harmonizing reporting protocols from the global to grassroots levels, ensuring consistency, accountability, and effective data flow for informed decision-making, improved resource allocation, and alignment with overarching sustainability goals. It may also involve providing cities with planning tools to craft innovative solutions to climate and other sustainability challenges. Finally, enhancing vertical or multilevel governance can involve creating fiscal incentives – direct resource transfers or tax incentives – to bring innovative solutions to scale for those challenges.

While multisectoral and multilevel reforms can help break down silos, they may not necessarily promote inclusion and social justice. Inclusion as part of an effort to promote democratizing environmental decision-making can help address structural barriers to transformation (Peet and Watts 2004). Inclusive governance reforms can consist of

targeted techniques familiar to those working on just transitions that limit job losses and dislocation. Further, as discussed and illustrated by examples in **Box 21.8**, such reforms may also limit trade-offs that accompany rapid transformations.

In addition to limiting trade-offs, more inclusive forms of governance can empower and harness the power-interest dynamics of different agents of change. Enabling meaningful participation can bring in overlooked agents who could be natural allies in the drive for a sustainable future. This may involve promoting participation in line with provisions of the Aarhus Convention on Access to Information, Public Participation, and Access to Justice in Environmental Matters (Council of the European Union 2005). It could also entail efforts to enhance youth participation in the Voluntary National Reviews of the SDGs (Fukuda and Zusman 2024). The emergence of climate assemblies in some cities, which enable deliberation over public budgets in relation to sectoral targets, can similarly empower citizen groups to help shape transformations (Gillespie *et al.* 2013; Elstub *et al.* 2021).

Beyond empowering and enabling agents of change, inclusion can also help recognize sustainability solutions that already exist. This is particularly relevant when it comes to Indigenous Peoples who have often performed well on measures of sustainability such as rates of biodiversity loss (IPBES 2019). Many Indigenous Peoples recognize the intrinsic values of nature and may be more attuned to crafting nature-based solutions (IPBES 2022). Ensuring Indigenous Peoples have the opportunities and rights to manage their lands and share those experiences can also ensure that Indigenous ontologies and practices inform and inspire transformations (UNEP and ISC 2024). This inclusion may be particularly important for climate adaptation as it often entails integrating diverse forms of knowledge – mitigation, adaptation, and resilience-building – to address the global environmental crises (Bhandari 2024).

A final reason that efforts to move fast should also be inclusive involves complementarities between different dimensions of a transformation. Participation and inclusion can move forms of governance from a whole-of-government to a whole-of-society approach. Inclusion and participation can also bring inputs and resources from non-governmental organizations, businesses, academic institutions, and community representatives that help align the interests of government agencies (O'Brien *et al.* 2021; Paskaleva *et al.* 2015). Hence, framing the transformation as a win-win model, while highlighting the costs of inaction for all actors across different time periods, is essential to a multidimensional transformation.

21.6 Concluding thoughts

This chapter has argued that accelerating a sustainable transformation is both urgently needed and eminently possible. Making it possible requires taking tangible action that can contribute to three processes – the co-production of pathways, the removal of lock-ins, and the empowerment of agents of change – that can expedite the pace of transformation. Those actions range from efforts to transform food systems with clear policy directions, adequate financing, and institutional support in many parts of Latin America, to combinations of actions aimed at transforming energy systems in several parts of China. These actions are likely to be most successful when agents of change with varying levels of interest and power expand the opportunities for change. They are also most likely to succeed when governance arrangements align the interests of government agencies and agents of change as part of a whole-of-government and whole-of-society approach to a multidimensional transformation.

Plurilateral alliances of like-minded countries, or so-called 'coalitions of the willing', can play a crucial role in accelerating transformations to sustainability by enabling ambitious action beyond the pace of global consensus. These coalitions, whether they focus on energy, food, or material/waste systems, or transformation of economic and financial systems, allow members to coordinate policies, share technology and best practices, and pool resources to achieve scale and impact more quickly. By setting high standards and demonstrating viable pathways, they create momentum that can influence global norms and markets, encourage lagging countries to follow suit. Plurilateral cooperation offers a pragmatic route to speed up progress while keeping the door open for broader inclusion and multilateral UN level actions over time.

References

Allen, C. and Malekpour, S. (2024). Unlocking and accelerating transformations to the SDGs: a review of existing knowledge. Sustainability Science 18(4), 1939-1960. https://doi.org/10.1007/s11625-023-01342-z

Allen, C., Biddulph, A., Wiedmann, T., Pedercini, M. and Malekpour, S. (2024). Modelling six sustainable development transformations in Australia and their accelerators, impediments, enablers, and interlinkages. Nature Communications 15(1), 594. https://doi.org/10.1038/s41467-023-44655-4

Arnold, R.D. and Wade, J.P. (2015). A Definition of Systems Thinking: A Systems Approach. Procedia Computer Science 44, 669-678. https://www.sciencedirect.com/science/article/pii/S1877050915002860

Arora, S. and Stirling, A. (2023). Colonial modernity and sustainability transitions: A conceptualisation in six dimensions. Environmental Innovation and Societal Transitions 48, 100733. https://www.sciencedirect.com/science/article/pii/S2210422423000436

Bandola-Gill, J., Arthur, M. and Leng, R.I. (2023). What is co-production? Conceptualising and understanding co-production of knowledge and policy across different theoretical perspectives. Evidence & Policy 19(2), 275-298. https://bristoluniversitypressdigital.com/view/journals/evp/19/2/article-p275.xml

Bardin, S., Finkel, A., Leroux, J. and Petrucci, L. (2008). FAST: acceleration from theory to practice. International Journal on Software Tools for Technology Transfer 10(5), 401-424. https://doi.org/10.1007/s10009-008-0064-3

Beck, U. and Rosa, H. (2022). Chapter 11: Escalating side effects, The transformation of modern society through processes of cosmopolitanization, acceleration and increasing global risks. In The Routledge Handbook of Democracy and Sustainability. Bornemann, B., Knappe, H. and Nanz, P. (eds.). Routledge. 536. https://www.taylorfrancis.com/chapters/edit/10.4324/9780429024085-14/escalating-side-effects-ulrich-beck-hartmut-rosa

Beery, T., Stahl Olafsson, A., Gentin, S., Maurer, M., Stålhammar, S., Albert, C. et al. (2023). Disconnection from nature: Expanding our understanding of human–nature relations. People and Nature 5(2), 470-488. https://besjournals.onlinelibrary.wiley.com/doi/abs/10.1002/pan3.10451

Bendor, R., Maggs, D., Peake, R., Robinson, J. and Williams, S. (2017). The imaginary worlds of sustainability: observations from an interactive art installation. Ecology and Society 22(2). https://www.ecologyandsociety.org/vol22/iss2/art17/

Béné, C. (2022). Why the Great Food Transformation may not happen – A deep-dive into our food systems' political economy, controversies and politics of evidence. World Development 154, 105881. https://www.sciencedirect.com/science/article/pii/S0305750X22000717

Benini, L. and Viaud, V. (2020). Drivers of change of relevance for Europe's environment and sustainability. European Environment Agency (EEA) report. Luxembourg: Publications Office of the European Union. https://www.eea.europa.eu/en/analysis/publications/drivers-of-change

Bentz, J., do Carmo, L., Schafenacker, N., Schirok, J. and Corso, S.D. (2022). Creative, embodied practices, and the potentialities for sustainability transformations. Sustainability Science 17(2), 687-699. https://doi.org/10.1007/s11625-021-01000-2

Berg, L. (2022). Governing Security After War: The Politics of Institutional Change in the Security Sector. Oxford University Press. https://doi.org/10.1093/oso/9780197572382.001.0001

Bertelsmann Stiftung (2013). Winning Strategies for a Sustainable Future: Reinhard Mohn Prize 2013. Verlag Bertelsmann Stiftung. https://books.google.co.uk/books?id=cgP2DwAAQBAJ

Bhandari, M.P. (2024). Live and Let Others Live- in Reference to Sustainability and Environment Conservation. New York: Nova Science Publisher. https://novapublishers.com/shop/live-and-let-others-live-in-reference-to-sustainability-and-environment-conservation/

Bharucha, Z.P., Mitjans, S.B. and Pretty, J. (2020). Towards redesign at scale through zero budget natural farming in Andhra Pradesh, India. International Journal of Agricultural Sustainability 18(1), 1-20. https://doi.org/10.1080/14735903.2019.1694465

Bicchieri, C. (2017). Norms in the Wild: How to Diagnose, Measure, and Change Social Norms. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780190622046.001.0001

Birchall, S.J. and Bonnett, N. (2021). Climate change adaptation policy and practice: The role of agents, institutions and systems. Cities 108, 103001. https://www.sciencedirect.com/science/article/pii/S0264275120313494

Bouzarovski, S. (2022). Just Transitions: A Political Ecology Critique. Antipode 54(4), 1003-1020. https://onlinelibrary.wiley.com/doi/abs/10.1111/anti.12823

Brandi, C., Cabani, T., Hosang, C., Schirmbeck, S., Westermann, L. and Wiese, H. (2015). Sustainability Standards for Palm Oil:Challenges for Smallholder Certification Under the RSPO. The Journal of Environment & Development 24(3), 292-314. https://journals.sagepub.com/doi/abs/10.1177/1070496515593775

Büscher, B. and Fletcher, R. (2019). Towards Convivial Conservation. Conservation and Society 17(3), 283-296. 10.4103/cs.cs_19_75 https://journals.lww.com/coas/fulltext/2019/17030/towards_convivial_conservation.6.aspx

Castoriadis, C. (1994). Chapter 7: Radical imagination and the social instituting imaginary. In Rethinking Imagination. Robinson, G. and Rundell, J.F. (eds.). Routledge. https://www.taylorfrancis.com/chapters/edit/10.4324/9781315003528-10/radical-imagination-social-instituting-imaginary-cornelius-castoriadis?context=ubx&refId=a9e5ed41-46c2-47eb-8364-0de3a6aa83a7

Chambers, J.M., Wyborn, C., Klenk, N.L., Ryan, M., Serban, A., Bennett, N.J. et al. (2022). Co-productive agility and four collaborative pathways to sustainability transformations. Global Environmental Change 72, 102422. https://www.sciencedirect.com/science/article/pii/S0959378021002016

Chinyio, E. and Olomolaiye, P. (2009). Construction Stakeholder Management. John Wiley & Sons. https://doi.org/10.1002/9781444315349

Christensen, C.M., McDonald, R., Altman, E.J. and Palmer, J.E. (2018). Disruptive Innovation: An Intellectual History and Directions for Future Research. Journal of Management Studies 55(7), 1043-1078. https://onlinelibrary.wiley.com/doi/abs/10.1111/joms.12349

Colvile, R. (2016). The Great Acceleration: How the World is Getting Faster, Faster. Bloomsbury. https://books.google.co.uk/books?id=u6QyEAAAQBAJ

Cordella, M. and Sala, S. (2022). Chapter 5 - The European Green Deal in the global sustainability context. In Assessing Progress Towards Sustainability. Teodosiu, C., Fiore, S. and Hospido, A. (eds.). Elsevier. 73-90. https://www.sciencedirect.com/science/article/pii/B9780323858519000195

Council of the European Union (2005). Council Decision 2005/370/EC on the conclusion, on behalf of the European Community, of the Convention on access to information, public participation in decision-making and access to justice in environmental matters, adopted 17 February 2005, entered into force 17 May 2005., 2005. http://data.europa.eu/eli/dec/2005/370/oj

Crane, M., Lloyd, S., Haines, A., Ding, D., Hutchinson, E., Belesova, K. et al. (2021). Transforming cities for sustainability: A health perspective. Environment International 147, 106366. https://www.sciencedirect.com/science/article/pii/S0160412020323205

Cullinan, C. (2011). Wild law: A manifesto for earth justice. United Kingdom: Bloomsbury Publishing. https://www.google.co.uk/books/edition/Wild_Law/yj3JEAAAQBAJ?hl=en&gbpv=0

Darpö, J. (2021). Can Nature Get it Right? A Study on Rights of Nature in the European Context. Brussels, Belgium: European Parliament: Policy

Department for Citizens' Rights and Constitutional Affairs. https://www.europarl.europa.eu/RegData/etudes/STUD/2021/689328/IPOL_STU(2021)689328_EN.pdf

Dasgupta, P. (2021). The Economics of Biodiversity: The Dasgupta Review. London: HM Treasury. https://assets.publishing.service.gov.uk/media/602e92b2e90e07660f807b47/The_Economics_of_Biodiversity_The_Dasgupta_Review_Full_Report.pdf

de Miguel, C., Martínez, K., Pereira, M. and Kohout, M. (2021). Economía circular en América Latina y el Caribe: oportunidad para una recuperación transformadora. Santiago: Comisión Económica para América Latina y el Caribe (CEPAL). https://repositorio.cepal.org/server/api/core/bitstreams/5fceda72-3fed-4ace-bb87-5688547cf2f5/content

Dechezleprêtre, A. and Sato, M. (2017). The Impacts of Environmental Regulations on Competitiveness. Review of Environmental Economics and Policy 11(2), 183-206. https://www.journals.uchicago.edu/doi/abs/10.1093/reep/rex013

Djenontin, I.N.S. and Meadow, A.M. (2018). The art of co-production of knowledge in environmental sciences and management: lessons from international practice. Environmental Management 61(6), 885-903. https://doi.org/10.1007/s00267-018-1028-3

Duerbeck, G., Schaumann, C. and Sullivan, H. (2015). Human and Non-human Agencies in the Anthropocene // Agencialidades humanas y no-humanas en el Antropoceno. 6, 118-136. https://ecozona.eu/article/download/642/689

Duporge, I., Isupova, O., Reece, S., Macdonald, D.W. and Wang, T. (2021). Using very-high-resolution satellite imagery and deep learning to detect and count African elephants in heterogeneous landscapes. Remote Sensing in Ecology and Conservation 7(3), 369-381. https://zslpublications.onlinelibrary.wiley.com/doi/abs/10.1002/rse2.195.

Elliot, S. (2011). Transdisciplinary Perspectives on Environmental Sustainability: A Resource Base and Framework for IT-Enabled Business Transformation. MIS Quarterly 35(1), 197-236. http://www.jstor.org/stable/23043495

Elstub, S., Carrick, J., Farrell, D.M. and Mockler, P. (2021). The Scope of Climate Assemblies: Lessons from the Climate Assembly UK. Sustainability 13(20), 11272. https://www.mdpi.com/2071-1050/13/20/11272

Esipisu, I. (2013). Kenyan MPs to champion rural women's influence on climate policy | UNW WRD Knowledge Hub. UN Women. https://wrd.unwomen.org/explore/insights/kenyan-mps-champion-rural-womens-influence-climate-policy

European Commission Directorate-General for Environment (2021). Turning the tide on single-use plastics. Publications Office of the European Union. https://data.europa.eu/doi/10.2779/800074

Feola, G., Vincent, O. and Moore, D. (2021). (Un)making in sustainability transformation beyond capitalism. Global Environmental Change 69, 102290. https://www.sciencedirect.com/science/article/pii/S0959378021000698

Flores, R. and Rodríguez, D. (2013). El cuestionamiento de las organizaciones ciudadanas a las empresas chilenas. Un análisis cualitativo. Sociológica 28(79), 167-198. https://www.redalyc.org/articulo.oa?id=305028347005

Fukuda, M. and Zusman, E. (2024). Meaningful Youth Engagement in Sustainability Processes in Japan and Finland: A Comparative Assessment. Sustainability 16(15), 6415. https://www.mdpi.com/2071-1050/16/15/6415.

Garver, G. (2020). Chapter 6: Are rights of nature radical enough for ecological law? In From Environmental to Ecological Law. Anker, K., Burdon, P.D., Garver, G., Maloney, M. and Sbert, C.S.E. (eds.). Routledge. https://www.taylorfrancis.com/chapters/edit/10.4324/9781003001256-10/rights-nature-radical-enough-ecological-law-geoffrey-garver?context=ubx&refId=9fe48ba0-5c8a-4323-a3e9-39e82e6015e5

Gerk, J.E.V. and Qassim, R.Y. (2008). Project Acceleration via Activity Crashing, Overlapping, and Substitution. IEEE Transactions on Engineering Management 55(4), 590-601. https://ieeexplore.ieee.org/document/4604760

Gicheru , M.N., Mwenda , M.J. and Omwami, D.O. (2024). Gender and Climate Change: The Role of Women in Climate Change Processes. Asian Journal of Geographical Research 7(1), 13-23. https://journalajgr.com/index.php/AJGR/article/view/210

Gillespie, S., Haddad, L., Mannar, V., Menon, P. and Nisbett, N. (2013). The politics of reducing malnutrition: building commitment and accelerating progress. Lancet 382(9891), 552-569. https://doi.org/10.1016/s0140-6736(13)60842-9

Ginige, K., Amaratunga, D. and Haigh, R. (2018). Mapping stakeholders associated with societal challenges: A Methodological Framework. Procedia Engineering 212, 1195-1202. https://www.sciencedirect.com/science/article/pii/S1877705818301802

Goldstein, J.E., Neimark, B., Garvey, B. and Phelps, J. (2023). Unlocking "lock-in" and path dependency: A review across disciplines and socio-environmental contexts. World Development 161, 106116. https://www.sciencedirect.com/science/article/pii/S0305750X22003060

Graham, J.D. and Rupp, J. (2022). The Governance of Fracking: History, Differences, and Trends. In Environmental Impacts from the Development of Unconventional Oil and Gas Reserves. Stolz, J., Bain, D. and Griffin, M. (eds.). Cambridge: Cambridge University Press. 79-102. https://www.cambridge.org/core/product/CA75616DFC7AA6A2BCFC0A7FD84B6390

Gupta, J., Bai, X., Liverman, D.M., Rockström, J., Qin, D., Stewart-Koster, B. et al. (2024). A just world on a safe planet: a Lancet Planetary Health–Earth Commission report on Earth-system boundaries, translations, and transformations. The Lancet Planetary Health 8(10), e813-e873. https://www.sciencedirect.com/science/article/pii/S2542519624000421

Hackett, C., Grim, B., Stonawski, M., Skirbekk, V., Potančoková, M. and Abel, G. (2012). The Global Religious Landscape. Washington, Dc: Pew Research Center. https://assets.pewresearch.org/wp-content/uploads/sites/11/2014/01/global-religion-full.pdf

Hamilton, R.T.V. and Ramcilovic-Suominen, S. (2023). From hegemony-reinforcing to hegemony-transcending transformations: horizons of possibility and strategies of escape. Sustainability Science 18(2), 737-748. https://doi.org/10.1007/s11625-022-01257-1

Heras, M., Galafassi, D., Oteros-Rozas, D., Ravera, F., Berraquero-Díaz, L. and Ruiz-Mallén, I. (2021). Realising potentials for arts-based sustainability science. Sustainability Science 16(6), 1875-1889. https://doi.org/10.1007/s11625-021-01002-0

Heras, A. and Gupta, J. (2024). Fossil fuels, stranded assets, and the energy transition in the Global South: A systematic literature review. WIREs Climate Change 15(1), e866. https://wires.onlinelibrary.wiley.com/doi/abs/10.1002/wcc.866

Horlings, L.G. (2018). Chapter 16: Politics of Connectivity: The Relevance of Place-Based Approaches to Support Sustainable Development and the Governance of Nature and Landscape Marsden, T. The SAGE Handbook of Nature: Three Volume Set. SAGE Publications Ltd, London https://sk.sagepub.com/reference/the-sage-handbook-of-nature

Huambachano, M. (2024). Recovering Our Ancestral Foodways: Indigenous Traditions as a Recipe for Living Well. University of California Press. https://books.google.co.uk/books?id=vfIlEQAAQBAJ

Intergovernmental Panel on Climate Change (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change Core Writing Team, H.L.a.J.R. (ed.). Geneva, Switzerland: IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). Global Assessment Report On Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES Secretariat. https://doi.org/10.5281/zenodo.3831673

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2022). Methodological assessment of the diverse values and valuation of nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Balvanera, P., Pascual, U., Christie, M., Baptiste, B. and González-Jiménez, D. (eds.). Bonn, Germany: IPBES secretariat. https://doi.org/10.5281/zenodo.7687931

ITU News Magazine (2020). Space science for achieving the Sustainable Development Goals. https://www.itu.int/en/itunews/Documents/2020/2020-06/2020_ITUNews06-en.pdf

Ivanova, D., Barrett, J., Wiedenhofer, D., Macura, B., Callaghan, M. and Creutzig, F. (2020). Quantifying the potential for climate change mitigation

of consumption options. Environmental Research Letters 15(9), 093001. https://dx.doi.org/10.1088/1748-9326/ab8589

Jaffee, S., Henson, S., Unnevehr, L., Grace, D. and Cassou, E. (2019). The Safe Food Imperative: Accelerating Progress in Low- and Middle-Income Countries. Agriculture and Food Series. Washington, DC: World Bank. http://hdl.handle.net/10986/30568

Jasanoff, S. and Kim, S.H. (2015). Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power. University of Chicago Press. https://doi.org/10.7208/chicago/9780226276663.001.0001

Khodke, A., Watabe, A. and Mehdi, N. (2021). Implementation of Accelerated Policy-Driven Sustainability Transitions: Case of Bharat Stage 4 to 6 Leapfrogs in India. Sustainability 13(8), 4339. https://www.mdpi.com/2071-1050/13/8/4339

Kileo, A., Mwalongo, D., Mwaipopo, A., Mdoe, S. and Mkilaha, I. (2019). Challenges of Development of Regulatory Control for Uranium Mining in Developing Countries to Achieve Regulatory Compliance — Tanzanian Experience. International Atomic Energy Agency (IAEA): IAEA. http://inis.iaea.org/search/search.aspx?orig_q=RN:50067359

Kuschel, K., Lepeley, M.T., Espinosa, F. and Gutiérrez, S. (2017). Funding challenges of Latin American women start-up founders in the technology industry. Cross Cultural and Strategic Management 24(2), 310-331. https://doi.org/10.1108/CCSM-03-2016-0072

Kussul, N. and Drozd, S. (2023). Assessing Ukrainian Territory Suitability for Solar Power Station Placement Using Satellite Data on Climate and Topography. https://ieeexplore.ieee.org/document/10416483

Lambin, E.F. and Furumo, P.R. (2023). Deforestation-Free Commodity Supply Chains: Myth or Reality? Annual Review of Environment and Resources 48(Volume 48, 2023), 237-261. https://www.annualreviews.org/content/journals/10.1146/annurev-environ-112321-121436

Landman, W.A., Archer, E.R.M. and Tadross, M.A. (2020). Citizen Science for the Prediction of Climate Extremes in South Africa and Namibia. Frontiers in Climate 2. https://www.frontiersin.org/journals/climate/articles/10.3389/fclim.2020.00005

Li, R. and Ramanathan, R. (2018). Exploring the relationships between different types of environmental regulations and environmental performance: Evidence from China. Journal of Cleaner Production 196, 1329-1340. https://www.sciencedirect.com/science/article/pii/S0959652618317827

Lidström, A. and Madell, T. (2021). The charter of local self-government in Sweden. In Local Self-Government in Europe. Brezovnik, B. (ed.). Institute for Local Self-Government Maribor. https://doi.org/10.4335/978-961-7124-00-2

Liefferink, D. and Wurzel, R.K.W. (2017). Environmental leaders and pioneers: agents of change? Journal of European Public Policy 24(7), 951-968. https://doi.org/10.1080/13501763.2016.1161657

Lostal, M. (2024). The Environment and the ICC Legal Framework Concerning Victims SSRN Electronic Journal. https://ssrn.com/abstract=4840613

Marques, A.C., Fuinhas, J.A. and Pais, D.F. (2018). Economic growth, sustainable development and food consumption: Evidence across different income groups of countries. Journal of Cleaner Production 196, 245-258. https://www.sciencedirect.com/science/article/pii/S0959652618316603

Matti, S., Petersson, C. and Söderberg, C. (2021). The Swedish climate policy framework as a means for climate policy integration: an assessment. Climate Policy 21(9), 1146-1158. https://doi.org/10.1080/14693062.2021.1930510

McAdam, D. (2017). Social Movement Theory and the Prospects for Climate Change Activism in the United States. Annual Review of Political Science 20(Volume 20, 2017), 189-208. https://www.annualreviews.org/content/journals/10.1146/annurev-polisci-052615-025801

McDonald, J., Brent, K., McCormack, P. and McGee, J. (2023). Greenhouse gas removal in Australian climate law: A positive role for negative emissions. University of New South Wales Law Journal 46(1), 79-110. https://search.informit.org/doi/10.3316/informit.984616432167719

Mendelow, A.L. (1981). Environmental Scanning-The Impact of the Stakeholder Concept. International Conference on Interaction Sciences (ICIS) - 1981 Proceedings. https://aisel.aisnet.org/icis1981/20/

Moallemi, E.A., Zare, F., Hebinck, A., Szetey, K., Molina-Perez, E., Zyngier, R.L. et al. (2023). Knowledge co-production for decision-making in human-natural systems under uncertainty. Global Environmental Change 82, 102727. https://www.sciencedirect.com/science/article/pii/S0959378023000936

Mohr, A., Raman, S. and Gibbs, B. (2013). Which publics. When? Exploring the Policy Potential of Involving Different Publics in Dialogue around Science and Technology. Sciencewise-ERC. https://nottingham-repository.worktribe.com/output/1005108

Muhanga, M. (2019). An Examination of Some Key Issues on Legal and Policy Environment in the Mining Sector After the Economic Reforms in Tanzania. International and Public Affairs 3(2), 33-42. https://doi.org/10.11648/j.ipa.20190302.11

National Geophysical Data Center / World Data Service (2024). Deaths from volcanic eruptions – NCEI/WDS dataset. National Centers for Environmental Information (NOAA), https://ourworldindata.org/grapher/deaths-from-volcanic-eruptions

Ndicu, S., Ngui, D. and Barasa, L. (2024). Technological Catch-Up, Innovation, and Productivity Analysis of National Innovation Systems in Developing Countries in Africa 2010–2018. Journal of the Knowledge Economy 15(2), 7941-7967. https://doi.org/10.1007/s13132-023-01327-4

Negro, S.E. (2012). Fracking Wars: Federal, State and Local Conflicts over the Regulation of Natural Gas. https://www.ourenergypolicy.org/wp-content/uploads/2013/07/Fracking-Wars.pdf

Nenkov, G.Y. (2024). Shifting focus in the fight against core environmental challenges. Journal of the Academy of Marketing Science 52(5), 1273-1278. https://doi.org/10.1007/s11747-023-01001-w

Nkuba, M.R., Chanda, R., Mmopelwa, G., Kato, E., Najjingo Mangheni, M., Lesolle, D. et al. (2023). Effect of indigenous and scientific forecasts on pastoralists' climate change perceptions in the Rwenzori region, Western Uganda. Climate and Development 15(6), 522-534. https://doi.org/10.1080/17565529.2022.2119831

Nkuba, M.R., Chanda, R., Mmopelwa, G., Mangheni, M.N., Lesolle, D., Adedoyin, A. et al. (2021). Determinants of pastoralists' use of indigenous knowledge and scientific forecasts in Rwenzori region, Western Uganda. Climate Services 23, 100242. https://www.sciencedirect.com/science/article/pii/S2405880721000303

Northcott, M.S. (2013). A Political Theology of Climate Change. William B. Eerdmans Publishing Company. https://spckpublishing.co.uk/a-political-theology-of-climate-change

Nyadzi, E., Werners, S.E., Biesbroek, R. and Ludwig, F. (2022). Towards weather and climate services that integrate indigenous and scientific forecasts to improve forecast reliability and acceptability in Ghana. Environmental Development 42, 100698. https://www.sciencedirect.com/science/article/pii/S2211464521001081

O'Brien, R.M., Phelan, T.J., Smith, N.M. and Smits, K.M. (2021). Remediation in developing countries: A review of previously implemented projects and analysis of stakeholder participation efforts. Critical Reviews in Environmental Science and Technology 51(12), 1259-1280. https://doi.org/10.1080/10643389.2020.1755203

Oberthür, S. and Dupont, C. (2021). The European Union's international climate leadership: towards a grand climate strategy? Journal of European Public Policy 28(7), 1095-1114. https://doi.org/10.1080/13501763.2021.1918218

Organization for Economic Cooperation and Development (2017). OECD Reviews of Innovation Policy: Costa Rica 2017. Paris: Organization for Economic Cooperation and Development (OECD). http://dx.doi.org/10.1787/9789264271654-en

Oviedo, A.M., Sanchez, S.M., Lindert. Kathy A. and Lopez, J.H. (2015). Costa Rica's Development: From Good to Better. Systematic Country Diagnostic. Washington, DC: World Bank. https://documents1.worldbank.org/curated/en/215521468196163103/pdf/96280-REVISED-PUBLIC-CRI-SCD-ebook.pdf

Paskaleva, K., Cooper, I., Linde, P., Peterson, B. and Götz, C. (2015). Stakeholder Engagement in the Smart City: Making Living Labs Work. In Transforming City Governments for Successful Smart Cities. Rodríguez-Bolívar, M.P. (ed.). Cham: Springer International Publishing. 115-145. https://doi.org/10.1007/978-3-319-03167-5_7

Pattberg, P. and Bäckstrand, K. (2023). Enhancing the achievement of the SDGs: lessons learned at the half-way point of the 2030 Agenda.

