Cross-Chapter Boxes and Cross-Working Group Boxes

CCB
CWGB

Cross-Chapter Boxes and Cross-Working Group Boxes

These Cross-Chapter Boxes and Cross-Working Group Boxes have been extracted from the chapters and papers of the underlying report and are compiled here.

Table of Contents

Cross-Chapter Box and Cross-Working Group Box Citations

Cross-Chapter Box CLIMATE | Climate Reference Periods, Global Warming Levels and Common Climate Dimensions

Rose, S., R. Betts, P. Wester, and A. Koutroulis, 2022: Cross-Chapter Box CLIMATE | Climate Reference Periods, Global Warming Levels and Common Climate Dimensions. 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. 135–143.

Cross-Working Group Box ATTRIBUTION | Attribution in the IPCC Sixth Assessment Report

Hope, P., W. Cramer, M. van Aalst, G. Flato, K. Frieler, N. Gillett, C. Huggel, J. Minx, F. Otto, C. Parmesan, J. Rogelj, M. Rojas, S.I. Seneviratne, A. Slangen, D. Stone, L. Terray, R. Vautard, and X. Zhang, 2022: Cross-Working Group Box ATTRIBUTION | Attribution in the IPCC Sixth Assessment Report. 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. 149–152.

Cross-Chapter Box PALEO | Vulnerability and Adaptation to Past Climate Changes

Kiessling, W., T.A. Kohler, W. Cramer, G. Anshari, J.S. Hermansen, D.S. Kaufman, G. Midgley, N. Raja, D.N. Schmidt, N.C. Stenseth, and R. Sukumar, 2022: Cross-Chapter Box PALEO | Vulnerability and Adaptation to Past Climate Changes 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. 152–155.

Cross-Chapter Box ADAPT | Adaptation Science

Nalau, J., L. Rickards, T. Lissner, K.J. Mach, L. Schipper, C. Singh, W. Solecki, A. Thomas, and E. Totin, 2022: Cross-Chapter Box ADAPT | Adaptation Science. 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. 166–169.

Cross-Chapter Box EXTREMES | Ramifications of Climatic Extremes for Marine, Terrestrial, Freshwater and Polar Natural Systems

Harris, R., P. Boyd, R. Adrian, J. Birkmann, S. Cooley, S. Donner, M. Mauritzen, G. Midgley, C. Parmesan, D. Piepenburg, M.-F. Racault, B. Rost, D. Schoeman, S.E. Strutz, and M. van Aalst, 2022: Cross-Chapter Box EXTREMES | Ramifications of Climatic Extremes for Marine, Terrestrial, Freshwater and Polar Natural Systems. 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. 215–218.

Cross-Chapter Box ILLNESS | Infectious Diseases, Biodiversity and Climate: Serious Risks Posed by Vector- and Water-Borne Diseases

Racault, M.-F., S.E. Strutz, C. Parmesan, R. Adrian, G. Cissé, S. Cooley, M. Dhimal, L.E. Escobar, A. Gemeda, N.J.M. Hilmi, S.E. Lluch-Cota, E. Mordecai, G. Pecl, A.T. Peterson, J. Rocklöv, M. Romanello, D. Schoeman, J.C. Semenza, M.C. Tirado, G.H. Talukdar, and Y. Trisurat, 2022: Cross-Chapter Box ILLNESS | Infectious Diseases, Biodiversity and Climate: Serious Risks Posed by Vector- and Water-Borne Diseases. 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. 291–295.