International Environmental Agreements: Politics, Law and Economics 23(2), 107-114. https://doi.org/10.1007/s10784-023-09615-9

Peet, R. and Watts, M. (2004). Liberation Ecologies: Environment, Development and Social Movements. London: Routledge. https://doi.org/10.4324/9780203235096

Pereverza, K., Dierks, O. and Järvelä, E. (2022). 'Transformative portfolio-based approaches for urban transition governance: Insights from the recent City Lab workshop'. Medium: Viable Cities https://medium.com/viable-cities/transformative-portfolio-based-approaches-for-urban-transition-governance-insights-from-the-recent-6dca5d6fad02

Pincetl, S. (2017). Cities in the age of the Anthropocene: Climate change agents and the potential for mitigation. Anthropocene 20, 74-82. https://www.sciencedirect.com/science/article/pii/S2213305417300413

Polk, M. (2015). Transdisciplinary co-production: Designing and testing a transdisciplinary research framework for societal problem solving. Futures 65, 110-122. https://www.sciencedirect.com/science/article/pii/S0016328714001864

Pons-Seres de Brauwer, C. (2022). The Politics of Market Change towards Sustainability: Revisiting Germany's Policy Support Framework for Renewables. Energies 15(11), 3898. https://www.mdpi.com/1996-1073/15/11/3898

Pretty, J., Benton, T.G., Bharucha, Z.P., Dicks, L.V., Flora, C.B., Godfray, H.C.J. et al. (2018). Global assessment of agricultural system redesign for sustainable intensification. Nature Sustainability 1(8), 441-446. https://doi.org/10.1038/s41893-018-0114-0

Puig De La Bellacasa, M. (2017). Matters of Care Speculative Ethics in More than Human Worlds. University of Minnesota Press. http://www.jstor.org/stable/10.5749/j.ctt1mmfspt

Rajão, R. and Soares-Filho, B. (2015). Policies undermine Brazil's GHG goals. Science 350(6260), 519-519. https://www.science.org/doi/abs/10.1126/science.350.6260.519-a

Robbins, P. (2019). Political Ecology: A Critical Introduction. Wiley. https://books.google.co.uk/books?id=nOGvDwAAQBAJ

Robinson, C., Ortiz, A., Hughey, L., Stabach, J.A. and Lavista Ferres, J.M. (2021). Detecting Cattle and Elk in the Wild from Space. Proceedings of Fragile Earth '21: Fragile Earth: Accelerating Progress towards Equitable Sustainability https://arxiv.org/pdf/2106.15448.pdf

Rockström, J., Gupta, J., Qin, D., Lade, S.J., Abrams, J.F., Andersen, L.S. et al. (2023). Safe and just Earth system boundaries. Nature 619(7968), 102-111. https://doi.org/10.1038/s41586-023-06083-8

Rockström, J., Sachs, J.D., Öhman, M.C. and Schmidt-Traub, G. (2013). Sustainable development and planetary boundaries. JSTOR. https://www.jstor.org/stable/pdf/resrep16114.pdf?acceptTC=true&coverpage=false&addFooter=false

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F. et al. (2009). A safe operating space for humanity. Nature 461(7263), 472-475. https://doi.org/10.1038/461472a

Romanello, M., Napoli, C.d., Green, C., Kennard, H., Lampard, P., Scamman, D. et al. (2023). The 2023 report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. The Lancet 402(10419), 2346-2394. https://doi.org/10.1016/S0140-6736(23)01859-7

Rosa, H. (2003). Social Acceleration: Ethical and Political Consequences of a Desynchronized High–Speed Society. Constellations 10(1), 3-33. https://onlinelibrary.wiley.com/doi/abs/10.1111/1467-8675.00309

Roychowdhury, A., Chattopadhyay, V., Shukla, S., Ganguly, T., Bajaj, A., Singh, S. et al. (2019). Policy brief: BS VI readiness and roadmap in India. New Delhi, India: Centre for Science and Environment (CSE). http://cdn.cseindia.org/attachments/0.66574500_1564564273_BSVI-strategy-paper.pdf

Rydin, Y. and Turcu, C. (2019). Revisiting urban energy initiatives in the UK: Declining local capacity in a shifting policy context. Energy Policy 129, 653-660. https://www.sciencedirect.com/science/article/pii/S0301421519301375

Santika, T., Nelson, V., Flint, M., MacEwen, M., Cerretelli, S. and Brack, D. (2024). Leverage points for tackling unsustainable global value chains: market-based measures versus transformative alternatives. Sustainability Science 19(1), 285-305. https://doi.org/10.1007/s11625-023-01430-0

Scoones, I., Stirling, A., Abrol, D., Atela, J., Charli-Joseph, L., Eakin, H. et al. (2020). Transformations to sustainability: combining structural, systemic and enabling approaches. Current Opinion in Environmental Sustainability 42, 65-75. https://www.sciencedirect.com/science/article/pii/S1877343519300909

Seto, K.C., Davis, S.J., Mitchell, R.B., Stokes, E.C., Unruh, G. and Ürge-Vorsatz, D. (2016). Carbon Lock-In: Types, Causes, and Policy Implications. Annual Review of Environment and Resources 41(Volume 41, 2016), 425-452. https://www.annualreviews.org/content/journals/10.1146/annurev-environ-110615-085934

Sorrentino, M., Sicilia, M. and Howlett, M. (2018). Understanding co-production as a new public governance tool. Policy and Society 37(3), 277-293. https://doi.org/10.1080/14494035.2018.1521676

Southern, W.T. and Jones, E.D. (2004). Types of acceleration: Dimensions and issues. In A nation deceived: How schools hold back America's brightest students. Colangelo, N., Assouline, S.G. and Gross, M.U.M. (eds.). Iowa: The University of Iowa and The University of New South Wales. chapter 1. https://www.accelerationinstitute.org/Nation_Deceived/ND_v2.pdf

Sovacool, B.K. (2016). How long will it take? Conceptualizing the temporal dynamics of energy transitions. Energy Research & Social Science 13, 202-215. https://www.sciencedirect.com/science/article/pii/S2214629615300827

Stef, N. and Ashta, A. (2023). Dynamics in environmental legislation. International Review of Law and Economics 76, 106170. https://www.sciencedirect.com/science/article/pii/S0144818823000480

Stoddard, I., Anderson, K., Capstick, S., Carton, W., Depledge, J., Facer, K. et al. (2021). Three Decades of Climate Mitigation: Why Haven't We Bent the Global Emissions Curve? Annual Review of Environment and Resources 46(1), 653-689. https://www.annualreviews.org/doi/abs/10.1146/annurev-environ-012220-011104

Strand, R., Kovacic, Z., Funtowicz, S., Benini, L. and Jesus, A. (2023). 'Exiting The Anthropocene? Exploring Fundamental Change In Our Relationship With Nature'. https://www.eea.europa.eu/publications/exiting-the-anthropocene

Taylor, C. (2004). Modern Social Imaginaries. Duke University Press. http://www.jstor.org/stable/j.ctv11hpgvt

Termeer, K., Dewulf, A. and Biesbroek, R. (2024). Three archetypical governance pathways for transformative change toward sustainability. Current Opinion in Environmental Sustainability 71, 101479. https://www.sciencedirect.com/science/article/pii/S1877343524000666

The Hot or Cool Institute (2021). The Happy Planet Index. https://happyplanetindex.org/

Thunberg, G. (2021). No One Is Too Small to Make a Difference. Penguin Books. https://www.penguin.co.uk/books/315787/no-one-is-too-small-to-make-a-difference-by-thunberg-greta/9780241514573

Trask, B. (2009). Globalization and families: Accelerated systemic social change. New York, NY: Springer. https://doi.org/10.1007/978-0-387-88285-7

Tsingou, E. (2015). Club governance and the making of global financial rules. Review of International Political Economy 22(2), 225-256. https://doi.org/10.1080/09692290.2014.890952

Turcu, C. (2023). 'Three key issues for cities at COP28: How cities are central in fighting the global climate crisis'. UCL The Bartlett Review, https://bartlett-review.ucl.ac.uk/cities-at-cop28/index.html

Turcu, C. (2010). Examining the impact of housing refurbishment-led regeneration on community sustainability: a study of three Housing Market Renewal areas in England. PhD thesis, London School of Economics and Political Science. https://etheses.lse.ac.uk/635/

Turcu, C. (2017). Unequal spatial distribution of retrofits in Bucharest's apartment buildings. Building Research & Information 45(8), 892-909. https://doi.org/10.1080/09613218.2016.1229894

Turcu, C. (2018). Responsibility For Sustainable Development in Europe: What Does It Mean for Planning Theory and Practice? Planning Theory & Practice, 19, 385-404. https://doi.org/10.1080/14649357.2018.1478116

Turcu, C. (2025). Urban Greenspace, Climate Adaptation and Health Co-Benefits: Municipal Policy and Practice in London. International Journal of Environmental Research and Public Health 22(3), 409. https://www.mdpi.com/1660-4601/22/3/409

Turcu, C. and Gillie, H. (2020). Governing the Circular Economy in the City: Local Planning Practice in London. Planning Practice & Research 35(1), 62-85. https://doi.org/10.1080/02697459.2019.1703335

Turcu, C. and Rotolo, M. (2022). Disrupting from the ground up: community-led and place-based food governance in London during COVID-19. Urban Governance 2(1), 178-187. https://www.sciencedirect.com/science/article/pii/S2664328622000195

Turnhout, E., Metze, T., Wyborn, C., Klenk, N. and Louder, E. (2020). The politics of co-production: participation, power, and transformation. Current Opinion in Environmental Sustainability 42, 15-21. https://www.sciencedirect.com/science/article/pii/S1877343519301010

United Nations (2016). Global Framework for Climate Services https://sustainabledevelopment.un.org/index.php?page=view&type=30022&nr=123&menu=3170

United Nations (2023). Global Sustainable Development Report 2023: Times of crisis, times of change: Science for accelerating transformations to sustainable development. New York: United Nations: Independent Group of Scientists appointed by the Secretary-General. https://sdgs.un.org/sites/default/files/2023-09/FINAL%20GSDR%202023-Digital%20-110923_1.pdf

United Nations Environment Programme (2018). Legal Limits on Single-Use Plastics and Microplastics: A Global Review of National Laws and Regulations. https://www.unep.org/resources/publication/legal-limits-single-use-plastics-and-microplastics-global-review-national

United Nations Environment Programme (2023). Environmental Rule of Law: Tracking Progress and Charting Future Directions. Nairobi: UNEP. https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/43943/Environmental_rule_of_law_progress.pdf?sequence=3

United Nations Environment Programme (2024). Nature in the Boardroom: Guidance for boards of financial institutions in asking the right questions to identify, manage, and report on nature-related risks and opportunities. Geneva. https://www.unepfi.org/wordpress/wp-content/uploads/2024/10/Nature-in-the-boardroom-3.pdf

United Nations Environment Programme and International Science Council (2024). Navigating New Horizons: A global foresight report on planetary health and human wellbeing. https://wedocs.unep.org/20.500.11822/45890

United Nations Environment Programme and United Nations Human Settlements Programme (2021). Global Environment for Cities-GEO for Cities: Towards Green and Just Cities. Nairobi: UNEP. https://wedocs.unep.org/bitstream/handle/20.500.11822/37413/GEOcities.pdf

Unruh, G., C. (2002). Escaping carbon lock-in. Energy Policy 30(4), 317-325. https://www.sciencedirect.com/science/article/pii/S0301421501000982

Unruh, G.C. (2000). Understanding carbon lock-in. Energy Policy 28(12), 817-830. https://www.sciencedirect.com/science/article/pii/S0301421500000707

Vaara, E. and Whittle, A. (2022). Common Sense, New Sense or Non-Sense? A Critical Discursive Perspective on Power in Collective Sensemaking. Journal of Management Studies 59(3), 755-781. https://onlinelibrary.wiley.com/doi/abs/10.1111/joms.12783

van Beek, L. (2025). Artists-in-residence to foster more reflective modelling practices. Sustainability Science. 10.1007/s11625-025-01673-z https://doi.org/10.1007/s11625-025-01673-z

van den Berg, L., Teixeira, H.M., Behagel, J.H., Verschoor, G., Turnhout, E., Cardoso, I.M. et al. (2022). From managing transitions towards building movements of affect: Advancing agroecological practices and transformation in Brazil. Geoforum 131, 50-60. https://www.sciencedirect.com/science/article/pii/S0016718522000410

van Vuuren, D.P., Doelman, J.C., Schmidt Tagomori, I., Beusen, A.H.W., Cornell, S.E., Röckstrom, J. et al. (2025). Exploring pathways for world development within planetary boundaries. Nature 641(8064), 910-916. 10.1038/s41586-025-08928-w https://doi.org/10.1038/s41586-025-08928-w

Veteto, J.R. and Carlson, S.B. (2014). Climate Change and Apple Diversity: Local Perceptions from Appalachian North Carolina. Journal of Ethnobiology 34(3), 359-382. https://journals.sagepub.com/doi/abs/10.2993/0278-0771-34.3.359

World Business Council for Sustainable Development (2020). Unlocking Systems Transformation: Vision 2050 issue brief. https://docs.wbcsd.org/2020/06/WBCSD-Unlocking-systems-transformation.pdf

World Economic Forum (2022). Future Focus 2025: Pathways for Progress from the Network of Global Future Councils 2020–2022. https://www3.weforum.org/docs/WEF_Future_Focus_2025.pdf

Yoo, I. and Yi, C. (2022). Economic Innovation Caused by Digital Transformation and Impact on Social Systems. Sustainability 14(5), 2600. https://www.mdpi.com/2071-1050/14/5/2600

Young, C. (2023). Between a Rock and a Hard Place: Governing Unconventional Natural Gas at the Local Level in the United States. Sustainability 15(7), 5925. https://www.mdpi.com/2071-1050/15/7/5925

Zusman, E. and Amanuma, N. (2018). Governance for integrated solutions to sustainable development and climate change: from linking issues to aligning interests. Institute for Global environmental Strategies (IGES). https://www.iges.or.jp/en/publication_documents/pub/books/en/6577/SDGs_all_fin_180715.pdf

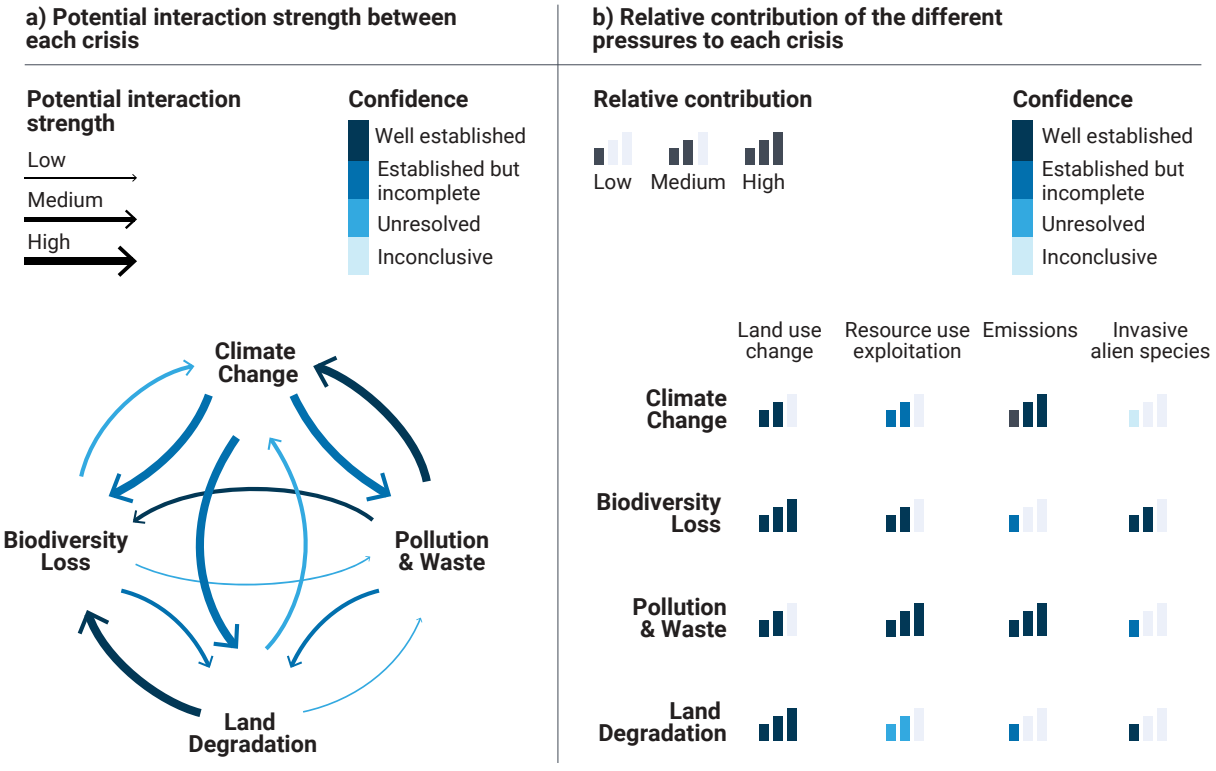
Annex 1 Global Environmental Crises Diagram

1. Illustration of interacting crises

We introduce a stylised figure to illustrate how different pressures contribute to each crisis and the potential interlinkages between crises (**Figure A1.1**).

Each environmental crisis can be defined along multiple axes and is subject to, and emerges from, various pressures. The interactions (arrows; Figure A1.1a) between some crises are stronger than between other crises, with arrow width indicative of interaction strength (low, medium and high). Depth of shading reflects the qualitative assessment of confidence in the assigned interaction strengths (well established, established but incomplete, unresolved, and inconclusive). Pressures (Figure A1.1b) are as defined in Chapter 2: (1) Land use change represents the conversion from one land use type to another, with the most prevalent land use transitions occurring between cropland and forest; (2) Resource use/exploitation considers multiple resources, including exploitation of fish and wildlife, fossil fuels, minerals and rare elements, wood and timber, and water extraction; (3) Emissions encompass greenhouse gases and other pollutants, including short-lived climate pollutants, such as black carbon, and chemical pollutants from industry and agriculture; (4) Invasive alien species are defined as species introduced to areas outside their native range that have become successfully established and cause substantial impacts on the new environment. The relative contribution (low, medium and high) of pressures to the different crises is indicated by the histograms, with depth of shading reflecting the qualitative assessment of confidence in the assigned contribution weights (well established, established but incomplete, unresolved, and inconclusive).

Figure A1.1: **The interconnected global environmental crises of climate change, biodiversity loss, land degradation and desertification, and pollution and waste**



1. Illustration of interacting crises

We introduce a stylised figure to illustrate how different pressures contribute to each crisis and the potential interlinkages between crises (**Figure A1.1**).

Each environmental crisis can be defined along multiple axes and is subject to, and emerges from, various pressures. The interactions (arrows; Figure A1.1a) between some crises are stronger than between other crises, with arrow width indicative of interaction strength (low, medium and high). Depth of shading reflects the qualitative assessment of confidence in the assigned interaction strengths (well established, established but incomplete, unresolved, and inconclusive). Pressures (Figure A1.1b) are as defined in Chapter 2: (1) Land use change represents the conversion from one land use type to another, with the most prevalent land use transitions occurring between cropland and forest; (2) Resource use/exploitation considers multiple resources, including exploitation of fish and wildlife, fossil fuels, minerals and rare elements, wood and timber, and water extraction; (3) Emissions encompass greenhouse gases and other pollutants, including short-lived climate pollutants, such as black carbon, and chemical pollutants from industry and agriculture; (4) Invasive alien species are defined as species introduced to areas outside their native range that have become successfully established and cause substantial impacts on the new environment. The relative contribution (low, medium and high) of pressures to the different crises is indicated by the histograms, with depth of shading reflecting the qualitative assessment of confidence in the assigned contribution weights (well established, established but incomplete, unresolved, and inconclusive).

2. Process for deriving qualitative estimates of the contribution of pressures to crises and interaction strengths among crises, along with confidence levels

In part (a) the direction of each arrow reflects the path of causality. Arrow width indicates the comparative strength of interactions between the crises, indexed on an ordinal scale: low, medium and high. For example, in the illustration above, pollution has a medium impact on biodiversity, but biodiversity has a low impact on pollution.

In part (b) the relative contribution weights of pressures are qualitative and follow the same ordinal scale adopted for interaction strengths (i.e., low, medium and high). Pressure contributions broadly consider both the impact of the pressure on the crisis and the spatio-temporal scale over which pressures are experienced (**Figure A1.2**). Weights reflect the direct effect of the pressure on the crisis, for example, the effect of emissions on biodiversity is largely through their effects on climate chanage; thus the contribution weight of emssions on biodiversity is low, but the interaction strength between climate change and biodiversity is high.

Weights assigned to arrows and pressures reflect the views of the GEO subject matter experts and are not intended to represent a formal evaluation of the literature or data analysis, which is beyond the remit of the GEO assessment process (see Procedure for GEO expert consultation; **Figure A1.3**).

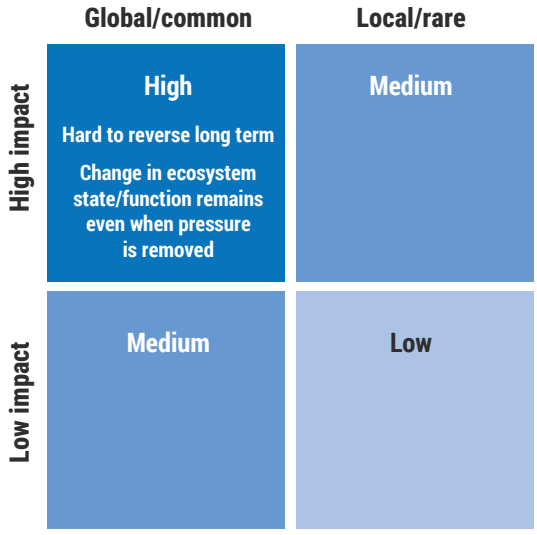
The different shading for both arrows and histograms indicates the level of confidence in weights assigned by GEO subject matter experts and represents their knowledge of the scientific literature, following the qualitative assessment guidelines detailed in the GEO Intergovernmental and Expert-led Scientific Assessment Procedures guidelines. Confidence statements are classified as: well-established, established but incomplete, unresolved, and inconclusive.

We provide fully referenced examples of the potential pairwise interactions between crises in the global environmental crises Chapeau (**Table C.1-C.6**), demonstrating how each crisis is multifaceted and can thus be described along many possible axes. In some cases, our knowledge of the impacts of interactions between crises may be data-limited or full impacts may only become apparent in the future; this adds to uncertainty in the assigned weights and may be captured in the confidence statements. Importantly, interaction strengths between crises can also vary by temporal or spatial scale and between regions and ecosystems. For example, island nations will be disproportionately impacted by climate change–mainly through sea level rise and increasing frequency of storm events. Thus, solution pathways need to be region-specific.

We recognise that the pairwise interaction structure shown in **Figure A1.1** is overly simplistic and that

the crises are all interconnected spatially, temporally and causally. The pairwise connections between crises can also form longer chains of interactions that may include complex feedbacks, challenging simple extrapolations (Pfenning-Butterworth et al. 2024). While we do not attempt to capture these added complexities here, as doing so would inevitably reduce interpretability, they should be considered when identifying solution pathways.

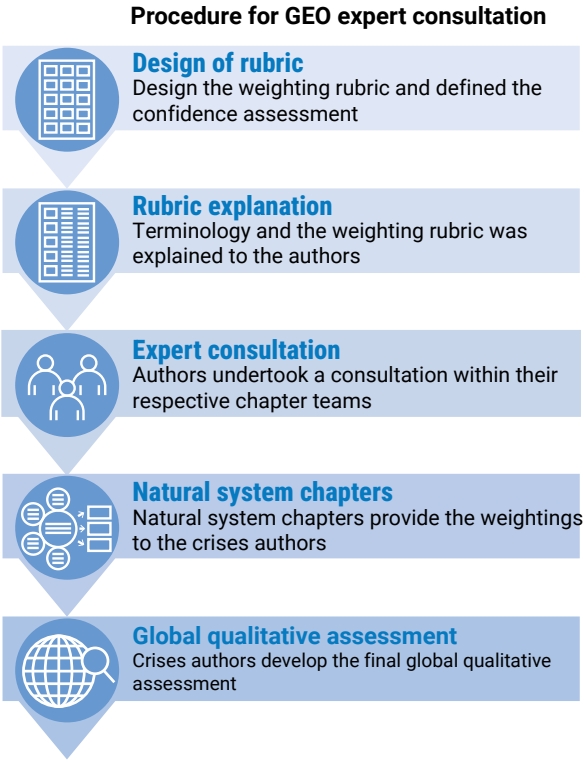
Figure A1.2: Guide to assist with the qualitative assesment of the contribution of pressures to crises



Impacts of pressures on crises were defined as high impact (top row) if they result in crisis-induced changes in the natural system (i.e., ecosystem state or function) that are hard to reverse and/or long term such that changes in the natural system remain even when the pressure is removed. Low impact pressures (bottom row) are pressures not classified as high impact (i.e., impacts on crisis-induced change to the natural system are easy to reverse and/or short-term such that changes in the natural system are not sustained when the pressure is removed). Pressure weights (quadrats) reflect both impacts of pressures and their spatiotemporal scale. With higher weights assigned to pressures that occur over larger geographical extents and/or with greater frequency.

The contribution weight (histograms, **Figure A1.1b**) of a pressure was indexed as high if the pressure was assessed as high impact and was spatially widespread/global and/or temporally frequent/common (**Figure A1.2** top left). The contribution weight of a pressure to a crisis was indexed as low if the pressure was assessed as low impact and was spatially restricted/local and/or temporally infrequent (**Figure A1.2** bottom right). A pressure that did not meet criteria for high or low, was indexed as medium (Figure A1.2 top right and bottom left).

Figure A1.3: Procedure for GEO expert consultation



Annex 2 General information on the inclusion of Indigenous Knowledge and Local Knowledge in the Seventh Global Environment Outlook (GEO-7)

Introduction

During the Scoping Meeting held in October 2022, Member States requested that Indigenous Knowledge and Local Knowledge (IK & LK) should be incorporated into the GEO assessment. The scoping document stated that GEO-7 should build on information from diverse credible data sources, including Indigenous Knowledge, and where possible local knowledge. In order to fulfill this request, GEO-7 has, for the first time, systematically drawn upon IK & LK and addressed issues related to Indigenous Peoples. This was done through the following mechanisms:

1. **The IK & LK Task Force**: A group of Indigenous and non-Indigenous experts who guided the process of including IK & LK into GEO-7 in collaboration with the Co-Chairs and contributed to the text as Lead Authors and Fellows.

2. **The inclusion of IK & LK related issues in the text**: This content was included in all the chapters, as well as in five IK & LK chapeaus - one for each of report's sections. It was also included in a dedicated section in the Executive Summary and throughout its messages where appropriate.

3. **The IK & LK Dialogues**: Four dialogues with representatives from Indigenous Peoples and local communities were held as part of the process. In addition to the existing literature, the Outcome report of these dialogues represents the key reference for the IK & LK related content in the report.

The Indigenous Knowledge and Local Knowledge Task Force

The IK & LK task force was formed in May 2023. It initially consisted of 10 Indigenous and non-Indigenous researchers and knowledge holders selected from the nominations to the GEO-7 process and was led by two co-convenors who were appointed by the Co-Chairs among its members. A gap-filling exercise took place in January 2024 and the members of the task force increased to 17 with 2 fellows providing support to the process, of whom 12 identify as Indigenous or representatives of a local community. The taskforce was balanced in terms of gender and geographical representation, with only the Eastern Europe not being represented (**Table A2.1**).

Besides overseeing the overall process of including IK & LK into the GEO-7 report, the IK & LK task force's tasks were to develop and carry out IK & LK methods, to develop an overarching IK&LK narrative, to conduct a series of dialogues with representatives from Indigenous Peoples as well as local communities, to contribute as Lead Authors in different chapters and suggest contributing authors where needed, and to develop cross chapter linkages

The IK & LK task force met regularly online (predominantly bi-weekly), and active communication and regular interaction were maintained throughout the process between the task force, the rest of the authors team, the assessment Co-Chairs, and the Secretariat to ensure coherence and effective collaboration. It met in-person at their first face-to-face meeting in October 2023 and thereafter, engaged with the author teams and Co-chairs remotely and during GEO-7 author meetings. Several IK & LK task force members contributed to the IK & LK Dialogues as facilitators and others were included in the team of authors who drafted and revised the Executive Summary.

Table A2.1: GEO-7 IK & LK Taks Force Members Regional Distribution

UN Region	Male	Female	Total
Africa Group	4	0	4
Western Europe	1	5	6
Eastern Europe	0	0	0
Asia Pacific	3	1	4
Latin America and the Caribbean	1	4	5
	8	10	19

The Inclusion of IK & LK in the Text

Since the IK & LK task force was created after the scoping phase and the definition of the structure and content of the assessment and its chapters, the following approach was adopted to include IK & LK-related content into the GEO-7:

- Full embeddedness into the main body of each chapter and the corresponding chapter summaries, thanks to the work of the task force members as Lead Authors. This ensured that IK & LK could complement the scientific perspectives.
- Five IK & LK chapeaux, present at the beginning of each of the parts of the report, allowing for introduction of specific IK & LK concepts and perspectives and fully written by the IK & LK task force members.
- Content from the chapters' summaries and from the five IK&LK chapeaux informed a dedicated section in the Executive Summary and throughout its messages where appropriate

In order to ensure IK & LK was covered in the GEO-7 report, members of the IK & LK task force were nominated as Lead Authors, at least one per chapter based on their expertise. The content of the IK & LK contribution varied from chapter to chapter as agreed upon by the author teams. Depending on the scope of the chapter, the four types of content included: 1) Indigenous conceptualizations and perspectives, 2) IK & LK on the specific issues discussed in the chapter, 3) impacts or potential impacts of the issues discussed in the chapter on Indigenous Peoples as well as local communities, and 4) potential contributions of IK & LK and of Indigenous Peoples as well as local communities to the proposed solutions pathways. The main sources of knowledge to contribute to the chapters were: 1) existing peer-reviewed and non-peer-reviewed literature, and 2) IK & LK Dialogues Outcome Report. When needed, contributing authors (identifying themselves as IK & LK-holder or not) were invited to fill specific gaps in expertise.

The Indigenous Knowledge and Local Knowledge Dialogues

A total of four IK & LK dialogues were planned during the production and launching of GEO-7 for mobilizing IK & LK data and information for the assessment (see **Table A2.2**). The IK & LK dialogues were set up as a participatory approach that builds upon previous successful experiences of working with Indigenous Peoples as well as local communities to inform global environmental assessments. The methodology for the design of these dialogues were informed by

experiences of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and of the Panamerican Health Organization (PAHO). The dialogues were facilitated by a team of facilitators from SENDAS Asociacion Civil and by the IK & LK task force members. In addition to the participants, the dialogues were attended by "learners" (MESAG members and in the case of the first dialogues also Coordinating Lead Authors) who listed to the discussions without participating in the exchanges.

The first three dialogues resulted in the GEO-7 IK & LK Dialogue Outcome report, which was published in June 2025 by the facilitation team, the IK & LK task force Members and all the organizations of those who participated. A fourth, final, dialogue is tentatively planned to be held after the release of the GEO-7.

Table A2.2: Overview of the GEO-7 IK & LK Dialogues

Dialogues	Thematic focus	Participants	Meeting Dates	Meeting Location & co-host
First Dialogue	Indigenous perspectives, experiences, challenges, actions and desired futures related to the environment and Indigenous communities	28 IK & LK-holders from Asia-Pacific, Africa, Europe and Latin America; 7 learners.	26-28 March 2024	Virtual
Second Dialogue	IK & LK around some transversal thematic axes of the GEO-7 report.	18 IK & LK-holders from Asia, Africa, America, and especially Latin America; 2 learners.	11-13 June 2024	Oaxaca, Mexico, Universidad Nacional Autónoma de México (UNAM)
Third Dialogue	Review of the Second Order Draft of GEO-7 and the First Order Draft of the Executive Summary.	22 IK & LK-holders from Africa, the Arctic, Asia, Central and South America, North America, and the Pacific; 2 learners.	13-15 January 2025 (preparatory sessions in November and December 2024)	Chiang Mai, Thailand, Asia Indigenous Peoples Pact (AIPP)
Fourth Dialogue	"Giveback" workshop: IK & LK methodology used in GEO-7 and lesson learned for future similar processes.	TBD	January 2026 TBD	Virtual

Annex 3 Qualitative assessment of confidence

Assessments and their Executive Summary include a qualitative assessment of confidence associated with their main findings. The following factors will be considered to evaluate the validity of the message or finding: the type, quantity, quality and consistency of evidence (e.g. the existing peer reviewed literature and grey literature), as well as the level of agreement (the level of concurrence in the data, literature and amongst experts, not just across the author team). The author team's expert judgement on the level of evidence and agreement will then be used to apply a confidence term as described below and in **Figure A3.1**:

(d) Inconclusive – existing as or based on a suggestion or speculation; no or limited evidence. Will typically be used infrequently butis intended to provide authors with the flexibility to emphasize issues that are not established in science but that are important to policymakers or might have been highlighted by a different audience.

(d) Unresolved – multiple independent studies exist but conclusions do not agree.

(d) Established but incomplete – general agreement although only a limited number of studies exist but with no comprehensive synthesis, or the studies that do exist imprecisely address the question.

(d) Well established – comprehensive meta-analysis or other syntheses/multiple independent studies that agree. The 'well-established' box in **Figure 11.1** may be further subdivided in order to give author teams the flexibility to emphasize key messages and findings that the author team has very high confidence in:

(ii) Very well established – very comprehensive evidence base and very low amount of disagreement.

(ii) Virtually certain – very robust data covering multiple temporal and spatial scales and almost no disagreement.

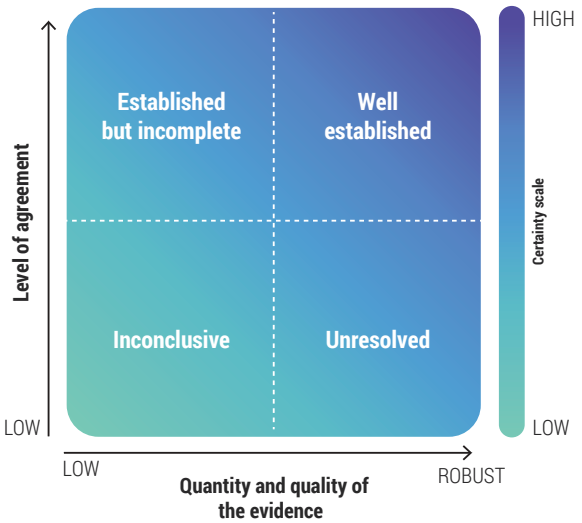
The qualitative confidence terms discussed in this section should not be interpreted probabilistically and are distinct from "statistical significance". The degree of confidence in findings that are conditional on other findings should be evaluated and reported separately.

Quantitative assessment of confidence

Where possible, quantitative assessments of confidence will be communicated as likelihoods. Likelihood expresses a probabilistic estimate of the occurrence of a single event or of an outcome within a given range. Probabilistic estimates are based on statistical analyses of observations or model results, or both, combined with expert judgment.

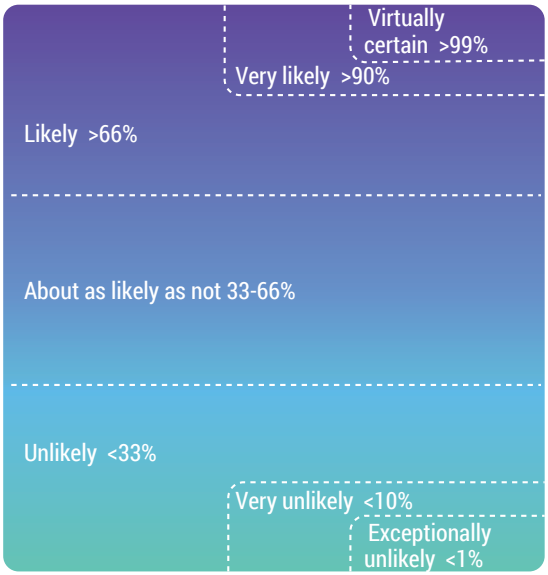
When sufficient probabilistic information is available, consider ranges of outcomes and their associated probabilities with attention to outcomes of potentially high consequence. The author team's expert judgement on the magnitude of the probability should then be used to apply a likelihood term (see **Figure A3.2**).

Figure A3.1: Qualitative Assessment of Confidence Statements



Categories in **Figure A3.2** can be considered to have nested boundaries. For example, describing an outcome as likely or very likely conveys in both cases that the probability of this outcome could fall within the range of >90% probability. However, in the case of likely, the larger range (66-100%) indicates a higher degree of confidence than very likely (>90%). In making their expert judgement, author teams should start at about as likely as not and consider whether there is sufficient quantitative information available to assign either a likely or unlikely probability range. Only after considering this initial range should the author teams consider whether there is sufficient evidence to move to more extreme levels of probability. Author teams should note that using a likelihood term for a specific outcome implies that alternative outcomes have the inverse likelihood, e.g. if an outcome is likely (a range of >66%) then that would imply that other outcomes are unlikely (<33% probability).

Figure A3.1: Quantitative Assessment of Confidence Statements



Contributors

GEO-7 Author Teams

Assessment Co-chairs: Edgar E. Gutierrez-Espeleta [University of Costa Rica (retired), Costa Rica]; Nyovani Madise [African Institute for Development Policy, Malawi, United Kingdom of Great Britain and Northern Ireland]; Bob Watson [University of East Anglia, United States of America, United Kingdom of Great Britain and Northern Ireland]; Ying Wang [Tongji University, China]

Coordinating Lead Authors of Parts: Ghassem Asrar [Universities Space Research Association (Retired), United States of America]; Paul Lucas [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of the)]; Diego Martino [Asesoramiento Ambiental Estrategico and Universidad ORT Uruguay, Uruguay]; Fang Yu [Chinese Academy of Environmental Planning, China], Detlef van Vuuren [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of the)]

Chapter 1 Introduction

Sofia Belardinelli [University of Padova, Italy]; Leila Dagher [Lebanese American University, Lebanon]; Valerie Nelson [National Resource Institute/University of Greenwich, United Kingdom of Great Britain and Northern Ireland]; Jan Plesnik [Nature Conservancy Agency of the Czech Republic, Czechia]; Maria-Cristina Tirado-von der Pahlen [University of California, Spain]

Chapter 2 Historical, Current, and Projected Drivers and Pressures of Environmental Change

Susana Beatriz Adamo [CIESIN-Climate School-Columbia University, Argentina]; Quosay Awad Ahmed [University of Khartoum, Sudan]; Raphael Villela Almeida [Institute for Applied Economic Research, IPEA, Brazil]; Ricardo O. Barra [University of Concepción, Chile]; Jonathan Davies [University of British Columbia, Canada]; Jagath Premakumara Dickella Gamaralalage [Institute for Global Environmental Strategies, Sri Lanka]; Rozana Himaz [University College London, United Kingdom of Great Britain and Northern Ireland]; Miho Kamei [Institute for Global Environmental Strategies (IGES), Japan]; Jinlong Liu [Renmin University of China, China]; David Lopez-Carr [University of California, United States of America]; Astride Messaga Maffo [Institut de Formation et de Recherche Demographiques, IFORD, Cameroon]; Indu K Murthy [Center for Study of Science, Technology and Policy, India]; Evans Osabuohien [Covenant University/ DePECOS Institutions and Development Research Centre-DIaDeRC, Nigeria]; Jacob Park [University of Johannesburg/ Vermont State University, United States of America]; Chao Ren [The University of Hong Kong, China]; Adina Manuela Relicovschi [European Investment Bank, Romania]; Roopesh Kevin Sungkur [University of Mauritius, Mauritius]; Thomas Thornton [University of Alaska, United States of America]; Chiara Varazzani [Organisation for Economic Cooperation and Development, Australia]; Samanta Villegas [Jocotoco Conservation Foundation, Ecuador]; Le Yu [Tsinghua University, China]

Chapter 3 Air

Nadege Amizero [Environmental Pulse Institute, Rwanda]; Claudio Belis [European Commission, Joint Research Centre, Italy]; Stephan Harrison [University of Exeter, United Kingdom of Great Britain and Northern Ireland]; Min Hu [Peking University, China]; Mulako Kabisa [University of the Witwatersrand - Global Change Institute, Zambia]; Indu Murthy [Center for Study of Science, Technology and Polic, India]; Graciela Raga [Instituto de Ciencias de la Atmósfera y Cambio Climático, Universidad Nacional Autónoma de México, Argentina]; Stefan Reis [German Aerospace Centre's Project Management Agency, Unit Environment and Sustainability]; Pallavi Saxena [Department of Environmental Science, Hindu College, University of Delhi, India]; Sotiris Vardoulakis [HEAL Global Research Centre, University of Canberra, Australia]; Carol Zavaleta-Cortijo [Universidad Peruana Cayetano Heredia, Peru]

Chapter 4 Land and Soils

Zoe Barr [Yale School of the Environment, United States of America]; Bhabananda Biswas [Global

Centre for Environmental Remediation, the University of Newcastle and crc for Contamination Assessment and Remediation of the Environment, Australia]; Jonathan Davies [University of British Columbia, Canada]; Jyotsna Krishnakumar [Keystone Foundation, India]; Andrei Kirilenko [University of Florida, Russian Federation]; Lydie-Stella Koutika [Soil Care and Environmental Studies (SCES), Republic of the Congo]; Ravendra Naidu [Global Centre for Environmental Remediation, the University of Newcastle and crc for Contamination Assessment and Remediation of the Environment, Australia]; Leisa Perch [SAEDI Consulting (Barbados) Inc, Barbados]; Xiyan Xu [Chinese Academy of Sciences, China]; Le Yu [Tsinghua University, China]; Pandi Zdruli [International Centre for Advanced Agronomic Mediterranean Studies (CIHEAM) Mediterranean Agronomic Institute of Bari, Albania]

Chapter 5 Oceans and Coast

Fagr Abdel-Gawad [National Research Centre, Egypt]; Salud Deudero Company [Instituto Español de Oceanografia, Spain]; Catia Motta Domingues [National Oceanography Centre, Brazil]; Isa Olalekan Elegbede [Lagos State University, Nigeria]; Pedro Fidelman [Centre for Policy Futures, The University of Queensland, Australia]; Rose Foster [Centre for Policy Futures, The University of Queensland, Australia]; Sandya Gunasekara [Centre for Policy Futures, Sri Lanka]; Britta Denise Hardesty [Commonwealth Scientific and Industrial Research Organisation, United States of America]; Paul Overduin [Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Netherlands (Kingdom of the)]; Helen Spence-Jones [Alfred-Wegener-Institute Centre for Polar and Marine Research and Trinity College Dublin, United Kingdom of Great Britain and Northern Ireland]; Karen Helen Wiltshire [Alfred Wegener Institute, Centre for Polar and Marine Research and Trinity College Dublin, Ireland]

Chapter 6 Freshwater

Tamiru A. Abiye [University of the Witwatersrand, Johannesburg, Ethiopia]; Lindsay Beevers [University of Edinburgh, United Kingdom of Great Britain and Northern Ireland]; Shaneel Chandra [Central Queensland University, Fiji]; Maryam Eqan [Global Youth Biodiversity Network, United Nations Major Group for Children and Youth, Pakistan]; Vinicius F. Farjalla [Federal University of Rio de Janeiro, Brazil]; Erica Brown Gaddis [SWCA Environmental Consultants, United States of America]; Slobodan Gnjato [University of Banja Luka, Bosnia and Herzegovina]; Yolanda López-Maldonado [Indigenous Science, Mexico]

Chapter 7 Implication of Environmental Crises on the Socioeconomic Dimensions of the Sustainable Development Goals

Aliyu Aliyu [University of Lincoln, Nigeria]; Farshad Amiraslani [University of Tehran, Iran (Islamic Republic of)]; Alison Amoussou [United Nations Resident Coordinator Office in UAE, France]; Lindsay Beevers [University of Edinburgh, United Kingdom of Great Britain and Northern Ireland]; Elliot Boateng [Kwame Nkrumah University of Science and Technology, Ghana]; Mark Elder [Institute for Global Environmental Strategies, United States of America]; Erica Gaddis [SWCA Environmental Consultants, United States of America]; Sandya Gunasekara [Centre for Policy Futures, Sri Lanka]; Maryna Henrysson [Royal Institute of Technology, Sweden]; Saleemul Huq [Late, Bangladesh];Govind Kelkar [GenDev Centre for Research and Innovation, India]; Andrei Kirilenko [University of Florida, Russian Federation]; Mahdi Kolahi [Ferdowsi University of Mashhad, Iran (Islamic Republic of)]; Jyotsna Krishnakumar [Keystone Foundation, India]; Tao Lin [Institute of Urban Environment, Chinese Academy of Sciences, China]; Nomanesi Madikizela-Madiya [University of South Africa, South Africa]; Valerie Nelson [University of Greenwich, United Kingdom of Great Britain and Northern Ireland]; Jaee Nikam [Stockholm Environment Institute, India]; Simon Høiberg Olsen [Institute for Global Environmental Strategies, Denmark]; Iryna Ponedelnik [Independent, Belarus]; Riya Rahiman [Coalition for Disaster Resilient Infrastructure, India]; Savio Rousseau Rozario [International Centre for Climate Change and Development, Bangladesh]; Kamaljit K Sangha [Charles Darwin University, Australia]; Ekaterina Terenteva [Russian Federation, Russian Federation]; Maria Cristina Tirado-von der Pahlen [University of California, SHE Foundation, Spain]

Chapter 8 Interlinkages across Environmental Changes, Scales and Geographic Regions and Subregions

Overall Coordinating Lead Authors: Keisha Garcia (ANSA Merchant Bank Limited), Jeff Seadon (Seadon Consulting)

Kofi Akamani [Southern Illinois University, Carbondale; Ghana]; Adenike Akinsemolu [Afe Babalola University, Nigeria]; Maryam Alkharusi [Independent, Oman]; Tarik Alkharusi [University of Technology and Applied Sciences, Oman]; Francis Boafo Asamoah [International Forestry Students' Association, Ghana]; Janelle Baker [Athabasca University, Canada]; Marianna Baslandze [SOGAZ, Russian Federation]; Lorenzo Benini [European Environment Agency (EEA), Italy]; Suruchi Bhadwal [The Energy and Resources Institute, India]; Gillian Bowser [Colorado State University, United States of America]; Acasia Broomes [Santa Rosa First Peoples Community, Trinidad & Tobago]; Joanne Clarke [Durham University, Australia]; Jan Cools [University of Antwerp, Belgium]; Tatenda Dalu [Stellenbosch, Zimbabwe]; Kenel Delusca [Institute of Technology, Science and Advanced Studies of Haiti, Haiti]; Danielle Mendes Thame Denny [Centre for Advanced Studies in Applied Research, Brazil]; Mark Elder [Institute for Global Environmental Strategies, United States of America]; Eduardo Erazo Acosta [Independent researcher on Indigenous communities, Colombia]; Laura Fanciulli [Italian Ministry of Environment and Energy Security, Italy]; Steven Fletcher [University of Portsmouth, United Kingdom of Great Britain and Northern Ireland]; Keisha Garcia [ANSA Merchant Bank Limited, Trinidad and Tobago]; Elisabeth Gilmore [Carleton University, Canada]; Sarah A. Green [Michigan Technological University, United States of America]; Andres Guhl [Universidad de los Andes, Colombia]; Henry Häkkinen [Zoological Society of London, Finland]; Susie Ho [Monash University, Australia]; Beata Houšková [National Agricultural and Food Centre, Slovakia]; Ekhtekharul Islam [Independent University Bangladesh, Bangladesh]; Efitre Jackson [Makerere University, Uganda]; Qian Jia [Tongji University, China]; Modupe O. Jimoh [University of Warwick, Nigeria]; Mizanur Khan [LDC Universities Consortium on Climate Change (LUCCC), LDC Group, Bangladesh]; Kyung Ah Koo [Korea Environment Institute, Republic of Korea]; Vojtech Kotecky [Charles University Environment Centre, Czechia]; Gabriela Kreutzberger [World Economic Forum, Chile]; Joanna Kulczycka [Mineral and Energy Economy Research Institute, Polish Academy of Sciences, Poland]; Mengxing Li [Monash University, China]; Jianguo Liu [Michigan State University, China]; Melisa Ljusa [University of Sarajevo, Bosnia and Herzegovina]; Clever Mafuta [GRID-Arendal, Zimbabwe]; Troy McGee [Monash University, Australia]; Karina Miglioranza [Universidad Nacional de Mar del Plata, IIMyC-CONICET, Argentina]; Ruben Mnatsakanian [Central European University, Armenia]; Indu K Murthy [Center for Study of Science, Technology and Policy, India]; Didacus Namanya [Government of Uganda, Uganda]; S. Nadia Ouedraogo [UNECA, Burkina Faso]; Leisa Perch [SAEDI Consulting (Barbados) Inc, Barbados]; Ramon Pichs-Madruga [Centre for World Economy Studies, Cuba]; Kamal Kumar Rai [Indigenous Knowledge and Peoples Networks, IPs Society for Wetland Biodiversity Conservation Nepal, Nepal]; Jimena Reyeros Sanchez [Fundación Avina, Mexico]; Jeff Seadon [Seadon Consulting, New Zealand]

Chapter 9 Scenario Methodology: Current Trends and Transformation Pathways

Paul Lucas [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of the)]; Ana Paula Aguiar [INPE, Brazilian Institute for Space Research, Brazil]; Alaa Al Khourdajie [Imperial College London, United Kingdom of Great Britain and Northern Ireland]; Vassilis Daioglou [PBL Netherlands Environmental Assessment Agency, Utrecht University, Greece]; Sibel Eker [International Institute for Applied Systems Analysis, IIASA, Türkiye]; Mariana Guttieres-Paz [United Nations Development Programme, Brazil]; Yolanda López-Maldonado [Indigenous Science, Mexico]; Audrone Telesiene [Kaunas University of Technology, Lithuania]; Pushp Raj Tiwari [University of Hertfordshire, India]; Detlef van Vuuren [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of the)]

Chapter 10 Continuation of Current Trends – Global Implications

Paul Lucas [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of the)]; Alaa Al Khourdajie [Imperial College London, United Kingdom of Great Britain and Northern Ireland]; Rob Alkemade [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of the)]; Michel Bakkenes [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of the)]; Ricardo O. Barra [University of Concepcion, Chile]; Lindsay Beevers [University of Edinburgh, United Kingdom of Great Britain and Northern Ireland]; Claudio Belis [European Commission, Joint Research Centre, Italy]; Arthur Beusen [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of

the)]; Hester Biemans [Wageningen University and Research, Netherlands (Kingdom of the)]; Fiffy Hanisdah Binti Saikim [Universiti Malaysia Sabah, Malaysia]; Edward Byers [International Institute for Applied Systems Analysis, IIASA, Ireland]; Vassilis Daioglou [PBL Netherlands Environmental Assessment Agency, Utrecht University, Greece]; Jonathan Davies [University of British Columbia, Canada]; Jonathan Doelman [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of the)]; Sibel Eker [International Institute for Applied Systems Analysis, IIASA, Türkiye]; Dulce Flores-Renteria [Center for Research and Advanced Studies of the National Polytechnic Institute, Mexico]; Panagiotis Fragkos [E3 Modelling, Greece]; Dimitris Fragiadakis [E3-Modelling, Greece]; Shinichiro Fujimori [Kyoto University, Japan]; Taylor Hanna [Pardee Institute University of Denver, United States of America]; Stephan Harrison [University of Exeter, United Kingdom of Great Britain and Northern Ireland]; Tomoko Hasegawa [Ritsumeikan University, Japan]; Mulako Kabisa [University of the Witwatersrand, Zambia]; Kejun Jiang [Hong Kong University of Science and Technology, China]; Yingying Lu [CSIRO, China]; Yolanda López-Maldonado [Independent Scientist, Mexico]; Jonathan D. Moyer [Pardee Institute University of Denver, Netherlands (Kingdom of the)]; Indu K Murthy [Center for Study of Science, Technology and Policy, India]; Ravendra Naidu [University of Newcastle, Australia]; Yuki Ochi [E-konzal, Japan]; Ken Oshiro [Hokkaido University, Japan]; Leonidas Paroussos [E3 Modelling, Greece]; Michael Ruggeri [University of Oxford, Italy]; Heinz Schandl [CSIRO, Australia]; Elias Symeonakis [Manchester Metropolitan University, Greece]; Natalia Tarasova [D.Mendeleev University of Chemical Technology of Russia, Russian Federation]; Audrone Telesiene [Kaunas University of technology, Lithuania]; Pushp Raj Tiwari [University of Hertfordshire, India]; Kazuaki Tsuchiya [National institute for Environmental Studies, Japan]; Kaj-Ivar van der Wijst [Utrecht University, Netherlands (Kingdom of the)]; Detlef van Vuuren [PBL Netherlands Environmental Assessment Agency, Utrecht University, Netherlands (Kingdom of the)]; Laszlo Vreedenburgh [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of the)]; Michaela Werning [International Institute for Applied Systems Analysis, IIASA, Germany]; Le Yu [Tsinghua University, China]; Carol Zavaleta-Cortijo [Universidad Peruana Cayetano Heredia, Peru]

Chapter 11 Transformation Pathways towards Achieving Global Goals – Global Implications

Ana Paula Aguiar [INPE, Brazilian Institute for Space Research, Brazil]; Alaa Al Khourdajie [Imperial College London, United Kingdom of Great Britain and Northern Ireland]; Rob Alkemade [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of the)]; Michel Bakkenes [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of the)]; Lindsay Beevers [The University of Edinburgh, United Kingdom of Great Britain and Northern Ireland]; Claudio Belis [European Commission, Joint Research Centre, Italy]; Arthur Beusen [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of the)]; Hester Biemans [Wageningen University, Netherlands (Kingdom of the)]; Edward Byers [International Institute for Applied Systems Analysis, Ireland]; Vassilis Daioglou [PBL Netherlands Environmental Assessment Agency, Utrecht University, Greece]; Jonathan Doelman [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of the)]; Panagiotis Fragkos [E3-Modelling, Greece]; Dimistris Fragkiadakis [E3 Modelling, Greece]; Shinichiro Fujimori [Kyoto University, Japan]; Taylor Hanna [Pardee Institute University of Denver, United States of America]; Kejun Jiang [Hong Kong University of Science and Technology, China]; Paul Lucas [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of the)]; Yingying Lu [CSIRO, China]; Yolanda López-Maldonado [Independent Scientist, Mexico]; Stephen Maycock [PBL Netherlands Environmental Assessment Agency, South Africa]; Jonathan Moyer [Pardee Institute University of Denver, Netherlands (Kingdom of the)]; Leonidas Paroussos [E3 Modelling, Greece]; Michael Ruggeri [University of Oxford, Italy]; Heinz Schandl [CSIRO, Australia]; Audrone Telesiene [Kaunas University of technology, Lithuania]; Kaj-Ivar van der Wijst [Utrecht University, Netherlands (Kingdom of the)]; Detlef van Vuuren [PBL Netherlands Environmental Assessment Agency, Utrecht University, Netherlands (Kingdom of the)]; Laszlo Vreedenburgh [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of the)]; Michaela Werning [International Institute for Applied Systems Analysis, Germany]; Carol Zavaleta-Cortijo [Universidad Peruana Cayetano Heredia, Peru]

Chapter 12 Transforming Systems – Principles and Levers in Action

Leila Devia [Instituto Nacional de Tecnología Industrial, Argentina]; Monica Kerretts-Makau [Thunderbird School of Global Management, Arizona State University, Kenya]; Christian Löwe [German Environment Agency, Germany]; Fanni Moilanen [Finnish Institute of Occupational Health, Finland]; Valerie Nelson [University of Greenwich, United Kingdom of Great Britain and Northern Ireland]; Laura Pereira [University of the Witwatersrand, South Africa]; Fred Steward [University of Westminster, United Kingdom of Great Britain and Northern Ireland]; Bruno Turnheim [Institut National de la Recherche en Agriculture, Alimentation et Environnement, France]

Chapter 13 Methodology for Developing Solution Pathways towards System Transformations

Parfait M. Eloundou-Enyegue [Cornell University, Cameroon]; Zhuang Han [Cornell University, The London School of Economics and Political Science, China]; Julia Hammann [Food and Agriculture Organization of the United Nations, Germany]; Joanna Kámiche Zegarra [Universidad del Pacífico, Peru]; Annamaria Lammel [Université Paris 8 Vincennes-Saint Denis, France]; Aynur Mammadova [University of Padova, Azerbaijan]; Sarah-Lan Mathez-Stiefel [University of Bern, Switzerland]; Claude Mbarga Ella [IFORD, Cameroon]; Thang Nguyen Trung [Institute of Strategy and Policy on Agriculture and Environment, Viet Nam]; Karachepone N. Ninan [Centre for Economics, Environment and Society-CEES, India]; Henri Rueff [Centre for Development and Environment, University of Bern, Switzerland]

Chapter 14 Solution Pathways for the Transformation of Economic and Financial Systems

Sofia Belardinelli [University of Padova, Italy]; David Broadstock [National University of Singapore, United Kingdom of Great Britain and Northern Ireland]; Kelo Uchendu [Students Organising for Sustainability, Nigeria]; Tegan Evans [University of Portsmouth, Centre for Blue Governance, United Kingdom of Great Britain and Northern Ireland]; Pierre Failler [University of Portsmouth, France]; Laura Fanciulli [Italian Ministry of Environment and Energy Security, Italy]; Juliana Subtil Lacerda [European Environment Agency (EEA), Brazil]; Patricia Maccagno [Moreno National University, Argentina]; Ronaldo Seroa Da Motta [State University of Rio de Janeiro, Brazil]; Nkechi Owoo [University of Ghana, Ghana]; Adina Manuela Relicovschi [European Investment Bank, Romania]; Kamaljit K Sangha [Charles Darwin University, Australia]; Stella Tsani [National and Kapodistrian University of Athens, Greece]; Jianhua Xu [Peking University, China]

Chapter 15 Solution Pathways for Transformation towards Circularity

Patrick Schröder [Chatham House, New Zealand]; Apoorva Arya [Circular Innovation Lab, India]; Bonmwa Fwangkwal [African Circular Economy Alliance Secretariat, AfDB, Nigeria]; Sigrid Kusch-Brandt [Ulm University of Applied Sciences, University of Southampton, Germany]; Olena Maslyukivska [National University of Kyiv-Mohyla Academy, University of Vaasa, Ukraine]; Botho Bahumi Motlhanka [Global Green Growth Institute, Botswana]; Kamal Kumar Rai [ITT-Nepal, Indigenous Knowledge and Peoples Network, Nepal]; Arthur Silva [Federal University of Rio de Janeiro, Brazil]; Maria Cristina Tirado-von der Pahlen [University of California, SHE Foundation, Spain]; Ken Webster [Cranfield University, Cambridge Institute for Sustainability Leadership, United Kingdom of Great Britain and Northern Ireland]; Xianlai Zeng [Tsinghua University, China]

Chapter 16 Energy System Transformation Pathways

Aseel Ibrahim Mohammed Abo-Taleb [Global Youth and Sustainability Organization, Yemen]; Adedoyin Adeleke [Green Growth Africa Sustainability Network, Nigeria]; Ayodeji Stephen Adekanbi [HydroGEM Energy Advisory, Nigeria]; Janelle Baker [Athabasca University, Canada]; Loïc De Weerdt [University of Antwerp, Belgium]; Sybil Derrible [University of Illinois Chicago, United States of America]; Sabine Fuss [Potsdam Institute for Climate Impact Research, Germany]; Elisabeth Gilmore [Carleton University, Canada]; Chenmin He [Zhejiang University of Technology, China]; Nandakumar Janardhanan [Institute for Global Environmental Strategies, India]; Peter King [Late, Australia]; Debora Ley [United Nations Economic Commission for Latin America and the Caribbean, Ministry of Environment and Natural Resources of Guatemala, Mexico]; Kevin Nnanye Nwaigwe [Clean Energy Research Centre, University of Botswana, Nigeria]; Daniel Alejandro

Pacheco Rojas [Universidad Nacional Autónoma de Mexico,Mexico]; Ruben Prütz [Potsdam Institute for Climate Impact Research, Germany]; Hareenanden Ramasawmy [University of Mauritius, Mauritius]; Maria Virginia Vilariño [Argentine Business Council for Sustainable Development, Argentina]

Chapter 17 Food Systems Transformation Pathways

Peter Alexander [University of Edinburgh, United Kingdom of Great Britain and Northern Ireland]; Jessica Fanzo [Columbia University, United States of America]; Michele Fontefrancesco [Università Cattolica del Sacro Cuore, Italy]; Jessica Fuller [GRID-Arendal, United States of America]; Juliana Merçon [Universidad Veracruzana, Brazil]; Katie Noble [University of York, United Kingdom of Great Britian and Northern Ireland]; Alice Odingo [University of Nairobi, Kenya]; Lucia Reisch [University of Cambridge, Germany]; Tek Sapkota [International Maize and Wheat Improvement Center (CIMMYT), Nepal]

Chapter 18 Solution Pathways Enabling a Sustainable and Resilient Environment for Systems Transformation

Adolf Acquaye [Khalifa University of Science and Technology, Ghana]; Alex Godoy-Faundez [Universidad del Desarrollo, Chile]; Olga Illarionova [Lomonosov Moscow State University, Russian Federation]; William Armand Mala [Department of Plant Biology, University of Yaoundé I, Cameroon]; Svetlana Radionova [Natural Resources of the Russian Federation, Russian Federation]; Kalim Shah [University of Delaware, Trinidad and Tobago]; Binaya Raj Shivakoti [Institute for Global Environmental Strategies, Nepal]; Gail Taylor [University College London, United Kingdom of Great Britain and Northern Ireland]; Soham Vaidya [Global Shield Secretariat, India]

Chapter 19 Implications for Different Economic Development Contexts

Alaa Al Khourdajie [Imperial College London, United Kingdom of Great Britain and Northern Ireland]; Steve Arquitt [Millennium Institute, United States of America]; Lynette Cheah [University of the Sunshine Coast, Singapore]; Isa Elegbede [Lagos state university, Nigeria]; Pankaj Kumar [Institute for Global Environmental Strategies, India]; Estee Miltz [Millennium Institute, South Africa]; Heinz Schandl [CSIRO, Australia]

Chapter 20 Regional Dimensions of the Transformative Solutions for the Global Environmental Crises

Overall Coordinating Lead Authors: Lindsay Beevers (The University of Edinburgh), Madhav Bahadur Karki (Centre for Green Economy Development, Nepal)

Sanchit Saran Agarwal [The Energy and Resources Institute (TERI), India]; Barbara Amon [Leibniz Institute for Agricultural Engineering and Bioeconomy, Germany]; Aistė Balžekienė [Kaunas University of Technology, Lithuania]; Aliyu Salisu Barau [Bayero University Kano; Urban Climate Change Research Network (UCCRN), Nigeria]; Lindsay Beevers [The University of Edinburgh, United Kingdom of Great Britain and Northern Ireland]; Meena Bohara [National Young Academy of Nepal, ForestAction Nepal, Nepal]; Souhila Bouilouta [National Economic Social and Environmental Council, Algeria]; Tanya Brodie Rudolph [University of Stellenbosch, South Africa]; Edward Byers [International Institute for Applied Systems Analysis (IIASA), Ireland]; Monday Businge [University of Nairobi, Uganda]; Donovan Campbell [The University of the West Indies, Jamaica]; Shaneel Chandra [Central Queensland University, Fiji]; Kalpana Chaudhari [Shah and anchor Kutchhi engineering college, institute for sustainable development and research (ISDR) , India]; Ruijun Chen [Fuzhou University, China]; Kateřina Černý Pixová [Czech University of Life Sciences Prague, Czechia]; Hancheng Dai [Peking University, China]; Danielle Mendes Thame Denny [University of São Paulo - Research Centre for Greenhouse Gas Innovation and Centre for Carbon Research in Tropical Agriculture]; Peter Edwards [Manaaki Whenua Group, Bioeconomy Science Institute, Wellington, New Zealand]; Alan Feest [University of Bristol, United Kingdom of Great Britain and Northern Ireland]; Michele Fontefrancesco [Università Cattolica del Sacro Cuore, Italy]; Emmanuelle Freitas [Center of Mineral Technology, Brazil]; Gladys Cecilia Hernandez-Pedraza [Centro de Investigaciones de la Economia Mundial (CIEM), Cuba]; Gensuo Jia [Chinese Academy of Sciences, China]; Madhav Bahadur Karki [Centre for Green Economy Development, Nepal]; Shaneica Lester [The University of the West Indies, Jamaica]; Jianguo Liu [Michigan State University, China]; Jinlong Liu [Renmin University of China, China]; William Armand Mala

[Department of Plant Biology, University of Yaoundé I, Cameroon]; Jan Matuštík [University of Chemistry and Technology Prague, Czechia]; Alma Mendoza-Ponce [National Autonomous University of Mexico (UNAM), Mexico]; Amy Molotoks [Stockholm Environment Institute, University of York, United Kingdom of Great Britain and Northern Ireland]; Rachid Mrabet [National Institute of Agricultural Research (INRA), Morocco]; Veronica Mwangi [University of Nairobi, Kenya]; Jiayi Ng [Agency for Science, Technology and Research, Singapore]; Judit Oláh [John von Neumann University Doctoral School of Management and Business Administration, University of Debrecen, Hungary]; Jean Pierre Ometto [National Institute for Space Research (INPE), Brazil]; József Popp [John von Neumann University Doctoral School of Management and Business Administration, Hungary]; Joana Portugal Pereira [Coppe/Federal University of Rio de Janeiro and IST/ULisboa]; Fangxia Shen [Beihang University, China]; George Florin Staicu [Academy for Economic Studies, Bucharest, Romania]; Paul Sutton [University of Denver, United States of America]; Sénankpon Stephane Marcel Tcheton [Global Change Institute of the University of the Witwatersrand, Benin]; Thomas Thornton [University of Alaska, National Academy of Sciences, United States of America]; Leila Zamani [Department of Environment of Iran, Iran (Islamic Republic of)]

Chapter 21 Driving the Transformations

Catalina Turcu [University College London, Romania]; Eric Zusman [Institute for Global Environmental Strategies, United States of America]; Medani Bhandari [Atlantic States Legal Foundation, Nepal]; Sibel Eker [Radboud University/ International Institute for Applied Systems Analysis, Türkiye]; Simone Lucatello [Instituto Mora – SECHITI, Mexico]; Paul Lucas [PBL Netherlands Environmental Assessment Agency, Netherlands (Kingdom of the)]; Valerie Nelson [University of Greenwich, United Kingdom of Great Britain and Northern Ireland]; Martina Rotolo [University College London, Italy]; Audrone Telesiene [Kaunas University of Technology, Lithuania]; Sandra Torrusio [Faculty of Natural Sciences and Museum UNLP, Argentina];

Global Environmental Crises Chapeau

Ricardo O. Barra [University of Concepcion, Chile]; Fiffy Hanisdah Binti Saikim [Universiti Malaysia Sabah; Member of the Young Scientists Network – Academy of Sciences Malaysia, Malaysia]; Jonathan Davies [University of British Columbia, Canada]; Dulce Flores-Renteria [Center for Research and Advanced Studies of the National Polytechnic Institute, Saltillo Unit, Mexico]; Stephan Harrison [University of Exeter, United Kingdom of Great Britain and Northern Ireland]; Mulako Kabisa [University of the Witwatersrand - Global Change Institute, Zambia]; Christina Karakizi [National Technical University of Athens, Greece]; Indu K Murthy [CSTEP; Center for Study of Science, Technology and Policy, India]; Ravendra Naidu [Global Centre for Environmental Remediation, the University of Newcastle and crc for Contamination Assessment and Remediation of the Environment, Australia]; Eleni Sofik [National Technical University of Athens, Greece]; Elias Symeonakis [Manchester Metropolitan University, Greece]; Natalia Tarasova [D.Mendeleev University of Chemical Technology of Russia, Russian Federation]; Maria Cristina Tirado-von der Pahlen [University of California, SHE Foundation, Spain]; Le Yu [Tsinghua University, China]

Indigenous Knowledge and Local Knowledge Task Force and Chapeaux Authors

Janelle Baker [Athabasca University, Canada]; Victoria Del Pilar Chicmana Zapata [Universidad Peruana Cayetano Heredia, Peru]; Isa Elegbede [Lagos state university, Nigeria]; Eduardo Erazo Acosta [Universidad de Nariño, Colombia]; Jyotsna Krishnakumar [Keystone Foundation, India]; Yolanda Lopez-Maldonado [Indigenous Science, Mexico]; Jinlong Liu [Renmin university of China, China]; William Armand Mala [University of Yaoundé I, Cameroon]; Juliana Merçon [Universidad Veracruzana, Brazil]; Didacus Namanya [Ministry of Health, Uganda]; Valerie Nelson [University of Greenwich, United Kingdom of Great Britain and Northern Ireland]; Kamal Kumar Rai [ITT-Nepal, Indigenous Knowledge and Peoples Network, Society for Wetland Biodiversity Conservation, Nepal Indigenous Forum for Biodiversity, Nepal]; Aibek Samakov [University of Central Asia, Kyrgyzstan]; Kamaljit K Sangha [Charles Darwin University, Australia]; Sénankpon Stephane Marcel Tcheton [Global Change Institute of the University of the Witwatersrand, Benin]; Thomas Thornton [University of Alaska, United States of America]; Maria Cristina Tirado-von der Pahlen [University of California, SHE Foundation, Spain]; Sarah-Lan Mathez-Stiefel [Centre for Development and Environment, University of Bern

and Wyss Academy for Nature, University of Bern, Switzerland]; Carol Zavaleta-Cortijo [Universidad Peruana Cayetano Heredia, Indigenous Peoples Observatory Network (IPON), Peru]

Behavioural, Social and Cultural (BSC) Task Group

Aistė Balžekienė [Kaunas University of Technology, Lithuania]; Medani Bhandari [Atlantic States Legal Foundation, Nepal]; Elliot Boateng [Kwame Nkrumah University of Science and Technology, Ghana]; Sibel Eker [International Institute for Applied Systems Analysis, IIASA, Türkiye]; Richard Filcak [European Environmental Agency (EEA), Slovakia]; Razieh Ghayoumi [Biodiversity and Biosafety Group, Research Center for Environment and Sustainable Development, Iran]; Elisabeth Gilmore [Carleton University, Canada]; Alex Godoy-Faundez [Universidad del Desarrollo, Chile]; Mariana Guttieres-Paz [United Nations Development Programme, Brazil]; Julia Hammann [Food and Agriculture Organization of the United Nations, Germany]; Sigrid Kusch-Brandt [Ulm University of Applied Sciences, University of Southampton, Germany]; Annamaria Lammel [Université Paris 8 Vincennes-Saint Denis, France]; Aynur Mammadova [University of Padova, Azerbaijan]; Claude Mbarga Ella [IFORD, Cameroon]; Jaee Nikam [Stockholm Environment Institute, India]; Evans Osabuohien [Covenant University, DePECOS Institutions and Development Research Centre-DIaDeRC, Nigeria]; Leisa Perch [SAEDI Consulting (Barbados) Inc, Barbados]; Dan Poniachik Calderon [Social and Behavioral Change Agency Latam, Chile]; Audrone Telesiene [Kaunas University of Technology, Lithuania]; Catalina Turcu [University College London, Romania]; Chiara Varazzani [Organisation for Economic Cooperation and Development, Australia]; Jianhua Xu [Peking University, China]

Climate Change Adaptation (CCA) Task Group

Medani Bhandari [Atlantic States Legal Foundation, Nepal]; Donovan Campbell [The University of the West Indies, Jamaica]; Jan Cools [University of Antwerp, Belgium]; Bonmwa Fwangkwal [African Circular Economy Alliance Secretariat, AfDB, Nigeria]; Mariana Guttieres-Paz [United Nations Development Programme, Brazil]; Mulako Kabisa [University of the Witwatersrand – Global Change Institute, Zambia]; Miho Kamei [Institute for Global Environmental Strategies (IGES), Japan]; Govind Kelkar [GenDev Centre for Research and Innovation, India]; Debora Ley [United Nations Economic Commission for Latin America and the Caribbean, ECLAC, Ministry of Environment and Natural Resources of Guatemala, Mexico]; Simone Lucatello [Instituto Mora – SECHITI, Mexico]; S. Nadia Ouedraogo [UNECA, Burkina Faso]

Fellows

Aseel Ibrahim Mohammed Abo-Taleb [Global Youth and Sustainability Organization, Yemen]; Ayodeji Stephen Adekanbi [HydroGEM Energy Advisory, Nigeria]; Raphael Villela Almeida [Institute for Applied Economic Research, IPEA, Brazil]; Tarik Alkharusi [Imperial College London, UTAS-Oman, Oman]; Nadege Amizero [Environmental Pulse Institute, Rwanda]; Alison Amoussou [United Nations Resident Coordinator Office in UAE, France]; Francis Boafo Asamoah [International Forestry Students' Association, Ghana]; Zoe Barr [Yale School of the Environment, United States of America]; Marianna Baslandze [SOGAZ, Russia]; Sofia Belardinelli [University of Padova, Italy]; Acasia Broomes [Santa Rosa First Peoples Community, Trinidad & Tobago]; Ruijun Chen [Fuzhou University, China]; Maryam Eqan [Global Youth Biodiversity Network, United Nations Major Group for Children and Youth, Pakistan]; Tegan Evans [University of Portsmouth, Centre for Blue Governance, United Kingdom of Great Britain and Northern Ireland]; Laura Fanciulli [Italian Ministry of Environment and Energy Security, Italy]; Rose Foster [Centre for Policy Futures, The University of Queensland, Australia]; Emmanuelle Freitas [Center of Mineral Technology, Brazil]; Slobodan Gnjato [University of Banja Luka, Bosnia and Herzegovina]; Zhuang Han [Cornell University/The London School of Economics and Political Science, China]; Qian Jia [Tongji University, China]; Christina Karakizi [National Technical University of Athens, Greece]; Gabriela Kreutzberger [World Economic Forum, Chile]; Shaneica Lester [The University of the West Indies, Jamaica]; Astride Messaga Maffo [Institut de Formation et de Recherche Demographiques, IFORD, Cameroon]; Jan Matuštík [University of Chemistry and Technology Prague, Czechia]; Claude Mbarga Ella [IFORD, Cameroon]; Estee Miltz [Millennium Institute, South Africa]; Amy Molotoks [Stockholm Environment Institute, University of York, United Kingdom of Great Britain and Northern Ireland]; Fanni Moilanen [Finnish Institute of Occupational Health, Finland]; Botho Bahumi

Motlhanka [Global Green Growth Institute, Botswana]; Katie Noble [University of York, United Kingdom of Great Britain and Northern Ireland]; Iryna Ponedelnik [Independent, Belarus]; Jimena Reyeros Sanchez [Fundación Avina, Mexico]; Martina Rotolo [University College London, Italy]; Michael Ruggeri [University of Oxford, Italy]; Arthur Silva [Federal University of Rio de Janeiro, Brazil]; Eleni Sofik [National Technical University of Athens, Greece]; Helen Spence-Jones [Alfred-Wegener-Institute Centre for Polar and Marine Research and Trinity College Dublin, United Kingdom of Great Britain and Northern Ireland]; Sénankpon Stephane Marcel Tcheton [Global Change Institute of the University of the Witwatersrand, Benin]; Ekaterina Terenteva [Russian Federation, Russian Federation]; Pushp Raj Tiwari [University of Hertfordshire, India]; Kelo Uchendu [Students Organising for Sustainability, Nigeria]; Soham Vaidya [Global Shield Secretariat, India]; Victoria Del Pilar Chicmana Zapata [Universidad Peruana Cayetano Heredia, Peru]

Intergovernmental and Multi-stakeholder Advisory Group (IMAG)

Arthur Eijs [Ministry of Infrastructure & Water Management, Netherlands (Kingdom of the)]; Anna Mampye [Ministry of Forestry, Fisheries and Environment, South Africa]; Rolenas Baereleo [Department of Environmental protection and Conservation, Vanuatu]; Miroslav Havránek [Czech Environmental Information Agency, Czechia]; Ana Julieta Calvo-Obando [Ministry of Environment and Energy, Costa Rica]; Mohamed Abdelraouf [Gulf Research Center (GRC), Egypt]; Thuraya Said Al Sariri [President office- Environment Authority, Oman]; Zahra Abu Taha [ZATARI refugees camp, Oxfam, Jordan]; Silvio Albuquerque e Silva [Embassy of Brazil in Kenya, Brazil]; Djatougbe Aziaka [Welfare Togo, Togo]; Leila Bendifallah [M' hamed Bougara University, Algeria]; Thomas Chali [United Republic of Tanzania]; Merylene Chitharai [UKZN Howard College, South Africa]; Ingrid Coetzee [ICLEI Africa, South Africa]; Alexandra Gurgel Valente da Costa [Ministry of the Environment and Climate Change, Brazil]; Lisa Eriksson [Department for Outlook and Policy, Sweden]; Toghrul Feyziyev [Ministry of Ecology and Natural Resources, Azerbaijan]; Marek Haliniak [Ministry of Climate and Environment, Poland]; Meri Harutyunyan [Ministry of Environment, Armenia]; Neyra Herrera [Ministry of Environment, Panama]; Keri Holland [U.S. Department of State, United States of America]; Yi Huang [Peking University, China]; Claudia Kabel [German Environment Agency (UBA), Germany]; Christina Komorski [Environment and Climate Change Canada, Canada]; Maha Maayta [Ministry of Environment, Jordan]; Takashi Otsuka [Institute for Global Environmental Strategies (IGES), Japan]; Toral Patel-Weynand [U.S. Department of Agriculture Forest Service, United States of America]; Dušica Pešević [University of Banja Luka, Bosnia and Herzegovina]; Salla Rantala [Environmental Policy Centre, Finnish Environment Institute (SYKE), Finland]; Kenset Amaury Rosales Riveiro [Ministry of Environment and Resources Natural Resources (MARN), Guatemala]; Modibo Sacko [Permanent Interstate Committee for Drought Control in the Sahel (CONACILSS), Mali]; Jerome Lugumira Sebadduka [National Environment Management Authority (NEMA), Uganda]; Ruth Viola Spencer [Marine Ecosystems Protected Areas (MEPA) Trust, Antigua and Barbuda]; Gillian Stanislaus [Environmental Management Authority (EMA), Trinidad and Tobago]; Jan-Gustav Strandenaes [University of Stockholm, Norway]; Prem Singh Tharu [Asia Indigenous Peoples Pact (AIPP) under Environment Programme, Thailand]; Alexandra Gurgel Valente da Costa [Ministry of the Environment and Climate Change, Brazil]; Carlos Cordero Vega [Ministry of Environment and Energy, Costa Rica]; Fabian Wagner [IIASA, Germany]; Dominic Kailash Nath Waughray [CEO World Business Council for Sustainable Development, India]

Multidisciplinary Expert Scientific Advisory Group (MESAG)

Nicholas King [Wilderness Foundation Africa, South Africa]; Maria del Mar Viana Rodriguez [Spanish Ministry for the Ecological Transition and Demographic Challenge, Spain]; Ervin Balázs [Centre for Agricultural Research of the Hungarian Academy of Sciences, Hungary]; Rosemarie Casimiro [Nueva Ecija University of Science and Technology, Philippines]; Gian Carlo Delgado-Ramos [Institute of Geography, National Autonomous University of Mexico, Mexico] Dolors Armenteras Pascual [Universidad Nacional de Colombia, Colombia]; Ousséni Arouna [National University of Sciences, Technologies, Engineering and Mathematics, Benin]; Lorenzo Ciccarese [Higher Institute for Environmental Protection and Research (ISPRA), Italy]; Sandra Bibiana Correa [Mississippi State University, Colombia]; Eric Davidson [University of Maryland Center for Environmental Science, United States of America]; Nagwa El Karawy [Ministry of Environment (former), Egypt]; Tambe Honourine

Enow [Africa Climate and Environment Foundation (ACEF), Cameroon]; James D. Ford [Priestley Centre for Climate Futures, United Kingdom of Great Britain and Northern Ireland]; Catherine Ganzleben [European Environmental Agency (EEA), United Kingdom of Great Britain and Northern Ireland]; Razieh Ghayoumi [Research Center for Environment and Sustainable Development, Department of Environment, Iran (Islamic Republic of)]; Joyeeta Gupta [University of Amsterdam and IHE-Delft Institute for Water Education, Netherlands (Kingdom of the)]; Tatiana Kuznetsova [The Federal Service for Supervision of Natural Resources Management of the Russian Federation, Russian Federation]; Yonglong Lu [Xiamen University, China]; Mónica Moraes R. [Academia Nacional de Ciencias - Bolivia and Universidad Mavor de San Andrés, Bolivia (Plurinational State of)]; Amal Moufarreh [Ministry of Energy Transition and Sustainable Development, Morocco]; Janez Potocnik [UNEP International Resource Panel, Slovenia]; Nijavalli Ravindranath [Center for Sustainable Technologies, India]; Alberto Santos Capra [Basel Regional Center for South America under the Presidency of the National Institute of Industrial Technology (INTI), Argentina]; Majid Shafie pour Motlagh [University of Tehran, Iran (Islamic Republic of)]; Belay Simane [Addis Ababa University, Ethiopia]; Asha Singh [Environmental Governance Consulting, Guyana]; Inna Stecenko [Transport and Telecommunication Institute, Latvia]; Shau Hwai Aileen Tan [UNESCO-IOC Sub-Commission for Western Pacific (WESTPAC), University Sains Malaysia, Malaysia]; Alban Thomas [INRAE – French National Research Institute for Agriculture, Food and Environment, France]

Review Editors

Ahmed Abdelrehim [retired, formerly CEDARE, Egypt]; Bettina Hedden- Dunkhorst [Bundesamt für Naturschutz (BfN) Federal Agency for Nature Conservation, Germany]; Kofi Akamani [Southern Illinois University, Ghana]; Ramia Al Bakain [The University of Jordan, Jordan]; Chandani Appadoo [University of Mauritius, Mauritius]; Amanullah Bahriuloom [The University of Agriculture Peshawar, Pakistan]; William Balée [Tulane University, United States of America]; Suruchi Bhadwal [The Energy and Resources Institute, India]; Miranda Boettcher [German Institute for International and Security Affairs (SWP), Australia]; Ashok Das [SunMoksha, United States of America]; Naa Dodua Dodoo [African Institute for Development Policy, Ghana]; Oswaldo dos Santos Lucon [Secretary of Infrastructure and Environment Environment of the State of São Paulo, Brazil]; Timothy Dube [University of the Western Cape, Zimbabwe]; Paul Dumble [Independent Climate, Land, Waste and Environment Expert, United Kingdom of the Great Britain and Northern Ireland]; Samia Elfitouri Grimida [Food and Agriculture Organization, Libya]; Miguel Equihua [Institute of Ecology, Mexico]; Gabriela Fernandez [San Diego State University, United States of America]; Elsa Galarza [Pacific University, Research Center, Peru]; Nadezhda Gaponenko [Russian Academy of Sciences, Russian Federation]; Konstantin Gongalsky [A.N. Severtsov Institute of Ecology and Evolution, Russian Federation]; Wame Lucretia Hambira [Botswana University of Agriculture and Natural Resources. Botswana]; Shan Hu [Tsinghua University, China]; Arnulf Jaeger- Waldau [European Commission, Germany]; Rumiana Jeleva [Bulgarian Academy of Sciences, Bulgaria]; Injy Johnstone [Oxford Sustainable Finance Group, New Zealand]; Joni Jupesta [United Nations University, Indonesia]; Lian Pin Koh [National University of Singapore, Singapore]; Anil Markandya [Basque Centre for Climate Change, Spain]; David McCollum [Oak Ridge National Laboratory, United States of America]; Nibedita Mukherjee [Brunel University London, India]; Adetoun Mustapha [Shell Petroleum Development Company of Nigeria Ltd, Nigeria]; Alick Bulala Muvundika [National Institute for Scientific and Industrial Research (NISIR), Zambia]; Leonard Nurse [Centre for Resource Management and Environmental Studies, Barbados]; Eni Oko [Newcastle University, United Kingdom of the Great Britain and Northern Ireland]; Robert Onyeneke [Alex Ekwueme Federal University Ndufu-Alike, Nigeria]; Jiesper Pedersen [Copenhagen Business School, Denmark]; Dimitris Poursanidis [TerraSolutions Marine Environment research, Greece]; Kálmán László Rajkai [Institute for Soil Sciences Centre for Agricultural Research, Hungary]; Kilaparti Ramakrishna [Woods Hole Oceanographic Institution, United States of America]; Abdulkarim Rashed [RRC – London , Dubai branch, Bahrain]; Ariana Rossen [National Water Institute, Argentina]; Mayar Sabet [CEDARE, Egypt]; Georg Schiller [Leibniz-Institute of Ecological Urban and Regional Development, Germany]; Faizi Shahul Hameed [Japan International Coop Agency, India]; Diogo Silva [Federal University of São Carlos (UFSCar), Brazil]; Tannecia Stephenson [The University of the West Indies, Jamaica]; Saritha Sudharmma Vishwanathan [National Institute of

Environmental Studies, India]; Miguel Angel Taboada [Institute of Ecology, Argentina]; Ram Devi Tachamo Shah [Kathmandu University, Nepal]; Goran Trbic [University of Banja Luka, Bosnia and Herzegovina]; Oksana Volosko-Demkiv [Center for Environmental Consulting and Auditing (CECA), Ukraine]; Fei Wang [Chinese Academy of Sciences and Ministry of Water Resources, China]; Sarah Whitmee [London School of Hygiene & Tropical Medicine, United Kingdom of the Great Britain and Northern Ireland]; Lucia Helena Xavier [Mineral Technology Center, Brazil]; Xinzhu Zheng [University of Petroleum, China]; Malgorzata Zimniewska [Institute of Natural Fibers and Medicinal Plants National Research Institute, Poland]

UNEP Reviewers

Yassin Ahmed; Joana Akrofi; Carolina Jaramillo Alvarez; Michael Asquith; Libera Assini; Helena Rey de Assis; Abdelkader Bensada; Magda Biesiada; Raymond Brandes; Santiago Brenes; Llorenc Mila i Canals; Ludgarde Coppens; Ruth Coutto; John Crhistensen; Cyrille-lazare; Francesco Gaetani; Therese El Gemayel; Niklas Hagelberg; Andrea Hinwood; Jason Jabbour; Sinikinesh Jimma; Yujeong Kim; Thaddeus Kiplimo; Carmen Torres Ledezma; Peggy Lefort; Jade Roberts Maron; Bavelyne Mibei; Abdelmenam Mohamed; Rosemary Mukasa; Kakuko Nagatani-Yoshida; Javier Neme; Clementine O'Connor; Anne Olhoff; Martina Otto; Ekaterina Poleschchuk; Rula Qalyoubi; Nina Raasakka; Hala Razian; David Rubia; Marieta Sakalian; Charles Sebukeera; Sudhir Sharma; Sushant Shrestha; Harrison Simotwo; Miriam Liliana Hinostroza Suarez; Sjaheezah Subratty; Elisa Tonda; Frank Turyatunga; Feng Wang

UN Reviewers

Issoufou Abdoulkader; Sasha Alexander; Shikha Bhasin; Hany Besada; Zhuolun Chen; Wilfredo Cisneros; Ismaël Camara; Felipe Dall; Jacob Diamond; Maria del Rocio Gamboa Arias; Ula Garcia; Flávia Guerra; Omar Herrera Fajardo; Pa Sebastian Izquierdo Abad; Heather Jacobs; Junru Li; Xi Ling; Bavelyne Mibei; Anahí Membribe; Rajkumar Nagarajah; Shairoz Nathoo; Jolly Nguyen; Polycarp Ondieki; Percy Chuks Onianwa; Valéria Romão Pasqualini Nerio; Marta Pizano; Pages Naima; Mascha Samkova; Md. Golam Mahabub Sarwar; Romanas Savickas; Ernesto Sanchez-Triana; Benjamin Schachter; Question Ramontsho; Egline Tawuya; Maria Victoria Gobet; Sasha Alexander; Sheryl Rose Reyes

External Reviewers and Intergovernmental Reviewers

Asma Abahussain [Bahrain]; Bouchra Belhaj Abdallah [Tunisia]; Naglaa Abdelmoneim Abdallah [Egypt]; Mohamed Abdulrazzak [Saudi Arabia]; Akmal Abdurazakov [Uzbekistan]; Tamer Abogharara [Egypt]; Sameh Mansour Abosamra [Egypt]; Ahmed Abuthaher [State of Palestine]; Alex Adams [United Kingdom of Great Britain and Northern Ireland]; Adebayo Johnson Adeloye [Nigeria]; Timothy Aderemi [Nigeria]; Modupeola Morenike Adesemowo [Nigeria]; Abiodun Adewale [Nigeria]; Oyindamola Olajumoke Adeyemo [Nigeria]; Frank Adiga [United Kingdom of Great Britain and Northern Ireland]; Oluranti Agboola [Nigeria]; Eman Ahmad [Egypt]; Amina Ahmarech [Morocco]; Hisham Salaheldin Shazali Ahmed [Sudan]; Rayan Ahmed [Sudan]; Birgit Ahrens [Germany]; Monique Ainyakou-Sanga [Côte d'Ivoire]; Taofik Tola Ajagbe [Nigeria]; Chinenye Aja-Nwachuku [Nigeria]; Omowumi Monisola Ajeigbe [Nigeria]; Rashidat Akande [Nigeria]; Raimot Titilade Akanmu [Nigeria]; Akanni Akinyemi [Nigeria]; Archibong Akpan [Nigeria]; Viviana Patino Alcala [Mexico]; Francesco Aletta [Italy]; Barbosa Alexandre [Brazil]; John Leo Algo [Philippines]; Osman Mirghani Ali [Sudan]; Lacy Alison [United States of America]; Dora Almassy [Hungary]; Nawaf Almutairi [Kuwait]; Abdullah Hassan Al-Saqqaf [Yemen]; Moises Alvarez [Dominican Republic]; Christiam Álvarez-Vega [Costa Rica]; Mohammed Alzuhairi [Iraq]; George Amenchwi Amahnui [Cameroon]; Mary Amponsah [Ghana]; Lucía Andreussi [Argentina]; Maria Andrzejewska [Poland]; Anshuman Anshuman [India]; Justice Oyakhilome Anthony [Nigeria]; Johanna Appelhans [Germany]; Nana Yaa Appiah [Ghana]; Fernando Aragón-Durand [Mexico]; Yoseph Negusse Araya [Eritrea]; Antonella Arcangeli [Italy]; Omole Areguamen [Nigeria]; Karen Arnon [Netherlands (Kingdom of the)]; Ousséni Arouna [Benin]; Gisele Arruda [United Kingdom of Great Britain and Northern Ireland]; Daniela Arsenovic [Serbia]; Paulo Artaxo [Brazil]; Jones Lewis Arthur [Ghana]; Jharana Bhattarai Aryal [Australia]; Eslam Hamdy Ashour [Egypt]; Kishla Askins [United States of America]; Cyro Assahira [Brazil]; Reem Abou Assi [Iraq]; Diana Astudillo [Ecuador]; Kathleen Aviso [Philippines]; Andrew Bacchus [Canada]; Marcelo Alejandro Baeza [Chile]; Rosemarie Bähne [Germany]; Angeliki Balayannis [Greece]; Ervin Balazs [Hungary]; Aistė Balžekienė [Lithuania]; Alexandra Bancheva [Russian Federation]; Michael Bank [United States of America]; Martha Fidela Bargiela [Argentina]; Mohamed Ahmed

Barikalla [Mauritania]; Jack Barrie [United Kingdom of Great Britain and Northern Ireland]; Cristian Barros-Diaz [Colombia]; Vladimir Bashkin [Russian Federation]; Maria Battistel [Denmark]; Michelle Baumflek [United States of America]; Cyrille Bienvenu Bediang [Cameroon]; Stiphan Beher [New Zealand]; Martin Behnisch [Germany]; Claudia Béjar [Chile]; Pamela Zúñiga Bello [Mexico]; Violeta Bendersky [Argentina]; Leila Bendifallah [Algeria]; Hanusha Bhakhoa [Mauritius]; Medani Bhandari [United States of America]; Xinxin Bi [China]; Volodymyr Bilokon [Ukraine]; Samuel Olanrewaju Binuomote [Nigeria]; Ekaterina Bliznetskaya [Russian Federation]; Gerardo Bocco V. [Mexico]; Manevasoa Christina Boda [Madagascar]; Wilfredo Marimon Bolivar [Colombia]; Sophie Emilie Germaine Bonnard [France]; Guilberto Borongan [Philippines]; Rethobogile Botebele [Botswana]; Ayat-Allah Bouramdane [Morocco]; Yevhen Bovsunovskyi [Ukraine]; Francisca Bown [Chile]; Diego Rafael Galvão Cesar Braga [Brazil]; Bruna Angela Branchi [Italy]; Camilla Brattland [Norway]; Thomas Breu [Switzerland]; Claire Wiliams Bridgwater [United States of America]; Leonie Bronkalla [Germany]; Maximillian Brown [United States of America]; Deborah Brown [Jamaica]; Bradford Brown [United States of America]; Pavel Bubnov [Russian Federation]; Philipe Bujold Bujold [Canada]; Isabel Bunce [United Kingdom of Great Britain and Northern Ireland]; Bazartseren Bunchingiv [Mongolia]; Rosa Busquets [Spain]; Ruslan Butovskiy [Russian Federation]; Isabella Buttino [Italy]; Mariam Gibson Bwire [United Republic of Tanzania]; John Callahan [United States of America]; Joao Camara [Brazil]; Dora Maria Cañon [Colombia]; Alberto Capra [Argentina]; Manoel Ferreira Cardoso [Brazil]; Maria Elda Carletti [Argentina]; Beatriz Martins Carneiro [Brazil]; Ana Carolina Carvalho [Brazil]; Thaís de Carvalho [Brazil]; Alfonso Navarro Carvallo [Peru]; Carmela Cascone [Italy]; Victor M. Castaño [Mexico]; Luca Castellanza [Ireland]; Cecy Castillo [Belize]; Sergio Mora Castro [Costa Rica]; Jesus Ricardo Castro [Colombia]; John Paul Cauchi [Malta]; Ebrima Ceesay [Gambia]; Daniele Cespi [Italy]; Mohan Bahadur Chand [Nepal]; Kevin Chang [United States of America]; Partho Pratim Chatterjee [India]; Chetna Chauhan [India]; Clovis Awah Che [Cameroon]; Sammy Jamar Chemengich [Kenya]; Min Chen [China]; Guangqing Chi [United States of America]; Hernando Chindoy Chindoy [Colombia]; Chizoba Chinweze [Nigeria]; Benjamas Chotthong [Thailand]; Govinda Choudhury [India]; Irina Chubarenko [Russian Federation]; Natalia Chubarova [Russian Federation]; Lorenzo Ciccarese [Italy]; Aurélie Ciutat [France]; Hamish Clarke [Australia]; Loureiro Claudia [Brazil]; Teresa Coady [Canada]; Ingrid Coetzee [South Africa]; Carla Roberta Conkin [Canada]; Letícia Cordeiro [Brazil]; Alex Córdoba-Aguilar [Mexico]; Lorena Coronel [Ecuador]; Sandra Correa [Colombia]; Janice Cox [United Kingdom of Great Britain and Northern Ireland]; Gonéri Le Cozannet [France]; Daniel Cronin [United Kingdom of Great Britain and Northern Ireland]; Xochitl Cruz-Núñez [Mexico]; Florence Daguitan [Philippines]; Gopal Dahit [Nepal]; Robert Victor Dams [Canada]; Roberto Danovaro [Italy]; Daniel Amoako Darko [Ghana]; Ranjan Datta [Bangladesh]; Eric Davidson [United States of America]; Bradley Davis [Canada]; Mohamed Dawoud [Egypt]; Ephrème Dossavi Dayou [Benin]; Celine Delacroix [Canada]; Gian Carlo Delgado-Ramos [Mexico]; Gladis Demarchi [Argentina]; Aminata Dembele [Mali]; Volodymyr Demkine [Ukraine]; Peter Harvey Denton [Canada]; Jack DeWaard [United States of America]; Shalini Dhyani [India]; Cheikhouna Diagne [Senegal]; Fernando Diaz Lopez [Mexico]; Silvia Diaz-Cruz [Spain]; Aminata Mbow Diokhane [Senegal]; Achim Dobermann [Germany]; Flavia Donadelli [Brazil]; Joanna Doorghen [Mauritius]; Flaig Dorothee [Germany]; Kristof Douçot [Germany]; Arnaud Zlatko Dragicevic [France]; Sethi Dube [Zimbabwe]; Bikila Warkineh Dullo [Ethiopia]; Paul Dumble [United Kingdom of Great Britain and Northern Ireland]; Upma Dutt [Australia]; Chukwudi Norbert Egwuagu [Nigeria]; Arthur Eijs [Netherlands (Kingdom of the)]; Mohamed Eissawi [Egypt]; Nagwa El Karawy [Egypt]; Mohamed Elgamri [Sudan]; Elsadig Elhadi [Sudan]; Lorraine Elliott [New Zealand]; Hany El-Shemy [Egypt]; Shadia Elshishini [Egypt]; Sophia Engel [Germany]; Tambe Honourine Enow [Cameroon]; Norris Erhabor [Nigeria]; Lisa Eriksson [Sweden]; Nadia Eser [Germany]; Talia Esnard [Saint Lucia]; Victor Huamani Espetia [Peru]; Felix Daniel Espinoza [Bolivia (Plurinational State of)]; Cláucia Faganello [Brazil]; Mohamed Farahat [Egypt]; Adesoji Farayibi [Nigeria]; Marinella Farre [Spain]; Laurice Codou Faye [Senegal]; Alice Ferlin [Brazil]; Daniela Nunes dos Santos Ferreira [Brazil]; Francisco Ferreira [Brazil]; Shayna Fertig [United States of America]; Richard Filcak [Slovakia]; Geraldo José Diogo Filho [Brazil]; Jesse John Lee Fleay [Australia]; Rachel Clare Flint [United Kingdom of Great Britain and Northern Ireland]; Ebinezer Florano [Philippines]; Manuel Mendez Florian [Dominican Republic]; Manuella Folly [Brazil]; James Ford [United Kingdom of Great Britain and Northern Ireland]; Kwabena Fosu-Amankwah [Ghana]; Karla França [Brazil]; Ana Paula

Francisco [Brazil]; Ingrid Fritsche [Switzerland]; Rabab Gaber [Egypt]; Chimwemwe Gamulani [Malawi]; Kisito Gandji [Benin]; Yasinta Ganiza [Malawi]; Qingxian Gao [China]; Chazhong Ge [China]; Ibrahim Abdel Gelil [Egypt]; Ana Maria Gergely [Romania]; Markus Geupel [Germany]; Hesam Ghadaksaz [Iran (Islamic Republic of)]; Razieh Ghayoumi [Iran (Islamic Republic of)]; Fereydoun Ghazban [Iran (Islamic Republic of)]; Elisabeth Gilmore [Canada]; Gustavo Daniel Gimenez [Argentina]; Pascal Olivier Girot [Costa Rica]; Carlo Giupponi [Italy]; Nusirat Ojuolape Gold [Nigeria]; Marisa de Luján Gonnella [Argentina]; Catalina Gonzalez [Colombia]; Hermes Farfán González [Cuba]; Ashish Gosain [India]; Carmen Gottwald [Germany]; Andy Griffiths [United Kingdom of Great Britain and Northern Ireland]; Margarita Guerra [Panama]; Simon Guerrero-Cruz [Netherlands (Kingdom of the)]; Kevin Guittet [France]; Ru Guo [China]; Joyeeta Gupta [Netherlands (Kingdom of the)]; Anastasia Guretskaya [Germany]; Clara Bartram Gurreso [Denmark]; Mariana Gutierres-Paz [Brazil]; Gester Gutiérrez [Chile]; Jordan Hairabedian [France]; Mordechai Haklay [United Kingdom of Great Britain and Northern Ireland]; Ichiro Hama [Japan]; Ayman Hamada [Egypt]; Lubomír Hanel [Czechia]; Mark Hanson [Canada]; Jordan Harold [United Kingdom of Great Britain and Northern Ireland]; Peter Townsend Harris [Australia]; Stephan Harrison [United Kingdom of Great Britain and Northern Ireland]; Kristopher Hartley [United States of America]; Unalome Wetwatana Hartley [Thailand]; Upile Hassan [Malawi]; Neeraja Havaligi [Canada]; Jason Hawkins [Canada]; Jillian Hawley [Canada]; Christoph Helbig [Germany]; Yogi Hendlin [United States of America]; Hans-Joachim Hermann [Germany]; Francisco Ivan Hernandez-Cuevas [Mexico]; Juan Manuel Hernández-López [Mexico]; Neyra Herrera [Panama]; Tobias Herzfeld [Germany]; Kenneth Roy Hinga [United States of America]; Johan Holmén [Sweden]; Magali Houde [Canada]; Yi Huang [China]; Andreas Huck [Germany]; Gyubin Hwang [Republic of Korea]; Keith Hyams [United Kingdom of Great Britain and Northern Ireland]; Park HyeMin [Republic of Korea]; Tarig El Gamri Ibrahim [Sudan]; Toshiaki Ichinose [Japan]; Omowumi Idowu [Nigeria]; Gayanthi Ilangarathna [Sri Lanka]; Christopher Ilori [Nigeria]; Yusuf Isa [Nigeria]; Theophilus Olufemi Isimikalu [Nigeria]; Usha Iyer-Raniga [Australia]; Boujemaâ Jaber [Morocco]; Benjamin Bilalam JABIk [Ghana]; Salmon Jacob - [India]; Jairo N Jaramillo [Colombia]; Marek Jaskólski [Poland]; Sithuni M. Jayasekara [Sri Lanka]; Haihui Joy Jiang [China]; Sinikinesh Beyene Jimma [Ethiopia]; Tanaka Jin [Japan]; Ji Hye Jo [Republic of Korea]; Jiby Mariya Jose [India]; Gran Juan [Mexico]; Jobson Larrubia de Almeida Júnior [Brazil]; Claudia Kabel [Germany]; Mulako Kabisa [Zambia]; Sakdirat Kaewunruen [United Kingdom of Great Britain and Northern Ireland]; Miho Kamei [Japan]; Alhassan Abdul-Wakeel Karakara [Ghana]; Claudia Santiago Karez [Brazil]; Rebecca Kariuki [Kenya]; Jérémie Kasongo [Democratic Republic of the Congo]; Alice Akinyi Kaudia [Kenya]; Ashpreet Kaur [India]; Sukhdeep Kaur [India]; Justas Kažys [Lithuania]; Shailly Kedia [India]; Nadia Khalaf [United Kingdom of Great Britain and Northern Ireland]; Muhammad Khalifa [Sudan]; Raza Khan [Pakistan]; Ram Chandra khanal [Nepal]; Abdel Ghader Khdeim [Mauritania]; Hojeong Kim [Republic of Korea]; Nicholas King [South Africa]; Ephram Mwangi Kinyua [Kenya]; Naomi Kipuri [Kenya]; Anne Klatt [Germany]; Nikolay Klyuev [Russian Federation]; Marta Koch [United Kingdom of Great Britain and Northern Ireland]; Richard Anthony Kock [United Kingdom of Great Britain and Northern Ireland]; Santosh Koirala [Nepal]; Oleh Kokhan [Ukraine]; Olatunji Matthew Kolawole [Nigeria]; Christina Komorski [Canada]; Amenan Agnès Kouame [Côte d'Ivoire]; Dirk Krijgsman [Netherlands (Kingdom of the)]; Anatoly Krutov [Russian Federation]; Natalia Kucirkova [Slovakia]; Manasi Kumar [India]; Pankaj Kumar [India]; Bartholomew Thiong'o Kuria [Kenya]; Melike Kus [Türkiye]; Sigrid Kusch-Brandt [Germany]; Tatiana Kuznetsova [Russian Federation]; Tracey Leah Laban [South Africa]; Joan Frances Laborte [Philippines]; Franklin Lagat [Kenya]; German Flores Lagos [Argentina]; Miriam Laiser [United Republic of Tanzania]; Fabrice Lambert [Switzerland]; Martin Lambrecht [Germany]; Mario Lannotti [Italy]; Roberto Lava [Italy]; Simret Terefe Leggese [Ethiopia]; Fernanda Leite [Brazil]; Pablo Lepe [Mexico]; Pamela William Levira [United Republic of Tanzania]; Debora Ley [Mexico]; Ruo Ying Li [Canada]; Jinhui Li [China]; Thiago Lima [Brazil]; Santi Lisana [Indonesia]; Yongqiang Liu [United States of America]; Jixin Liu [China]; Vasiliy Lobkovskiy [Russian Federation]; Isnardo Lopez [Colombia]; Jessica Estefania Lopez [Ecuador]; Irene Lorenzoni [United Kingdom of Bettina Lorz [Germany]; Natasa Lovric [Croatia]; Angela Lorena Lozano [Argentina]; Simone Lucatello [Mexico]; Marcelino Jr Lunag [Philippines]; Yang Luo [China, Hong Kong Special Administrative Region]; Evelyn Najjemba Lutalo [Uganda]; Amitabye Luximon-Ramma [Mauritius]; Laíze Lantyer Luz [Brazil]; Sergey Lyulin [Russian Federation]; John Madin [Malaysia]; Filipe

Magalhães [Brazil]; Gabriel Magliano [Brazil]; Maria Celia Magno [Italy]; John Magugu [United States of America]; Parth Sarathi Mahapatra [India]; Nomfundo Thobeka Mahlangeni [South Africa]; Gerald Irungu Maina [Kenya]; Wilkson Makumba [Malawi]; C. Matshidiso Malatji [South Africa]; Ishfaq Hussain Malik [India]; Christos Mammides [Cyprus]; Anna Mampye [South Africa]; Archiebold Manasseh Manasseh [Kenya]; Javier Mancera [Colombia]; Shailenda Kumar Mandal [India]; Miranda Francisco Marcela [Brazil]; Caitrin Martin [United States of America]; Irving Martinez [Bolivia (Plurinational State of)]; María Fernanda Martínez [Honduras]; Anne Martinussen [Norway]; Joalane Rethabile Marunye [Lesotho]; Solomon Sone Masango [Cameroon]; Tooba Masood [Pakistan]; Anthony Matheri [Kenya]; Zenteno Mauricio [Mexico]; Gaesi Maviya [Botswana]; Elisa María Mazo [Spain]; Michael Ssekaayi Mbogga [Uganda]; Coby McDonald [United States of America]; Dianne McGrath [Australia]; Louise McRae [United Kingdom of Great Britain and Northern Ireland]; Iq Mead [United Kingdom of Great Britain and Northern Ireland]; Wilderson Medina [Colombia]; Camelo Mel [Brazil]; Regina Melo [Brazil]; Rodrigo Méndez-Alonzo [Mexico]; Hamza Merabet [Algeria]; Tayebeh Mesbahzadeh [Iran (Islamic Republic of)]; Thiago Metzker [Brazil]; Christopher Mihiar [United States of America]; Kaleem Anwar Mir [Pakistan]; Aditi Mishal [India]; Manasi Mishra [India]; Clara Mitchell [Argentina]; Luciana Mofati [Brazil]; Debouba Mohamed [Tunisia]; Mona Mohammed [Yemen]; Rajshree Mokool [Mauritius]; Fabio Mologni [Italy]; Kelly Moon [United States of America]; Paulina Carmona Mora [Chile]; Mónica Moraes [Bolivia (Plurinational State of)]; Félix Zumbado Morales [Costa Rica]; Teresa Moreno [Spain]; Boris Morgunov [Russian Federation]; Hadei Mostafa [Iran (Islamic Republic of)]; Amal Mouferrih [Morocco]; Moustafa Mourad [Egypt]; Lucy Mtilatila [Malawi]; John Kigongo Mubazi [Uganda]; Rosemary Mubuuke [Uganda]; Ackmez Mudhoo [Mauritius]; Innocent Muhire [Rwanda]; Jagoda Munic [Croatia]; Denise Dantas Muniz [Brazil]; Oyunsuren Munkhsaikhan [Mongolia]; Gabriela Munoz-Melendez [Mexico]; Maggie Munthali [Malawi]; Kamal Murari [India]; Cyril T. F. Murewi [Zimbabwe]; Margaret Wangui Muriuki [Kenya]; Faidess Dumbizgani Mwale [Malawi]; Alice Nabatanzi [Uganda]; Pradeep Nair [India]; MP Sukumaran Nair [India]; Rosemary Nalwanga [Uganda]; Francesco Nappo [Italy]; Milena Naranjo [Ecuador]; Saffar Narges [Iran (Islamic Republic of)]; Humood Naser [Bahrain]; Michelle Natukunda [Uganda]; Siddhartha Nauduri [India]; Nanetiaa Nchoko [Kenya]; Aubin Manassé Ndata [Central African Republic]; Thubelihle Rosyln Ndhlovu [Zimbabwe]; Ndeye Fatou Ndiaye [Senegal]; Jacques Andre Ndione [Senegal]; Shalini Neeliah [Mauritius]; Hudaa Neetoo [Mauritius]; Raquel Negrao [Brazil]; Chuck Chuan Ng [Malaysia]; Exauce Ngadande [Chad]; Judy Ngina [Kenya]; Assan Ng'ombe [Zambia]; Thu Quynh Nguyen [Viet Nam]; Hari Krishna NIbanupudi [India]; Jaqueline Nichi [Brazil]; Lameck Kabambalika Nkhonjera [Malawi]; Michael Nkuba [Uganda]; Hu Noémie [Belgium]; Aziamin Asongu Norah [Cameroon]; Yanira Ntupanyama [Malawi]; Fiona Nunan [United Kingdom of Great Britain and Northern Ireland]; Mensur Dessie Nuri [Ethiopia]; Philip Nuss [Germany]; Matthew Nuttall [United Kingdom of Great Britain and Northern Ireland]; Chinonso Nwanevu [United States of America]; Evelyne Nyafwono [Uganda]; Sarah Nyawira [Kenya]; Asime Oba [Nigeria]; Keneth Ochoa [Colombia]; Onyinye Ifeoma Ochuba [Nigeria]; Godwin Omenka Ode [Nigeria]; Loveth Chiduma Ode-Omenka [Nigeria]; Christo Odeyemi [New Zealand]; Unekwu Odiba [Nigeria]; Anna Odur [Uganda]; Philemon Ogieriakhi [Nigeria]; Abiodun Ogunbiyi [Nigeria]; Peter Oseghale Ohue [Nigeria]; Victoria Okafor [Nigeria]; Kingsley Chuks Okogor [Nigeria]; Nkiruka Stella Okonkwo [Nigeria]; Goodluck Okoro [Nigeria]; George Mmadubueze Okoye [Nigeria]; Adaoyibo Okpala [Nigeria]; Abiodun Okunlola [Nigeria]; John Okwaro [Kenya]; Alexander Olchev [Russian Federation]; Marcin Kamil Olejnik [Poland]; Tracey Oliveira-Harris [Trinidad and Tobago]; Ganiyat Oloyede [Nigeria]; Catherine Olsen [Australia]; Oluseye Oludoye [Nigeria]; Rita Bochaberi Ondari [Kenya]; Alexander Orlov [United States of America]; Andrew Oroke [Nigeria]; Frankie Orona [United States of America]; Romanus Osabohien [Nigeria]; Evans Osabuohien [Nigeria]; Matthew Osborne [Sweden]; Dirk Osiek [Germany]; Mauricio Velasquez Ospina [Colombia]; Takasha Otsuka [Japan]; S. Nadia Ouedraogo [Burkina Faso]; Danielle Carollo de Oliveira Ovalbr [Brazil]; Peter Oviroh [Nigeria]; Taiwo Owoeye [Nigeria]; Vince Davidson Pacañot [Philippines]; Urbano Fra Paleo [Spain]; Ram Pandit [Nepal]; Joshua Pangelinan [Micronesia (Federated States of)]; Konstantinos Pappas [Greece]; Seongyeol Park [Republic of Korea]; Afshana Parven [Bangladesh]; Ntahompagaze Pascal [Burundi]; Dolors Armenteras Pascual [Colombia]; Abhilash Kumar Paswan [India]; Dhundi Raj Pathak [Nepal]; Jordi Buckley Paules [Switzerland]; Anna Pauls [Germany]; David Pearce [United Kingdom of Great Britain and Northern Ireland]; Leisa Perch [Barbados]; Chrishma D. Perera [Sri Lanka];

Amukhale Peter [Kenya]; Robert Becker Pickson [Ghana]; Ligia Marc Pinto [Brazil]; Frederik Pischke [Germany]; Lika Pkhovelishvili [Georgia]; Maria Pogozheva [Russian Federation]; Viviana Polisena [Argentina]; Ramesh Poluru [India]; Diego Alejandro Pontorno [Argentina]; Alessandra Ponzetto [Italy]; Carlos Portillo [United States of America]; Paulette Eugenie Posen [United Kingdom of Great Britain and Northern Ireland]; Janez Potocnik [Slovenia]; Ramendra Prasad [Fiji]; Julieth Vanessa Prieto-Sandoval [Colombia]; Donatella Privitera [Italy]; Rosa Maria Prol-Ledesma [Mexico]; Mikhail Proskurnin [Russian Federation]; Anthonette Quayee [Liberia]; Scarlett Quinn-Savory [United Kingdom of Great Britain and Northern Ireland]; Veronica Quitiguiña [Ecuador]; Anju T R [India]; Raeni Raeni [Indonesia]; Mohammad Rahimi [Iran (Islamic Republic of)]; Elysé Odon Rakotonirainy [Madagascar]; Sarisha Ramanand [South Africa]; Andrés Ramírez [Uruguay]; Rafael Guimaraes Ramos [Brazil]; Nisha Ramsahai [Trinidad and Tobago]; Pushpendra Rana [India]; Paul Randrianarisoa [Madagascar]; Gene Rankey [United States of America]; Nijavalli Ravindranath [India]; Laura Revell [New Zealand]; Renee Richer [United States of America]; Daniela Rizzi [Brazil]; Yérali Cruz Rodríguez [Costa Rica]; Cesar Rojas [Colombia]; Licidia Rojas [Costa Rica]; Nicholas Rahiri Te Awherata Roskruge [New Zealand]; Ariana Rossen [Argentina]; Eniko Gazdagne Rozsa [Hungary]; Plinio Ruschi [Brazil]; Scott Rush [United States of America]; Hyeonju Ryu [Republic of Korea]; Nataliia Ryzhenko [Ukraine]; Samah Saad [Egypt]; Amal Saadeldin Ahmed Hussein Amal Saad-Hussein [Egypt]; Abdulwakil Olawale Saba [Nigeria]; Samraj Sahay [India]; Dalia Sakr [Egypt]; Juan F. Saldarriaga [Colombia]; Emmanuel Salifu [Nigeria]; Andrea Salinas [Bolivia (Plurinational State of)]; Joaquin Elias Salzberg [Argentina]; Gisella Lamas Samanamud [Brazil]; Maryum Samar [Pakistan]; Karime León Sánchez [Mexico]; Emily Sandall [United States of America]; Monica Sanders [United States of America]; Happiness Sanga [United Republic of Tanzania]; Daniela dos Santos [Brazil]; Estefanía Rodero Sanz [Spain]; Melissa Saoudy [Canada]; Gabriela Saqui [Brazil]; Anabel Saran [Argentina]; Daniel Sarmiento [Colombia]; Sawsan Sawsan Khair Elsied Abdelrahim Mustafa Sawsan [Sudan]; Jochen Schanze [Germany]; Dirk Schmeller [France]; Caroline Schmidt [Germany]; Tobias Schnitzler [Germany]; Veronika Schröpfer [Germany]; Karina von Schuckmann [France]; Stephanie Masiello Schuette [United States of America]; Luxshica Sellathurai [Canada]; Oleg Senchenko [Russian Federation]; Celsus Sente [Uganda]; Sivasakthivel Senthilvel [India]; Jose Sepulveda [United States of America]; Aysha Shafiq [Canada]; Parita Sureshchandra Shah [Kenya]; Ahmed Shallal [Iraq]; Qiushi Shen [China]; Natalia Shevchenko [Russian Federation]; Ajin Rajendran Shobha [India]; Kalterina Shulla [Albania]; Evgeny Shvarts [Russian Federation]; Emina Sijahović [Bosnia and Herzegovina]; Elba Alves Silva [Brazil]; Nilmini Silva-Send [United States of America]; Belay Simane [Ethiopia]; Radios Simanjuntak [Indonesia]; Kitgak Simon [Nigeria]; Louisa-Madeline Singer [Germany]; Tersha Singh [Trinidad and Tobago]; Asha Singh [Guyana]; Vinayak Sinha [India]; Olga Skaredina [Russian Federation]; Nolita Leonora Skenjana [South Africa]; József Slezák [Hungary]; Alexandra Savio Soares [Brazil]; Rivoniony Andriana Solo [Madagascar]; Gloria Soto-Montes-de-Oca [Mexico]; Symeoni-Eleni Soursou [Greece]; Cintia P. Souto [Argentina]; Welton Souza [Brazil]; Ana Paula Souza [Brazil]; Ramesh Soysa [Sri Lanka]; Roberto Spampinato [Italy]; Ursula Oswald Spring [Mexico]; Anupam Srivastava [India]; Francini van Staden [South Africa]; Gillian Stanislaus [Trinidad and Tobago]; Inna Stecenko [Latvia]; Martin Steinbacher [Switzerland]; Peter Stoett [Canada]; Andrew Stott [United Kingdom of Great Britain and Northern Ireland]; Alessandro Stracqualursi [Italy]; Martin Stuchtey [Germany]; Hanningtone Mudegu Sungu [Kenya]; Juraj Svajda [Slovakia]; Richard Swannell [United Kingdom of Great Britain and Northern Ireland]; Mohamed Sylla [Mali]; Eman Sylvain [Cameroon]; Sylvia Szabo [Poland]; Sophie Szopa [France]; Sadaf Taimur [Pakistan]; Jorge Tam [Peru]; Quanyin Tan [China]; Kanako Tanaka [Japan]; Ricardo Taniwaki [Brazil]; Tomohiro Tasaki [Japan]; Emmanuel Tebandeke [Uganda]; Roufida Binte Teemul-Jannoo [Mauritius]; Marc Teixido [Spain]; Audrone Telesiene [Lithuania]; Irma Janet Zegarra Tello [Peru]; Andrey Terentyev [Russian Federation]; Srinivasan Jeena Thathamath [India]; Gordon John Thomas [Philippines]; Alban Thomas [France]; Svetoslava Todorova [United States of America]; Alexandre Tofeti [Brazil]; Eduardo Torres [Chile]; Olivera Stojilovic Trivunic [Serbia]; Demetra Tsiamis [United States of America]; Richard Twine [United Kingdom of Great Britain and Northern Ireland]; Nnaemeka Thaddeus Ukwueze [Nigeria]; Chukwuemeka Ulor [Nigeria]; Mathias Ulrich [Germany]; Michael Darragh Ulyshen [United States of America]; Mônica Antunes Ulysséa [Brazil]; Era Upadhyay [India]; Dinoj Kumar Upadhyay [India]; Peter Urban [Slovakia]; Iryna Usava [Belarus]; Wells Robert Utembe [Malawi];

Claudio Valdovinos [Chile]; Fernando Vale De Almeida [Brazil]; Toon Vandyck [Belgium]; Bolivar Paypay Vanessa [Peru]; Odair Varela [Cabo Verde]; Araceli Suárez Vásquez [Mexico]; Javier Vazquez [Argentina]; Erik Velasco [Mexico]; Josman Velasco [Colombia]; Rossi Velasquez [Peru]; Guus Velders [Netherlands (Kingdom of the)]; Anita Pirc Velkavrh [Slovenia]; Heorhiy Veremiychyk [Ukraine]; Cleo Verkuilj [Netherlands (Kingdom of the)]; Gabriela Vieira [Brazil]; Javier Vitale [Argentina]; Ester van der Voet [Netherlands (Kingdom of the)]; Baerbel Monika Vogel [Germany]; Jeanel Volney [Saint Lucia]; Elizabeth Nakhungu Wafula [Kenya]; Fei Wang [China]; Juanle Wang [China]; Ellen Ward [United States of America]; Charlotte Kate Weatherill [United Kingdom of Great Britain and Northern Ireland]; Oliver Weber [Germany]; Moritz Weber [Germany]; Elic Weitzel [United States of America]; Poh Poh Wong [Singapore]; Tanya Wragg-Morris [Canada]; Dan Wu [China]; Simone Wulf [Germany]; Yang Xie [China]; Jianhua Xu [China]; Junko Yabuno [Japan]; Sunita Yadav [United States of America]; Tianren Yang [China]; He Yin [China]; Liu Yongbo [China]; Dandan Yu [China]; Dennis Zagermann [Germany]; Andrey Zaitsev [Russian Federation]; Heleana Zambonino [Ecuador]; Tilahun Zebene [Ethiopia]; Kahramana Zeidalkelani [State of Palestine]; Fadwa Zenati [Morocco]; Li Zeng [China]; Conglin Zhang [China]; Alvaro Zopatti [Argentina]; Вадим Петров [Russian Federation]; Priscilla Soares Dos Santos [Brazil]; Carla Vanessa Zapata Toapanta [Ecuador]; Roberto Ariel Abeldaño Zuñiga [Argentina]; Pathmalatha Abeykoon Rathnappuli Hewa Mynattuge [Sri Lanka]; César Martín Agurto Castillo [Peru]; Takem Ebangha Ah a Agbor Delphine [Cameroon]; Ramia Al Bakain [Jordan]; Rabie Al Rahbi [Oman]; Thuraya Al Sariri [Oman]; Wasan Al Taie [Iraq]; Matrah Almutairi [Kuwait]; Victoria Penélope Donají Arceo y Arceo [Mexico]; Jeane Estela Ayres de Lima [Brazil]; Sheilla Roxana Baldeon Aragon [Peru]; Ana Barragán de la Haza [Spain]; Pablo Damian Borges Guilherme [Brazil]; Julio César Calvo Alvarado [Costa Rica]; Maria Cecilia Cardozo Benitez [Argentina]; Denia Marlenis Cid Pérez [Dominican Republic]; Ramiro Alberto Cumbrera Gonzalez [Cuba]; Juliana da Costa Gomes Souza [Brazil]; Glacy Jaqueline da Silva [Brazil]; Maria de Fátima da Silva [Brazil]; Diego De la Merced Jimenez [Mexico]; Rocio de la Torre [Mexico]; Diego de Leon Segovia [Mexico]; Diogo De Lima Franco [Brazil]; Antonio De Lisio [Italy]; Mara de Menezes de Assis Gomes [Brazil]; Luiz G S De Oliveira [Brazil]; Lucas Gonçalves de Oliveira Ferreira [Brazil]; Johnne Petterson de Sousa Araujo [Brazil]; Elisa de Sousa Ribeiro [Brazil]; Yassine El Boukili [Morocco]; Caio César Ferreira Alverga [Brazil]; Karla Cirila Garces Garcia [Mexico]; Buddhini Sasanthi Ginigaddara Appuhamilage [Sri Lanka]; Jorge Antonio Gómez Díaz [Mexico]; Ana Belén Guerrero Hinojosa [Ecuador]; Alvaro José Hernández Alarcón [Colombia]; Mario Alberto Hernández Hernández [Mexico]; Isamar Anicia Herrera Piñuelas [Spain]; Daniel Darío Herrera Ramirez [Mexico]; Leticia Manzanera Herrera y Cairo [Mexico]; Nadezhdy Ginova Hortua Cortes [Colombia]; Luciana Aparecida Iotti Ziglio [Brazil]; Christopher Kurt Kiessling Ruiz [Argentina]; Dana Aly López Solís [Mexico]; Juan Lopez Villar [Spain]; Andrés Hernando Matiz Rojas [Colombia]; Maria Helena Mattos da Silva [Brazil]; Maritza Jesús Mayo D'Arrigo [Peru]; Llorenç Milà i Canals [Spain]; Tawanda Collins Muzamwese [Zimbabwe]; Vishal Narain [India]; Lilian Fátima Nunes Salas [Paraguay]; Jorge Humberto Núñez Cobo [Chile]; Victorine Ghislaine Nzino Munongo [Cameroon]; Alfred Owuor Opere [Kenya]; Angie Tatiana Ortega Ramirez [Colombia]; Adele Shafei Osman Osman [Egypt]; Gustavo César Pamplona de Sousa [Brazil]; Marcia Marisol Paredes Peralta [Peru]; Julio César Pérez Aguilar [Nicaragua]; Maria Camila Porras Rivera [Colombia]; Andrea Carolina Rivera Cevallos [Ecuador]; Verónica Cinthia Rojas Scheffer [Paraguay]; Maria de Lourdes Romo Aguilar [Mexico]; Gina Paola Ruiz Gil [Colombia]; Ricardo Andres Ruiz Herrera [Colombia]; Diego Pablo Ruiz Padillo [Spain]; Lizbet Elizabeth Sánchez Licea [Mexico]; Nadia Silvana Santini González [Mexico]; Samuel Antonio Scarpato Mejuto [Italy]; Mauricio Eleacer Serrano Meneses [Costa Rica]; Ana Maria Sierra [Colombia]; Juan Carlos Silva Tapia [Peru]; Maria de Lourdes Silva Huerta [Mexico]; Anirudh Singh [Fiji]; Ritu Singh [India]; Maria de Fatima Soares [Brazil]; Diego De la Merced Jimenez [Mexico]; Rocio de la Torre [Mexico]; Diego de Leon Segovia [Mexico]; Diogo De Lima Franco [Brazil]; Antonio De Lisio [Italy]; Mara de Menezes de Assis Gomes [Brazil]; Luiz G S De Oliveira [Brazil]; Lucas Gonçalves de Oliveira Ferreira [Brazil]; Johnne Petterson de Sousa Araujo [Brazil]; Elisa de Sousa Ribeiro [Brazil]; Yassine El Boukili [Morocco]; Caio César Ferreira Alverga [Brazil]; Karla Cirila Garces Garcia [Mexico]; Buddhini Sasanthi Ginigaddara Appuhamilage [Sri Lanka]; Jorge Antonio Gómez Díaz [Mexico]; Ana Belén Guerrero Hinojosa [Ecuador]; Alvaro José Hernández Alarcón [Colombia]; Mario Alberto Hernández Hernández [Mexico]; Isamar Anicia Herrera Piñuelas [Spain]; Daniel Darío Herrera

Ramirez [Mexico]; Leticia Manzanera Herrera y Cairo [Mexico]; Nadezhdy Ginova Hortua Cortes [Colombia]; Luciana Aparecida Iotti Ziglio [Brazil]; Christopher Kurt Kiessling Ruiz [Argentina]; Dana Aly López Solís [Mexico]; Juan Lopez Villar [Spain]; Andrés Hernando Matiz Rojas [Colombia]; Maria Helena Mattos da Silva [Brazil]; Maritza Jesús Mayo D'Arrigo [Peru]; Llorenç Milà i Canals [Spain]; Tawanda Collins Muzamwese [Zimbabwe]; Vishal Narain [India]; Lilian Fátima Nunes Salas [Paraguay]; Jorge Humberto Núñez Cobo [Chile]; Victorine Ghislaine Nzino Munongo [Cameroon]; Alfred Owuor Opere [Kenya]; Angie Tatiana Ortega Ramirez [Colombia]; Adele Shafei Osman Osman [Egypt]; Gustavo César Pamplona de Sousa [Brazil]; Marcia Marisol Paredes Peralta [Peru]; Julio César Pérez Aguilar [Nicaragua]; Maria Camila Porras Rivera [Colombia]; Helena Rey de Assis [Brazil]; Andrea Carolina Rivera Cevallos [Ecuador]; Verónica Cinthia Rojas Scheffer [Paraguay]; Maria de Lourdes Romo Aguilar [Mexico]; Gina Paola Ruiz Gil [Colombia]; Ricardo Andres Ruiz Herrera [Colombia]; Diego Pablo Ruiz Padillo [Spain]; Lizbet Elizabeth Sánchez Licea [Mexico]; Nadia Silvana Santini González [Mexico]; Samuel Antonio Scarpato Mejuto [Italy]; Mauricio Eleacer Troncoso San Martin [Chile]; Gerardo Omar Trujillo Vazquez [Mexico]; Joost van den Broek [Netherlands (Kingdom of the)]; Luc William van Vliet [Australia]; Ronald Job Vargas Rojas [Bolivia (Plurinational State of)]; Johan Andrés Vélez Henao [Colombia]; Maria del Mar Viana Rodriguez [Spain]; Xuantong Wang [China]

GEO Collaborating Centres

Agencia Estatal Consejo Superior de Investigaciones Cientificas (CSIC); Institute for Environmental Assessment and Water Studies (IDAEA) [Spain]; Centre for Environment and Development for the Arab Region and Europe (CEDARE) [Egypt]; Environmental Pulse Institute (EPI) [United States of America]; GRID-Arendal [Norway]; Institute for Global Environmental Strategies (IGES) [Japan]; Institute of Landscape Ecology, Slovak Academy of Sciences (SAS) [Slovakia]; Korea Environment Institute (KEI) [Republic of Korea]; Netherlands Environmental Assessment Agency (PBL) [Netherlands]; Society of Entrepreneurs & Ecology (SEE) [China]; The Energy and Resources Institute (TERI) [India]; The University of Agriculture Peshawar - Department of Agronomy [Pakistan]; Tyndall Centre, University of East Anglia [United Kingdom of Great Britain and Northern Ireland]; Universidad de los Andes Centro de los Objectivos de Desarrollo Sostenible para America Latina [Colombia]; Universidad Nacional Autonoma de Mexico El Programa de Investigación en Cambio Climático (PINCC) [Mexico]; Universidad Veracruzana [Mexico]

Abbreviations and Acronyms

AAGR	Average Annual Growth Rate
AAOKH	Alaska Arctic Observatory and Knowledge Hub
ACEA	European Automobile Manufacturers' Association
ACMI	Africa Carbon Markets Initiative
ACSS	Africa Center for Strategic Studies
ADB	Asian Development Bank
AEWC	Alaska Eskimo Whaling Commission
AfCFTA	African Continental Free Trade Area
AfDB	African Development Bank
AI	Artificial Intelligence
AIIB	Asian Infrastructure Investment Bank
AMAP	Arctic Monitoring and Assessment Programme
AMOC	Atlantic Meridional Overturning Circulation
ANR	Assisted natural regeneration
AP	Asia and the Pacific
ASEAN	Association of Southeast Asian Nations
ASF	Animal-sourced foods
AUC	African Union Commission
B.C.E.	Before the Common Era
BC	Black carbon
BECCS	Bioenergy with Carbon Capture and Storage
BII	Bio Intactness Index
C3S	Copernicus Climate Change Service
CAGR	Compound Annual Growth Rate
CAN	Climate Action Network
CAPEX	Capital Expenditures
CARICOM	Caribbean Community
CAT	Climate Action Tracker
CBAM	Carbon Border Adjustment Mechanism
CBD	Convention on Biological Diversity
CCAC	Climate and Clean Air Coalition
CDR	Carbon dioxide removal
CEC	Contaminant of emerging concern
CEE	Central and Eastern Europe
CFC-11	Trichlorofluoromethane
CFR	Case fatality rate
CGE	Computable General Equilibrium
CIAT	International Center for Tropical Agriculture
CII	Carbon Intensity Indicator
CIMMYT	International Maize and Wheat Improvement Center
CIWA	Cooperation for International Waters in Africa
CLIA	Clinical Laboratory Improvement Amendments
COACCH	CO-designing the Assessment of Climate CHange costs
CPI	Consumer Price Index
CR	Critically Endangered

CRED	Centre for Research on the Epidemiology of Disasters
CRI	Global Climate Risk Index
CSIRO	Commonwealth Scientific and Industrial Research Organization
DDT	Dichlorodiphenyltrichloroethane
DE	Domestic extraction
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DMC	Domestic material consumption
DNA	Deoxyribonucleic acid
DNS	Debt-for-nature swaps
DPP	Digital Product Passport
DPSIR	Driver-Pressure-State-Impact-Response
DRM	Disaster risk management
E. coli	Escherichia coli
EASAC	European Academies Science Advisory Council
EbA	Ecosystem based Adaptation
EBRD	European Bank for Reconstruction and Development
ECMWF	European Centre for Medium-Range Weather Forecasts
ECS	Equilibrium climate sensitivity
EDGAR	Emissions Database for Global Atmospheric Research
EE	Eastern Europe
EEA	European Environment Agency
EEDI	Energy Efficiency Design Index
EESC	European Economic and Social Committee
EEXI	Energy Efficiency Existing Ship Index
EEZ	Exclusive Economic Zone
EM-DAT	The International Disaster Database
EMEP	European Monitoring and Evaluation Programme
EN	Endangered
ENSO	El Niño Southern Oscillation
EOCIS	Earth Observation Climate Information Service
EPR	Extended Producer Responsibility
EPSCoR	Established Program to Stimulate Competitive Research
ESA	European Space Agency
ET	Evapotranspiration
ETS	Emissions Trading System
EU	European Union
EUDR	European Union Deforestation Regulation
E-waste	Electronic waste
FABLE	Food, Agriculture, Biodiversity, Land-use, Energy
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
FBDG	National Food-Based Dietary Guideline
FiBL	Research Institute of Organic Agriculture
FPIC	Free, Prior, and Informed Consent
FRLD	Fund for Responding to Loss and Damage
FSD-Africa	Financial Sector Deepening Africa
FWBON	Freshwater Biodiversity Observation Network
GAMS	General Algebraic Modeling System
GBD	Global Burden of Disease
GCA	Global Commission on Adaptation

GCA	Global Centre on Adaptation
GCC	Gulf Cooperation Council
GCEW	Global Commission on the Economics of Water
GDP	Gross domestic product
GEF	Global Environment Facility
GEM	Green Economy Model
GEM-E3	General Equilibrium Model for Economy, Energy and Environment
GEO	Global Environmental Outlook
GEO BON	Group on Earth Observations - Biodiversity Observation Network
GGW	Great Green Wall
GHG	Greenhouse gas
GIAHS	Globally Important Agricultural Heritage Systems
GLOBIO	Global Biodiversity Model for Policy Support
GLOBIOM	Global Biosphere Management Model
GMA	Global Mangrove Alliance
GMP	Global Monitoring Plan
GNI	Gross national income
GNM	Global Nutrient Model
GPAFSN	Global Panel on Agriculture and Food Systems for Nutrition
GRACE	Gravity Recovery and Climate Experiment
GRIP	Global Roads Inventory Project
GSL	Goals-Solutions-Levers
GTEM	Global Trade and Environment Model
HDI	Human Development Index
HEI	Health Effects Institute
HELCOM	Baltic Marine Environment Protecting Commission
HiAP	Health-in-All Policies
HIC	High-income country
HIV	Human immunodeficiency virus
HLPE	High Level Panel of Experts on Food Security and Nutrition
HS	Harmonized System
HVAC	Heating, ventilation, and air conditioning
IAASTD	International Assessment of Agricultural Knowledge, Science and Technology for Development
iAHO	Integrated African Health Observatory
IAM	Integrated Assessment Model
IAS	Invasive alien species
ICC	International Criminal Court
IDB	Inter-American Development Bank
IDMC	Internal Displacement Monitoring Centre
IEA	International Energy Agency
IFAD	International Fund for Agricultural Development
IFOAM	International Federation of Organic Agriculture Movements
IFRC	International Federation of Red Cross
IFRS	International Financial Reporting Standards
IFs	International Futures
IHA	International Hydropower Association
IIASA	International Institute for Applied Systems Analysis
IISD	International Institute for Sustainable Development
IK&LK	Indigenous Knowledge and Local Knowledge

ILC	Indigenous and local communities
ILK	Indigenous and local knowledge
ILO	International Labour Organization
IMAGE-GNM	Integrated Model to Assess the Global Environment – Global Nutrient Model
IMBIE	Ice Sheet Mass Balance Inter-comparison Exercise
IMED	Integrated Model of Energy, Environment and Economy for Sustainable Development
IMF	International Monetary Fund
IMO	International Maritime Organisation
INFORM	Index for Risk Management
INTERPOL	International Criminal Police Organization
IO	Input-Output
IOP	Institute of PhysicsIntergovernmental Science-Policy Platform on
IPBES	Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRP	International Resource Panel
ISA	International Seabed Authority
ISC	International Science Council
ISO	International Organization for Standardization
ISWA	International Solid Waste Association
ITDP	Institute for Transportation & Development Policy
ITPS	Intergovernmental Technical Panel on Soils
IUCN	International Union for Conservation of Nature
IWC	International Whaling Commission
IWMI	International Water Management Institute
JRC	Joint Research Cente
KMGBF	Kunming-Montreal Global Biodiversity Framework
LCA	Life Cycle Analysis
LDC	Least developed country
LIC	low-income country
LIFE-TP	Lifestyle Transformation Pathway
LLA	Locally led adaptation
LNOB	To Leave No One Behind
LPG	Liquefied petroleum gas
LPJmL	Lund-Potsdam-Jena managed Land
LUCCC	Least Developed Countries Universities Consortium on Climate Change
LULUCF	Land Use, Land-Use Change and Forestry
MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change
MAP	Mediterranean Action Plan
MARPOL	International Convention for the Prevention of Pollution from Ships
MI	Millennium Institute
MIC	Middle-income country
MIMOSA	Integrated Assessment Model for Cost-Benefit Analysis
MPA	Marine Protected Area
MSA	Mean species abundance
MSW	Municipal solid waste
NbS	Nature-based Solutions

NBSAP	National Biodiversity Strategies and Action Plan
NCD	Non-communicable diseases
NDC	Nationally Determined Contribution
NDVI	Normalized Difference Vegetation Index
NE	Not Evaluated
NGO	Non-governmental Organization
NMVOC	Non-methane volatile organic carbon
NT	Near Threatened
NUE	Nitrogen use efficiency
ODA	Official development assistance
ODS	Ozone-depleting substance
OECD	Organisation for Economic Co-operation and Development
OHI	Ocean Health Index
OPEX	Operational Expenditures
OSPAR Convention	Convention for the Protection of the Marine Environment of the North-East Atlantic
OXFAM	Oxford Committee for Famine Relief
PAH	Polycyclic aromatic hydrocarbon
PAHO	Pan American Health Organization
PAME	Protected Area Management Effectiveness
PCB	Polychlorinated biphenyl
PCR-GLOBWB	PCRaster Global Water Balance
PDSI	Palmer Drought Severity Index
PE	Primary energy
PES	Payment for environmental services
PFAS	Per- and polyfluoroalkyl substances
PHE	Population-Health-Environment
PIC	Prior Informed Consent
PLOS	Public Library of Science
POP	Persistent organic pollutant
PPCA	Powering Past Coal Alliance
PPP	Purchasing power parity
PV	Photovoltaic
R&D	Research and development
RCP	Representative concentration pathway
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RED	Report on Economic Development
REDD+	Reducing Emissions from Deforestation and Forest Degradation
RIME	Rapid Impact Model Emulator
RLI	Red List Index
SADC	Southern African Development Community
SAFE	Sustaining Abundance of Forest Ecosystems
SBFN	Sustainable Banking and Finance Network
SDG	Sustainable Development Goal
SDP-RC	Sustainable Development Pathway-Resilient Communities
SDSN	Sustainable Development Solutions Network
SEEMP	Ship Energy Efficiency Management Plan
SES	Socioecological System
SIDS	Small Island Developing States
SLL	Sustainability-linked loan
SLR	Statutory Liquidity Ratio

SME	Small and medium-sized enterprise
SST	Sea surface temperature
ST	Subsurface temperature
STS	Sociotechnological system
SWF	Sovereign Wealth Fund
TERI	The Energy and Resources Institute
TFP	Total factor productivity
TSCA	Toxic Substances Control Act
ULEZ	Ultra Low Emissions Zones
UN	United Nations
UN Comtrade	United Nations Commodity Trade Statistics Database
UNCCD	United Nations Convention to Combat Desertification
UNCLOS	United Nations Convention on the Law of the Sea
UNCTAD	United Nations Conference on Trade and Development
UNDESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNDROP	United Nations Declaration on the Rights of Peasants
UNDRR	United Nations Office for Disaster Risk Reduction
UNEA	United Nations Environment Assembly
UNECA	United Nations Economic Commission for Africa
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNEP-WCMC	United Nations Environment Programme World Conservation Monitoring Centre
UNESCAP	United Nations Economic and Social Commission for Asia and the Pacific
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNESCWA	United Nations Economic and Social Commission for Western Asia
UNFCCC	United Nations Framework Convention on Climate Change
UN-Habitat	United Nations Human Settlements Programme
UNICEF	United Nations Children's Fund
UNIDO	United Nations Industrial Development Organization
UN-OCHA	United Nations Office for the Coordination of Humanitarian Affairs
UNODC	United Nations Office on Drugs and Crime
UNPFII	United Nations Permanent Forum on Indigenous Issues
UNSD	United Nations Statistics Division
UNWTO	United Nations World Tourism Organization
UTAS	University of Technology and Applied Sciences
UV	Ultraviolet
VAT	Value-added tax
VOCs	Volatile organic compounds
VOS	Volatile organic substances
VTPI	Victoria Transport Policy Institute
VU	Vulnerable
VWT	Virtual water trade
WB	World Bank
WCO	World Customs Organization
WD-OECM	World Database on Other Effective Area-based Conservation Measures
WDPA	World Database on Protected Areas

WEF World Economic Forum

WEO World Energy Outlook

WEOG Western Europe and Others Group

WFD Water Framework Directive

WFP World Food Programme

WHO World Health Organization

WMO World Meteorological Organization

WRI World Resources Institute

WTO World Trade Organization

WWF World Wide Fund for Nature

Glossary

Actions and policies
Specified interventions carried out by (an) identified (group of) actor(s) according to their power, authority and competences to influence the operations, performance or configuration of a system or set of practices towards achieving long-term environmental sustainability goals.

Agrivoltaics
An agricultural technique proposed in 1982 that addresses the increasing competition for land between agriculture and renewable solar power installations and has the potential to facilitate the decarbonization of agriculture. The proponents of this approach suggest integrating agriculturalproduction and solar photovoltaic installations in the same area. There are three types of agrivoltaics. Interspersed PV arrays use the space between crop rows to install solar panels. Greenhouse-mounted PV arrays are installed to replace part of the greenhouse cover. Stilt-mounted PV arrays are installed on an open-air structure. These arrays can be static or dynamic. All these techniques rely on the understanding that plants utilize only certain portions of sunlight for growth and that there is a natural point of light saturation wherephotosynthesis levels off and no longer increases. Agrivoltaics can also be used to combine energy production with animal husbandry, potentially improving several aspects, such as providing shade for animal welfare. This concept is also known as agrophotovoltaics, agroPV, solar sharing or PV agriculture.

Agroecology
Agroecology applies ecological and social principles to create sustainable, resilient and equitable food systems.

Alternative proteins
Protein-rich foods that can substitute animal-sourced foods, including plant-based products, fermentation-derived products and cultivated meat.

Anthropogenic
This term denotes circumstances of, related to, or resulting from the influence of human beings on nature.

Bioaccumulation of pollutants
Bioaccumulation refers to the gradual build-up over a period of time of a chemical in an organism's body. When an organism absorbs a substance - in this case, a pollutant - from a medium such as water, that pollutant is then distributed throughout the organism's system. Predators that consume these organisms can receive the pollutants as well. The phenomena can cause significant environmental health risks. A variety of different pollutants commonly cause problems with bioaccumulation.

Biochar
Relatively stable, carbon-rich, charcoal-like material produced by heating biomass in an oxygen-limited environment. The main difference between biochar and charcoal lies in the purpose. Biochar is used as a soil amendment to improve soil functions rather than as a fuel for cooking and heating. In addition, biochar effectively locks away carbon that would otherwise be released as organic matter decomposes through the carbon cycle, making it a form of carbon sequestration. This technique was used by Indigenous communities of the Amazon for centuries.

Biocultural
Biocultural refers to the interwoven relationship between biology and culture, especially within the context of human beings. It encompasses how biology influences culture and vice versa, shaping human societies and their interactions with the environment. This approach is used in various fields like anthropology, sociology, and conservation to understand complex systems where biological and cultural aspects are intertwined.

Biodiversity
The variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes

of which they are part; this includes diversity within species, between species and of ecosystems.

Biodiversity loss
The reduction in the variety and abundance of life on Earth, encompassing genetic, species and ecosystem levels. This decline reflects a reduction in nature's functional capacity to deliver ecosystem services, such as pollination, climate regulation, water purification and nutrient cycling.

Bioeconomy
The bioeconomy is the production, utilization, conservation, and regeneration of biological resources, including related knowledge, science, technology, and innovation, to provide sustainable solutions (information, products, processes and services) within and across all economic sectors and enable a transformation to a sustainable economy.

Blended finance
Blended finance is the strategic combination of public, private, and philanthropic capital to mobilize additional investment for sustainable development projects. By blending different types of capital, blended finance aims to address market failures and create opportunities for private investors to support social and environmental goals.

Blockchain
A particular type of a distributed ledger comprised of unchangeable, digitally recorded data in packages called blocks. A block records some or all of the most recent transactions that have not yet entered any prior blocks. Each time a block is completed, it gives way to the next block in the blockchain. A block is thus a permanent store of records which, once written, cannot be altered or removed.

Blue carbon
Biologically driven carbon fluxes and storage in marine systems that are amenable to management. Coastal blue carbon focuses on rooted vegetation in the coastal zone, such as tidal marshes, mangroves and seagrasses. These ecosystems have high carbon burial rates on a per unit area basis and accumulate carbon in surrounding soils and sediments. They provide many non-climate benefits and can contribute to ecosystem-based adaptation. If degraded or lost, coastal blue carbon ecosystems are likely to release most of their carbon back to the atmosphere. There is ongoing debate about applying the blue carbon concept to other coastal and non-coastal processes and ecosystems, including the open ocean.

Blue economy
Sustainable and equitable use of ocean and coastal resources to support economic and societal wellbeing.

Business model
Describes how a company does business. It is the translation of strategic issues, such as strategic positioning and strategic goals into a conceptual model that explicitly states how the business functions. The business model serves as a building plan that allows designing and realizing the business structure and systems that constitute the company.

Capital
Resource that can be mobilized in the pursuit of an individual's goals. Thus, natural capital (natural resources such as land and water), physical capital (technology and artefacts), social capital (social relationships, networks and ties), financial capital (money in a bank, loans and credit), human capital (education and skills).

Capital market
Capital Markets allow businesses to raise long-term funds by providing a market for securities, both through debt and equity. Capital Markets offer a whole range of sometimes complicated products which allow businesses and banks not just to raise capital but also to hedge (or protect) against risks.

Carbon Dioxide Removal (CDR)
Anthropogenic activities that remove CO_2 directly from the atmosphere and durably store it in geological, terrestrial or ocean reservoirs, or in products; excludes natural uptake not directly caused by human activities.

Carbon market
A trading system through which countries and other actors (i.e. private actors) may buy or sell units of greenhouse-gas emissions in an effort to meet their national limits on emissions, either under the Kyoto Protocol or under other

agreements, such as that among member states of the European Union.

Carbon offset

Any activity that compensates for the emission of CO_2 or other greenhouse gases (measured in CO_2e) by providing for an emission reduction elsewhere. Because greenhouse gases are widespread in Earth's atmosphere the climate benefits from emission reductions regardless of where such cutbacks occur. If carbon reductions are equivalent to the total carbon footprint of an activity, then the activity is said to be carbon neutral. Carbon offsets can be bought, sold, or traded as part of a carbon market.

Carbon pricing

Initiatives that put an explicit price on greenhouse gas emissions, i.e. a price expressed as a value per ton of carbon dioxide equivalent (tCO_2e).

Carbon tax

A levy on the carbon content of fossil fuels. Because virtually all of the carbon in fossil fuels is ultimately emitted as CO_2, a carbon tax is equivalent to an emission tax on CO_2 emissions.

CBDR

Principle 7 of the 1992 Rio Declaration on Environment and Development reads as follows: "States shall cooperate in a spirit of global partnership to conserve, protect and restore the health and integrity of the Earth's ecosystem. In view of the different contributions to global environmental degradation, States have common but differentiated responsibilities. The developed countries acknowledge the responsibility that they bear in the international pursuit of sustainable development in view of the pressures their societies place on the global environment and of the technologies and financial resources they command"

Circular economy

A circular economy is a systems approach to industrial processes and economic activity that enables resources being used to maintain their highest value and function for as long as possible. Key considerations in implementing a circular economy are reducing and rethinking use, the pursuit of longevity, renewability, reusability, reparability, replaceability, upgradability for products, components and materials.

Circularity

Circularity describes feedback-rich, nested systems; it cues a number of practical approaches such as reduce, reuse, repair, recycling. In a socioecological context it balances natural systems and human production and consumption systems. Circularity concepts are also embedded in many Indigenous Knowledge systems and worldviews.

Co-production

It is a broad concept and approach applied in a variety of public-policy fields for opening up the process of knowledge production, problem-solving, decision-making and public-policy implementation by seriously involving all relevant stakeholders, including scientists, government, practitioners, indigenous groups, civil society, public service users, and others. In environmental sciences and sustainability research, co-production has been defined as an approach of knowledge creation where its producers and users collaborate to generate knowledge fit for the purpose. Such collaboration allows for a better acceptance of the conclusions reached by the decision-makers, based on perception of such decisions as salient, credible and legitimate, and may lead to a change of values and norms in the society (created based on Gerlak et al., 2023).

Cost recovery

A legal process that allows the government to recover the cost of cleanup at hazardous (Superfund) waste sites from those who cause the contamination.

Critical Energy Transition Minerals (CETMs)

Minerals and metals essential for clean energy technologies and infrastructure (e.g., lithium, cobalt, nickel, copper, rare earth elements) where supply risks could affect the energy transition (see also: Critical minerals).

Critical minerals

Critical minerals are a subset of minerals considered crucial for the manufacturing and technological needs of companies, industries, nations, or even the world. The criticality level of minerals is usually determined by the economic importance of the minerals and the risk of disruption to their supply chains.

Current trends scenario

An exploratory scenario that presents a future in which social, economic, and technological trends

follow historical patterns. The GEO-7 current trends scenario does not account for current policies and policy objectives.

Dead zones
Extremely low-oxygen areas in oceans and lakes, caused by excessive nutrient input from human activities coupled with other factors that deplete the oxygen required to support many marine organisms in bottom and near-bottom water.

Debt
Money borrowed by one party from another entity to serve a need that otherwise cannot be met outright.

Decent living standards
Decent living standards (DLS) provide a framework to estimate a practical threshold for the energy, GHG, and material consumption required to alleviate poverty.

Digital dumpsites
These are informal dumpsites and landfills of electrical and electronic waste in low and middle income countries across the globe. Such ineffective waste management and disposal threatens the health and well-being of impoverished city dwellers who live nearby and who also engage in materials recovery through informal processing, such as burning, heating and acid leaching. The resulting environmental pollution poses the greatest risk to children and to pregnant women and their fetuses. The associated pollutants include heavy metals, dioxins, furans and flame retardants, such as polychlorinated biphenyls, polybrominated diphenyl ethers and polycyclic aromatic hydrocarbons. The extent of the problem was brought to light by the World Health Organization report on children and the digital dumpsites in 2021.

Disinvestment strategies
Disinvestment strategy means the strategy by which units in Assets are disinvested where there is insufficient cash in the Product in order to pay charges: to pay Ongoing Adviser Remuneration; when there has been a Failed Payment; or when an Income Payment Strategy fails.

Do-no-significant-harm
The principle originates from the Hippocratic oath in medicine and recently has been expanded to apply in the settings of economic development and innovation, finance, development aid and humanitarian assistance. Various organizations and institutions at international and domestic levels apply it to a different degree and with different underlying definitions, which generally mean that no proposed activities should receive the support and be carried out if they may cause significant environmental and social damage.

Driver
The overarching socio-economic forces that exert pressures on the state of the environment.

Due diligence
The process of a business or organization undertaking a series of structured checks and investigations before undertaking a particular activity in order to ensure that they are fully compliant with the law and any other obligations (for example, in relation to their duty of care to their client, employees, or the general public). The structured nature of the due diligence process is designed to avoid situations in which potentially problematic issues may be accidentally overlooked, leading to allegations of breaking the law or of negligence.

Earth jurisprudence
It is a philosophical approach to legal and governance systems, rather than a theory of international environmental law. It refers to philosophies of law and governance which seek to guide humans to behave in ways that contribute to the integrity, healthy functioning, beauty, and ongoing evolution of the community of life known as "Earth". This approach seeks to promote the flourishing of the Earth Community and a mutually enhancing human-Earth relationship, rather than its subjugation and exploitation by humankind. While the international legal system and the legal systems of almost all states reflect a deeply anthropocentric view. The term was proposed by cultural historian, poet and "geologian" Thomas Berry.

Earth System Boundaries
Proposed safe and just limits – in relation to the climate, the terrestrial biosphere, freshwater, nutrients and air pollution – for maintaining the resilience and stability of the Earth system and minimizing exposure to significant harm to humans from Earth system change.

Economic activity
Economic Activity is the activity of making, providing, purchasing, or selling goods or services. Any action that involves producing, distributing, or consuming products or services is an economic activity. Economic activities exist at all levels within a society. Additionally, any activities involving money or the exchange of products or services are economic activities. For instance, running a small business is a great example of economic activity

Economic system
A means by which governments organize and distribute available resources, services, and goods across a geographic region or country.

Economy
The system of activity connected with the production, trade, and consumption of goods and services of a region, country, or other (not necessarily geographic) area.

Ecosystem services
The benefits people obtain from ecosystems, commonly grouped as provisioning, regulating and cultural services (supporting services underpin these in some frameworks).

Emerging contaminants
Emerging contaminants (ECs), also referred to as contaminants of emerging concern (CECs), are newly identified synthetic or naturally occurring chemicals or biological agents that are detected in the environment and potentially hazardous or recently determined to be hazardous to humans and ecosystems. The risks associated with these contaminants are not fully understood. They may include pharmaceuticals and personal care products (PPCPs), per- and poly-fluoroalkyl substances (PFAS), emerging pathogens, cyanotoxins and other natural toxins, pesticides, industrial chemicals, micro/nano plastics, nanomaterials, antibiotic resistance genes (ARGs), and other exogenous substances that are found in the environment but are not yet well understood in terms of their impacts on humans and natural ecosystems.

Endocrine disruptors
Any chemical, synthetic or natural in origin, that mimics or interferes with the normal actions of hormones in the body. Synthetic endocrine disruptors are used in a wide range of products and materials, from cosmetics and plastics to pesticides and industrial solvents. Because hormones are the chemical messengers of the endocrine system – the network of glands that regulates all essential biological processes, including development, metabolism, and reproduction – exposure to endocrine disruptors is a major health issue and an environmental concern worldwide. Examples of synthetic endocrine disruptors include bisphenol A, dioxin, lead, mercury, polychlorinated biphenyls, styrenes, glycol ethers, parabens, phthalates, and polybrominated diphenyl ethers.

Energy transition
An energy transition is a change in the primary form of energy consumption and production of a given society.

Environmental sustainability
The long term maintenance of ecosystems and other environmental systems for the benefit of future generations.

Environmental tax
Fiscal policy measures used to steer economic burdens away from economically beneficial activities (such as employment) towards environmentally harmful activities (such as the generation of pollution). With this approach, decision-making at every level, by the individual in society up to the highest national Government forum, is steered towards minimizing the environmental impacts of growth.

Environmentally harmful
Environmentally harmful refers to anything that negatively impacts the environment. This can include actions, substances, or conditions that damage air, water, land, or living organisms. Some common examples of environmentally harmful activities include: pollution, deforestation, overexploitation of resources, climate change, land degradation, etc.

Envirotyping
It is a concept and a methodological approach proposed in plant science that proposes to determine and measure the influence of all the environmental factors on plant growth. It has been proposed, as a third "typing" technology, complementing with genotyping and phenotyping. If genotyping aims to specify the genetic composition of a plant and phenotyping specifies the observable characteristics of a plant based on

its genetic information and environmental factors, then envirotyping aims to fill the gap between the two making the impact of environmental factors explicit on plant growth next to specifying its genotype and phenotype. External environmental factors proposed for studying are climate, soil factors, biotic factors, and crop management or cropping system.This approach holds a significant potential for future crop breeding strategies and more efficient crop production in the context of climate change adaptation, food security and sustainability of agriculture.

Equilibrium climate sensitivity
The equilibrium or steady state change in the surface temperature following a doubling of the atmospheric carbon dioxide concentration from pre-industrial conditions.

Eutrophication
The degradation of water or land quality due to enrichment by nutrients, primarily nitrogen and phosphorus, resulting in excessive plant growth and decay, principally of algae. Eutrophication of a lake normally contributes to its slow evolution into a bog or marsh and ultimately into dry land. Eutrophication may be accelerated by human activities that speed up the ageing process.

Externalities (environmental and health)
Costs or benefits arising from production or consumption that affect third parties and are not reflected in market prices (e.g., pollution damages to health and ecosystems).

Extinction debt
The future extinction of species due to events in the past, owing to a time lag between a cause, such as habitat destruction or climate change, and the subsequent disappearance of species.

Feed-in tariff
It is an energy policy supporting the development and dissemination of renewable power generation by individuals, communities, and businesses. In a feed-in tariff scheme, providers of energy from renewable sources, such as solar, wind or water, receive a price for what they produce based on the generation costs. This purchase guarantee is offered generally on a long-term basis, ranging from 5 to 20 years, but most commonly spanning 15-20 years. The cost of the tariff payments are typically shared with the electricity consumers.

Financial market
A market in which financial assets are traded.

Financial product
Any good or service provided by a financial institution. Financial products include loans, mortgages, insurance policies, advice, derivatives, etc.

Financial sector
The part of the economy concerned mainly with lending and borrowing, long or short term. This includes banks, non-bank financial intermediaries such as building societies (UK) or savings and loan associations (US), as well as merchant banks, insurance companies, pension funds, and a range of financial managers and advisers.

Financial system
A financial system is a network of financial institutions.

Fiscal
Fiscal means of or relating to taxation, public revenues, or public debt.

Food sovereignty
The right of peoples and communities to define their own food and agriculture systems.

Food system losses and waste
The combined reduction of food across the food system—from pre-harvest and on-farm handling through storage, processing and distribution to retail, food service and households—encompassing both food loss before retail and food waste at retail and consumption.

Foodshed model
It is a concept and approach gaining popularity in interdisciplinary urban food systems research. It is similar to the concept of watershed in a way that it also describes a flow in a certain geographical area – the flow of food from rural areas to urban areas. The urban foodshed model allows for examining links between urban consumers and rural agricultural production by mapping food flow networks or estimating the potential for local food self-sufficiency. Foodshed model analysis can inform policy related to multiple components of sustainable food systems, including navigating the social and environmental benefits and trade-offs of sourcing food locally, regionally, and globally.

Forever chemicals

These are per- and polyfluoroalkyl substances, a large family of fluorinated chemicals that have partially or completely fluorinated carbon chains of varied lengths. They possess stable structures that give them properties highly sought after in industry. They resist very high heat, protect surfaces from water, grease or friction, and have fire-retardant and stain-resistant properties. They are toxic, hazardous and persist in the environment and in the human body. They accumulate over time and have dangerous effects on the environment and our health. A few subgroups of per- and polyfluoroalkyl substances are currently listed under the Stockholm Convention as industrial persistent organic pollutants.

Fortress conservation

A conservation model based on the belief that biodiversity protection is best achieved by creating protected areas where ecosystems can function in isolation from human interference. It is assumed that local people use natural resources in irrational and destructive ways, and as a result, cause biodiversity loss and environmental degradation. Establishment of protected areas following this model often resulted in the forced displacement and human rights abuses of the Indigenous People who historically lived there and managed the natural resources sustainably. Three principles can characterize protected areas following the fortress model. Local people dependent on the natural resource base are excluded. Enforcement is implemented by park rangers patrolling the boundaries using a "fines and fences" approach to ensure compliance. The only appropriate interferences in the protected areas are tourism, safari hunting, and scientific research.

Free, prior and informed consent

A governance principle according to the Declaration on the Rights of Indigenous Peoples that requires States to consult and cooperate in good faith with the Indigenous Peoples concerned through their own representative institutions in order to obtain their free, prior and informed consent before adopting and implementing legislative or administrative measures that may affect them. Free implies that there is no coercion, intimidation or manipulation. Prior implies that consent is to be sought sufficiently in advance of any authorization or commencement of activities and respect is shown to time requirements of indigenous consultation and consensus processes. Informed implies that information is provided covering a range of aspects, including the nature, size, pace, reversibility and scope of any proposed project or activity; the purpose of the project as well as its duration; locality and areas affected. It also includes a preliminary assessment of the likely economic, social, cultural and environmental impacts, including potential risks; personnel likely to be involved in the execution of the project; and procedures the project may entail.

Fund

A fund is a pool of money set aside for a specific purpose. The pool of money in a fund is often invested and professionally managed in order to generate returns for its investors. Some common types of funds include pension funds, insurance funds, foundations, and endowments.

Fund for responding to Loss and Damage

It is a new climate finance mechanism under the United Nations Framework Convention on Climate Change. The fund has been established to assist developing countries that are particularly vulnerable to the adverse effects of climate change in responding to economic and non-economic loss and damage associated with the adverse effects of climate change, including extreme weather events and slow onset events. By financing recovery initiatives from climate-related losses and damage, the Fund empowers communities to rebuild and adapt. The fund provides resources directly to local actors in vulnerable developing countries through streamlined access processes. It strives for country-led locally driven solutions, ensuring interventions are aligned to country needs, priorities and contexts. Response to loss and damage is a core pillar of climate action, alongside mitigation and adaptation. The Fund mobilizes financial resources through government contributions, private sector partnerships and innovative financing mechanisms, ensuring a robust and sustainable approach to addressing climate-induced loss and damage. The Fund became operational in 2025.

Ghost forest

A maritime forest dieback is the result of saltwater intrusion into freshwater estuaries and other coastal freshwater bodies, as well as the flooding or submerging of low-lying maritime forests due to sea level rise resulting from climate change. Ghost forests may appear anywhere in the world where maritime forests occupy low-lying areas. The haunting sight

of lifeless and decomposing trees is what gives this phenomenon the name.

Global environmental crises

Global environmental crises are those environmental problems that threaten human well-being and hinder progress towards achieving the Sustainable Development Goals (SDGs) and international environmental agreements.

Global food system

Global food system encompasses all the actors and activities related to the production, processing, distribution, trade, retail, preparation, consumption, and end of life management of foods and drinks, as well as the outcomes of these activities, including socioeconomic and environmental, globally.

Global North

Although a formal definition does not exist due to changing socio-economic and political contexts, the Global North is generally comprised of a group of developed countries as classified by the the United Nations Conference on Trade and Development that are predominantly located in the Northern hemisphere, but not exclusively, and can be characterized by some or all features from the following list: high standard of living, high human development index, the presence of robust institutions, rule of law and democratic governance, and industrialized and diversified economies with developed service sectors and leaders in technological development and research. Historically, the core group of the countries in this list have been at the forefront of industrialization and involving geographical exploitation, conquest and colonization.

Global public good

It is a good, a service or a resource with benefits that are public or almost public and universal or near universal. Publicness of its benefits means that consumption or use of this good, service or resource does not diminish its quantity to the other consumers or users, or its consumption or use is non-rival. Secondly, no consumer or user can be excluded from using this good, service or resource, or its consumption and use is non-excludable. Public goods can be local, national, regional and global in scope. Global public goods can be enjoyed worldwide or at least by a group of countries and across generations. Few global public goods are pure in the sense of being truly global, non-rival and non-excludable, but one example is sunlight. Provision of most global public goods is a matter of international collective action by sovereign states, due to the unique characteristics of such goods and of controlling associated positive and negative externalities resulting from their use. Examples of global public goods in the field of environment include climate stability, the UV-protecting ozone layer, global biodiversity, and global knowledge products such as Global Environment Outlooks.

Global South

Although a formal definition does not exist due to changing socio-economic and political contexts, the Global South is best reflected by the scope of development-promoting activities of the United Nations Conference on Trade and Development since its establishment in 1964. The term refers to a group of countries classified by the United Nations Conference on Trade and Development as developing and characterized by some or all features from the following list: lower standard of living, lower human development index, higher poverty rates, underdeveloped infrastructure, poorer quality and outreach of public services such as health and education, higher rates of population growth, and poorer quality housing. The list of Global South countries generally includes those in Africa, Latin America and the Caribbean, Asia and Oceania with a number of notable exceptions, such as Japan, Australia and New Zealand and others. Historically, many countries in this list were subjected to colonialism, which arguably has left a still lasting imprint on their current development levels.

Governance

Governance provides the institutions and the spaces for establishing an overall direction of development, setting targets, coordinating actions, providing regulations, creating specialized organizations and enabling the flow of finance at national and subnational levels. Parliaments and state audit offices should ensure accountability for reporting on progress and learning from failures. Formal government institutions also need to work closely with the private sector, and civil society, providing "safe arenas" for deliberation on policies and instruments of transformation. Good governance enhances synergies and identifies trade-offs and connections while building engagement between politicians, civil society, businesses, youth, labour, media, Indigenous Peoples and local communities.

Green ammonia
Ammonia produced using renewable energy and leading to low life-cycle greenhouse gas emissions. The typical pathway is synthesis via the Haber–Bosch process using nitrogen from air and green hydrogen from renewable-powered electrolysis. Certification schemes set emissions-intensity thresholds and require stringent control of upstream energy sources and supply-chain emissions.

Green bond
A mode of private financing that tap the debt capital market through fixed income instruments (i.e. bonds) to raise capital to finance climate-friendly projects in key sectors of, but not limited to, transport, energy, building and industry, water, agriculture and forestry and waste.

Green finance
Green finance includes any structured financial process or activity that has been undertaken to ensure a better environmental outcome. This includes actions by private and public entities, including banks, governments, companies, non-profit organizations, and others. This finance includes all types of actions and initiatives, such as developing, implementing, and promoting projects that can have sustainable impacts or sustainable business models. Along with making funds available for green projects, another objective of green financing is to better quantify risks related to green projects.

Green growth
The Green Growth approach seeks to create an economic framework which opens up increased opportunities for maximizing the benefits of globalization, such as sharing and transferring knowledge and technologies for eco-efficient production processes, for renewable resource use and for integrated natural resources management as well as for creating new job opportunities. It also advocates eco-efficient and resource-saving economic and production activities based on the full life cycle analysis of production and consumption processes, in which more efficient and less materials-intensive production is cost-effective, reduces emissions and creates new job opportunities. By this means the Green Growth approach attempts to enhance the competitive edge and advantages of the countries in the region on the world trade market, which currently dominates their export-driven economic development.

Green investment
Green investments are traditional investment vehicles (such as stocks, exchange-traded funds and mutual funds) in which the underlying business(es) are somehow involved in operations aimed at improving the environment. This can range from companies that are developing alternative energy technology to companies that have the best environmental practices.

Green job
A green job, also called a green-collar job is, according to the United Nations Environment Programme, work in agricultural, manufacturing, research and development (R&D), administrative, and service activities that contribute(s) substantially to preserving or restoring environmental quality. Specifically, but not exclusively, this includes jobs that help to protect ecosystems and biodiversity; reduce energy, materials, and water consumption through high efficiency strategies; de-carbonize the economy; and minimize or altogether avoid generation of all forms of waste and pollution.

Green methane
Methane produced using renewable energy and leading to low life-cycle greenhouse gas emissions. Typical pathways are: (i) biomethane by upgrading biogas from sustainable biomass; and (ii) synthetic methane (e-methane) by methanating green hydrogen with captured CO_2 (biogenic or atmospheric). Certification schemes set emissions-intensity thresholds and require stringent control of methane leakage across the supply chain.

Green transformation
Green transformation has become one of the most important directions in the further development of the world. It involves the development of green technologies and the creation of legal regulations enforcing, for example, saving energy or reducing the emissions of greenhouse gases, as well as any other activities aimed at changing society's attitude towards the acceptance of frequently more expensive but more environment-friendly technological solutions and legal norms. Thus, green transformation can be defined as combining economic growth with caring about the environment to guarantee a high quality of life for present and future generations at a level which is attainable due to civilizational development, as well as to an effective and rational use of the available resources. Still, there is no single globally accepted

way to this transformation. It is proceeding in a variety of ways and depends on many different factors.

Greenwashing
A practice of presenting companies or products as more environmentally responsible than they are. Greenwashing involves exaggerating or misrepresenting sustainability efforts to mislead consumers into believing that they support meaningful environmental progress. These deceptive practices distort the truth and undermine genuine efforts to reduce environmental harm and improve quality of life.

Gross domestic product
The sum of gross-value-added, at purchasers' prices, by all resident and non-resident producers in the economy, plus any taxes and minus any subsidies not included in the value of the products in a country or a geographic region for a given period, normally one year. Gross domestic product is calculated without deducting for depreciation of fabricated assets or depletion and degradation of natural resources.

Heterozygosity
In the field of genetics it means possession of two different alleles of a particular gene or genes by an individual. Heterozygosity is a measure of genetic variation within a population. High heterozygosity values for a breed may be due to long-term natural selection for adaptation, to the mixed nature of the breeds, or to past mixing of strains of different populations. A low level of heterozygosity may be due to isolation with the subsequent loss of unexploited genetic potential. A high level of average heterozygosity is of critical importance for adaptive response to environmental changes.

Imaginaries
An interdisciplinary concept in humanities and social sciences that represents the ways in which people imagine their social existence, how they fit together with others, how things go between them and their fellows, the expectations that are normally met, and the deeper normative notions and images that underlie these expectations. As such, the concept of imaginaries has important implications for environmental governance. Imaginaries in the context of environment explore how the relationship between people and the environment depend on the specific features of that environment, how the relationships between the society and nature are being shaped by technology and politics, and how environmental governance is being formed. At the same time imaginaries can provide important insights on how the relationships between society and nature could be reconsidered and reshaped into radically different futures.

Inclusive wealth
It is the total value of a country's capital assets – natural capital, manufactured capital and human capital. Manufactured capital refers to investment in roads, buildings, machines, equipment and other physical infrastructure. Human capital comprises knowledge, education, skills, health and aptitude. Natural capital includes forests, fossil fuels, fisheries, agricultural land, sub-soil resources, rivers and estuaries, oceans, the atmosphere and ecosystems more generally. In contrast to the gross domestic product, which measures flows of products and services, inclusive wealth measures stocks of capital and accounts for its primary forms that support the well-being of current and future generations. The trajectory of inclusive wealth signals changes in a country's productive capacity and serves as a measure of its social well-being and sustainable development. The Inclusive Wealth Index is a measure pioneered by the United Nations Environment Programme in response to the beyond gross domestic product movement.

Indigenous and local knowledge
A cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings, including humans, with one another and with their environment. It is also referred to by other terms such as: Indigenous, local or traditional knowledge, traditional ecological/environmental knowledge, farmers' or fishers' knowledge, ethnoscience, indigenous science, folk science.

Indigenous Peoples and local communities
Indigenous Peoples – also known as first peoples, aboriginal peoples, native peoples, or autochthonous peoples – are ethnic groups who are descended from and identify with the original inhabitants of a given region, in contrast to groups that have settled, occupied or colonized the area more recently. The distinctive groups are protected by international or national legislation that grants them specific rights based

on their linguistic and historical ties to a particular territory, before the later settlement, development, or occupation of a region. A local community is a self-identified human group that relates to a life environment in collective ways and participates in defining a shared territory and culture. The members of a local community frequently have direct encounters and share a common history, traditions, institutions, language, values, and life plans. A local community can be long-standing or relatively new, include a single or multiple ethnic identities, and be permanently settled or mobile. A local community should have a form of political identity that enables it to exercise its rights and responsibilities with respect to its territory and neighbours.

Inequality
Inequality is a multidimensional concept generally understood as the state of being unequal, especially in terms of status, rights and opportunities.

Information asymmetry
According to Nobel laureate Joseph Stiglitz, information asymmetry is an imbalance of information between market participants, and it can lead to market failure. Information asymmetry occurs when different people in a market have different information. For example, a car seller may know more about the quality of their car than the buyer.

Internationally agreed goals
Internationally agreed goals refer to objectives set by international organizations, such as the United Nations, that member countries commit to achieving. These goals are designed to address global challenges and promote sustainable development, peace, and prosperity. A well-known example is the Sustainable Development Goals (SDGs), which were adopted by the United Nations in 2015. The SDGs are a set of 17 goals aimed at ending poverty, protecting the planet, and ensuring that all people enjoy peace and prosperity by 2030.

Invasive alien species
Species whose introduction and/or spread by human action outside their natural distribution threatens biological diversity, food security, and human health and well-being. Alien refers to the species' having been introduced outside its natural distribution (exotic, non-native and non-indigenous are synonyms for alien). Invasive means tending to expand into and modify ecosystems to which it has been introduced. Thus, a species may be alien without being invasive, or, in the case of a species native to a region, it may increase and become invasive, without actually being an alien species.

Investment
In finance, investment is putting money into an activity with the expectation of gaining revenue, which upon thorough analysis, has a high degree of security of principle, as well as security of return, within an expected period of time. For the purpose of UNCCD reporting, investment refers to the use of non-grant instruments allocating financial resources, public or private, for projects, programmes and other relevant activities related to UNCCD implementation.

Key biodiversity areas
These are sites contributing significantly to the global persistence of biodiversity. They represent the most important sites for biodiversity conservation worldwide, and are identified nationally using globally standardized criteria and thresholds. Key biodiversity areas do not necessarily overlap with networks of protected areas. Key biodiversity areas initiative aims to steer the action of governments, business sector, donors, civil society, international organizations, secretariats of multilateral environmental agreements towards a more systemic and global view of preventing species extinctions. It is a global initiative by the world's leading conservation organizations, among them the International Union for Conservation of Nature, Birdlife International, the World Wildlife Fund and others.

Land degradation
A long-term loss of ecosystem function and services, caused by disturbances from which the system cannot recover unaided.

Land Degradation Neutrality (LDN)
A state whereby the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remains stable or increases; commonly assessed via land cover, land productivity and soil organic carbon.

Levers
Domain of societal influence that shares a configuration of a broad range of actors, actions and analysis.

Local communities
Local Communities as used in IPBES documents that Local communities can be understood as non-indigenous communities which, while highly diverse, are recognized for having historical linkages to places and natural resources, multiple domains of ecological knowledge, dynamic and hybrid resource management techniques and technologies, customary and formal institutions to manage natural resources, and distinctive worldviews and relationships to nature.

Local knowledge
Local knowledge refers to the understandings and skills developed by individuals and populations, specific to the places where they live

Marginalized groups
Those who are systematically excluded and disadvantaged due to factors like gender, age, ethnicity, disability, sexual orientation, or socioeconomic status, leading to their lack of access to power, resources, and opportunities

Market
A market is any place or venue where buyers and sellers can exchange goods and services. A market may be physical, like a retail outlet, or virtual, like an online brokerage with no physical contact between buyers and sellers.

Materials as a service
It is a newly proposed business model by Imperial College London, United Kingdom where companies that supply raw and intermediary materials do not sell their supplies to the end-product manufacturing companies, but instead offer temporary access to them in the form of subscription, usage fee or rent. At the end of the life-cycle, the materials are recovered and repurposed again by the raw material and intermediary goods supplier. It is believed that if adopted, such business models could incentivize sustainable design, support a fairer resource distribution globally, and accelerate progress towards circular economy goals.

Mean species abundance
It is an indicator of naturalness or biodiversity intactness. It is defined as the mean abundance of original species relative to their abundance in undisturbed ecosystems. A mean species abundance of 0% indicates a completely destroyed ecosystem, with no original species remaining.

Multilevel cooperation
Multi-level governance and cooperation mean governments successfully consult one another and work together.

Nationally determined contributions
These are national climate action plans submitted by countries under the Paris Agreement to the United Nations Framework Convention on Climate Change. Nationally determined contributions outline how a country plans to reduce greenhouse gas emissions to help meet the global goal of limiting temperature rise to 1.5°C and adapt to the impacts of climate change. These plans are updated every five years with increasingly higher ambitions, taking into consideration each country's capacity.

Natural capital
Natural assets in their role of providing natural resource inputs and environmental services for economic production. Natural capital includes land, minerals and fossil fuels, solar energy, water, living organisms, and the services provided by the interactions of all these elements in ecological systems.

Nature-based Solutions (NbS)
Actions to protect, conserve, restore, sustainably use and manage natural or modified ecosystems to address societal challenges effectively and adaptively, while simultaneously providing human well-being, resilience and biodiversity benefits.

Non-pricing
Non-pricing tools can play a critical role in reducing emissions and lowering the social and political cost of carbon emissions, especially in countries where typical pricing instruments are difficult to implement due to domestic political, economic, institutional, and social constraints. Higher carbon prices may deliver more emission reductions faster, but national political economy constraints may make this approach difficult to implement, and there are significant challenges in adopting or creating a high carbon price in the short term amid rising inflationary and macroeconomic pressure, particularly in developing countries.

Ocean acidification
The term is used to describe significant changes to the chemistry of the ocean. It occurs when carbon dioxide gas is absorbed by the ocean and reacts with seawater to produce acid. Although carbon dioxide gas naturally

moves between the atmosphere and the oceans, the increased amounts of carbon dioxide gas emitted into the atmosphere, mainly as a result of human activities, such as burning fossil fuels, has been increasing the amount of carbon dioxide absorbed by the ocean, which results in seawater that is more acidic.

One Health

It is an approach to address a health threat at the human-animal-environment interface based on collaboration, communication, and coordination across all relevant sectors and disciplines, with the ultimate goal of achieving optimal health outcomes for people, animals and ecosystems. A One Health approach is applicable at the subnational, national, regional, and global level. The WHO One Health Initiative was established in 2021 and coordinates a quadripartite collaboration involving the Food and Agriculture Organization, the United Nations Environment Programme, the World Health Organization and the World Organisation for Animal Health. It promotes a One Health-related research agenda and leverages cross-sectoral solutions to support regions and countries.

Performance standard

Performance standards in the environment refer to established guidelines or benchmarks that set a level of acceptable environmental impact for businesses or industries, usually requiring them to minimize pollution, resource consumption, and other negative effects on the ecosystem, often measured through emissions limits, waste reduction targets, or specific operational practices; essentially, a set of criteria defining how well a company or activity should perform environmentally, encouraging sustainable practices.

Planetary health

It is a solutions-oriented, transdisciplinary field of research and social movement focused on analyzing and addressing the consequences of human disruptions to Earth's natural systems for human health and all life on Earth. The Planetary Health Alliance is a growing consortium of hundreds of universities, non-governmental organizations, research institutes, and government entities from more than eighty countries around the world committed to understanding and addressing the impacts of global environmental change on human health and well-being. The start of the initiative was the Safeguarding human health in the Anthropocene epoch report published by the Rockefeller Foundation-Lancet Commission on Planetary Health.

Plastic

Non-metallic compounds that result from a chemical reaction, and are molded or formed into rigid or pliable construction materials or fabrics.

Pluriverse

A term that originates from the fields of cosmology and philosophy, it contrasts with the term "universe" as a single unified reality and wholesomeness. Instead, pluriverse presents the theoretical idea of multiple possible universes, where different realities can coexist independently or interdependently. The term has been used in many fields of social sciences, implying underlying complexities of a non-uniform world. In sustainability research, the term is used in the context of post-development theories, critical ecology, and post-colonial studies. The concept of pluriverse in sustainability questions the origins of power, the monopoly of Western thought, knowledge and technology, and their manifestations in the global sustainability agenda, as well as in proposed sustainability solutions. The concept of pluriverse in sustainability research highlights the importance of local contexts and openness to diverse perspectives and solutions. It challenges the shortcomings of universal one-size-fits-all approaches and technical quick-fixes that neglect social justice and preservation of culture. The term multiverse can be used as a synonym for pluriverse.

Polar amplification

Polar amplification describes the phenomenon where surface-temperature change at high latitudes exceeds the global average surface-temperature change. The terms Arctic amplification or Antarctic amplification are used when describing the phenomenon occurring at one of the poles.

Pollution

The presence of minerals, chemicals or physical properties at levels that exceed the values deemed to define a boundary between good or acceptable and poor or unacceptable quality, which is a function of the specific pollutant.

Pressure

Pressure resulting from human activities which bring about changes in the state of the environment (e.g.,

land-use change, resource extraction, emissions of greenhouse gases and air pollutants, introduction and spread of invasive alien species).

Pricing instrument
Pricing instruments can be flexible and provide incentives for cost-effectiveness. They can also reduce long-term abatement costs by encouraging climate-friendly technological change.

Prosumer
A term combining "producer" and "consumer" to describe individuals who are both active creators and consumers of goods and services.

Protected areas
Protected areas and Other effective area-based conservation measures contributing to effective conservation and management; under the Kunming–Montreal Global Biodiversity Framework Target 3, at least 30% of terrestrial, inland water, coastal and marine areas should be effectively conserved and managed by 2030.

Public investment
Public investment refers to investment by the state in particular assets, whether through central or local governments or through publicly owned industries or corporations

Regenerative agriculture
An inclusive agroecosystems approach focused on regenerating living soils, improving biodiversity and ecosystem services while producing food.

Savannization
It is a substitution of tropical rainforests by savanna-like dry grasslands – a replacement of primary rainforest. This refers to both direct human activities, such as deforestation and human-induced forest fires, and self-reinforcing cycles due to climate change, such as higher frequency of natural forest fires and disrupted hydrological systems. The environmental consequences of this process are wide-ranging: biodiversity loss, disruption of the carbon and other mineral cycles, disruption of regional and global climate stability, and land degradation. Some authors discourage the use of this term because it reinforces prejudices against natural savannas. Bottino et al (2024) encourage replacing the term with tropical forest dieback or tropical forest degradation.

Scenario
A plausible, coherent and internally consistent description of how the future may unfold under specified assumptions about key drivers and relationships (not a prediction).

Shared socioeconomic pathways
They are a set of distinct global scenarios describing the future evolution of key aspects of society to analyze possible trajectories for human development and global environmental change during the 21st century. They were developed principally to support climate research, but used extensively for other fields, including biodiversity loss, land degradation and air pollution.

Shock
Shocks, in the environmental context, may include a range of phenomena that are natural or human-caused, from earthquakes, through ecosystem collapses, to abrupt climate changes, wildfires, floods, droughts, pandemics, armed conflicts or any other event with an unpredictable element that damages the environment on which we depend. Such events also weaken political, economic and social systems.

Social capital
Networks together with shared norms, values and understandings that facilitate co-operation within or among groups. Social capital represents the capacity of a community (local or international like the UN) to gather and achieve common goals.

Social cost
Private costs are carried by individuals, companies or other private entities that undertake an action, whereas social costs include additionally the external costs on the environment and on society as a whole.

Social Cost of Carbon
The net present value of climate damages (with harmful damages expressed as a positive number) from one more tonne of carbon in the form of CO_2, conditional on a global emissions trajectory over time.

Social value
Social values refer to value indicators at a social scale, such as social willingness to pay in economics. They can be established by aggregation from individual

values through analytical procedures, or through social processes, such as deliberative valuation, that lead to shared social values.

Socioeconomic
Of, relating to, or involving a combination of social and economic factors.

Solution pathways
A package of actions for system transformation with a sequence that creates a self-sustaining momentum towards achieving recognized goals.

Stranded assets
Assets exposed to devaluations or conversion to liabilities because of unanticipated changes in their initially expected revenues due to innovations or evolutions of the business context, including changes in public regulations at the domestic and international levels.

Structural adjustment
This term refers to governmental policy changes required of developing countries in the 1980s and 1990s to qualify for International Monetary Fund or World Bank financial assistance. This conditional loan and policy reform package came to the rescue of developing countries experiencing economic and financial crises and aimed at restructuring national economies, increasing their trade linkages and altering government spending. The adjustments typically included liberalization of trade and investment policies, removal of government imposed anti-competitive agricultural policies, removal of exchange and price controls, reform of tax policies, cutbacks in government spending, wage reductions, privatization of state enterprises. These reform packages have been criticized based on many problematic aspects. Economically the results were disappointing, while the social and environmental consequences were widespread and have raised concerns.

Subsidies
In the context of international trade, there are two kinds of subsidies: export and domestic. An export subsidy is a benefit conferred on a firm by the government that is contingent on exports. A domestic subsidy is a benefit not directly linked to exports.

Sustainable development
Development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs.

Sustainable finance
Sustainable finance is the process of taking environmental, social, and governance (ESG) principles into account when making investment decisions in the financial sector. This results in more long-term investments in sustainable economic projects and activities.

Sustainable governance
Sustainable government refers to a government that is committed to creating and maintaining conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations

Sustainable infrastructure
Sustainable infrastructure systems are those that are planned, designed, constructed, operated and decommissioned in a manner that ensures economic and financial, social, environmental (including climate resilience), and institutional sustainability over the entire infrastructure life cycle. Sustainable infrastructure can include built infrastructure, natural infrastructure or hybrid infrastructure that contains elements of both.

Sustainable intensification
Increasing food production from agricultural land while minimising environmental impacts and enhancing natural capital.

Target-seeking scenarios
Target-seeking scenarios are scenarios that start with the definition of a clear objective, or a set of objectives, specified either in terms of achievable targets, or as an objective function to be optimized, and then identify different pathways to achieving this outcome (e.g. through backcasting). Also known as "normative scenarios".

Telecoupling
It represents socioeconomic and environmental interactions over distances and time. It is an umbrella concept encompassing various types of distant interactions including international trade, tourism, migration, foreign investment, species invasion,

payments for ecosystem services, water transfer, information dissemination, knowledge transfer, and technology transfer and others.

Tipping point
The critical point in an evolving situation that leads to a new and sometimes irreversible development.

Total cost
Total cost, in economics, is the sum of all costs incurred by a firm in producing a certain level of output. It is typically expressed as the combination of all fixed costs (e.g., the costs of a building lease and of heavy machinery), which do not change with the quantity of output produced, and all variable costs (e.g., the costs of labour and of raw materials), which do change with the level of output.

Transformation
A change in the fundamental attributes of natural and human systems, or a thorough or dramatic change in form, composition, structure, appearance, or functionality. In terms of systems, it refers to changes that are fundamental, broad and deep; Transformations can lead to both desirable and undesirable outcomes.

Transformation pathways
Consistent trajectories of change to possible futures stemming from coherent sets of actions to achieve societal goals. Two qualitative and quantitative target-seeking scenarios are developed for GEO-7 that represent alternative Transformation Pathways. They result from integrated solutions that transform the economic and financial, food, energy, materials, and environmental systems, to achieve a set of internationally agreed goals. The set includes limiting global warming to 1.5°C global mean-temperature increase, halting and reversing biodiversity loss, achieving land-degradation neutrality, improving air quality, ending hunger and achieving universal access to clean water and modern energy services. These pathways describe alternative changes in how energy, food, and materials are used and produced, how natural resources are managed, and the pace and direction of technological and behavioural changes.

Transition
The process of changing from one state or condition to another in a given period of time. Transition can occur in individuals, firms, cities, regions and nations, and can be based on incremental or transformative change.

Transition finance
Transition is the journey to sustainable development, and transition finance the financing of that journey.

Unabated fossil fuels
Fossil fuel use without technologies that significantly reduce CO_2 emissions at the point of generation (e.g., high-rate carbon capture and storage).

Universal basic dividend
It is a way of making regular payments to all citizens from revenue raised by charging fees for the use and exploitation of common resources. Universal basic dividend would redistribute a portion of the excess wealth generated by the use and exploitation of the commons to each and every one of a country's citizens. Companies that pollute the commons, extract natural resources, or earn rents on financial assets, would pay fees from their profits into a country's citizen fund. This fund would then distribute equal payments to all citizens in the form of a dividend; the right of every citizen as a co-owner of the commons. It is not means tested or dependent upon government funds. Besides redistributing income to citizens as co-owners, this regular payout would, at the right level, provide essential individual economic security. Such security would likely reduce social tensions, especially during periods of disruption, and encourage the creativity, innovation, and entrepreneurship needed to design the societies of the future.

Value chain
A value chain refers to the full lifecycle of a product or process, including material sourcing, production, consumption and disposal/recycling processes. Value chains are an integral part of strategic planning for many businesses today.

Whole-of-government
A whole-of-government approach refers to deliberates effort to coordinate and integrate actions across government, spanning different departments, agencies, and levels —to achieve shared environmental goals. Rather than limiting environmental responsibility to a single ministry (such as environment or natural resources), this approach sustainability challenges are treated as cross-cutting, requiring collaboration across sectors like finance, transportation, energy, agriculture,

health, and education. Inter-agency committees, staffing rotations, cross-agency budgeting practices and harmonized reporting protocols can facilitate that collaboration. Changes to government structures may also be required for a more far-reaching transformative change approach.

Whole-of-society

A whole-of-society approach refers to a deliberate effort to include and engage all segments of society and plural forms of knowledge —social movements, citizens, Indigenous rightsholders, labour groups, civil society, communities, citizens, and private companies, large corporations, financial institutions, the informal economy, as well as governments —in addressing environmental challenges. Instead, it requires the active and meaningful participation of all actors and agents of change.

Special thanks to UNEP's funding partners. For more than 50 years, UNEP has served as the leading global authority on the environment, mobilizing action through scientific evidence, raising awareness, building capacity and convening stakeholders. UNEP's core programme of work is made possible by flexible contributions from Member States and other partners to the Environment Fund and UNEP Planetary Funds. These funds enable agile, innovative solutions for climate change, nature and biodiversity loss, and pollution and waste.

Support UNEP. Invest in people and planet.
www.unep.org/funding

UN environment programme

www.unep.org
unep-communication-director@un.org