Cross-Chapter Box NATURAL | Nature-Based Solutions for Climate Change Mitigation and Adaptation

Parmesan, C., G. Anshari, P. Buotte, D. Campbell, E. Castellanos, A. Cowie, M.R. Ferre, P. Gonzalez, E.L. Gunn, R. Harris, J. Hicke, R. Bezner Kerr, R. Lasco, R. Lempert, B. Mackey, P. Martinetto, R. Matthews, T. McPhearson, M. Morecroft, A. Mukherji, G.-J. Nabuurs, H. Neufeldt, R. Pedace, J. Postigo, J. Price, J. Pulhin, J. Rogelj, D. Schmidt, D. Schoeman, P.K. Singh, P. Smith, N. Stevens, S.E. Strutz, R. Sukumar, G.H. Talukdar, M.C. Tirado, and C.H. Trisos, 2022: Cross-Chapter Box NATURAL | Nature-Based Solutions for Climate Change Mitigation and Adaptation. 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. 303–309.

Cross-Chapter Box SLR | Sea Level Rise

Le Cozannet, G., J. Lawrence, D.S. Schoeman, I. Adelekan, S.R. Cooley, B. Glavovic, M. Haasnoot, R. Harris, W. Kiessling, R.E. Kopp, A. Mukherji, P. Nunn, D. Piepenburg, D. Schmidt, C.T. Simmons, C. Singh, A. Slangen, and S. Supratid, 2022: Cross-Chapter Box SLR | Sea Level Rise. 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. 477–480.

Cross-Chapter Box DISASTER | Disasters as the Public Face of Climate Change

Mukherji, A., G. Cissé, C. Zickgraf, P. Aldunce, L.R. Miranda Sara, W. Solecki, F. Otto, F. Gemenne, M.A. Caretta, R. Jones, R. Betts, M. van Aalst, J. Zscheischler, K. Murray, and M.E. González, 2022: Cross-Chapter Box DISASTER | Disasters as the Public Face of 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 [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. 588–591.

Cross-Chapter Box MOVING PLATE | Sourcing Food When Species Distributions Change

Gurney-Smith, H., W. Cheung, S. Lluch Cota, E. Ojea, C. Parmesan, J. Pinnegar, P. Thornton, M.-F. Racault, G. Pecl, E.A. Nyboer, K. Holsman, K. Miller, J. Birkmann, G. Nelson, and C. Möllmann, 2022: Cross-Chapter Box MOVING PLATE | Sourcing Food When Species Distributions 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 [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. 768–773.

Cross-Working Group Box BIOECONOMY | Mitigation and Adaptation via the Bioeconomy

Neufeldt, H., G. Berndes, A. Arneth, R. Bezner Kerr, L.F. Cabeza, D. Campbell, J. Carnicer Cols, A. Cowie, V. Daioglou, J. House, A. Leip, F. Meza, M. Morecroft, G.-J. Nabuurs, C. Parmesan, J.C. Postigo, M.G. Rivera-Ferre, R. Slade, M.C. Tirado von der Pahlen, P.K. Singh, and P. Smith, 2022: Cross-Working Group Box BIOECONOMY | Mitigation and Adaptation via the Bioeconomy. 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. 828–831.

Cross-Working-Group Box URBAN | Cities and Climate Change
Bai X., V. Castán Broto, W. Chow, F. Creutzig, D. Dodman, R. Hamdi, B. Hayward, Ş. Kılkış, S. Lwasa, T. McPhearson, M. Pathak, M. Pelling, D. Reckien, K. Seto, A. Sharifi, and D. Ürge- Vorsatz, 2022: Cross-Working-Group Box URBAN | Cities and 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 [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. 988–991.

Cross-Chapter Box COVID | COVID-19
van Aalst, M., G. Cissé, A. Ayanlade, L. Berrang-Ford, R. Bezner Kerr, R. Biesbroek, K. Bowen, M.A. Caretta, S.-M. Cheong, W. Chow, M.J. Costello, K. Ebi, E. Gilmore, B. Glavovic, W. Leal, S. Langsdorf, E. Lopez-Gunn, R. Morgan, A. Mukherji, C. Parmesan, M. Pelling, E. Poloczanska, M.-F. Racault, D. Reckien, J.C. Semenza, P.K. Singh, S.E. Strutz, M.C. Tirado von der Pahlen, C. Schuster-Wallace, A. Woodward, and Z. Zommers, 2022: Cross-Chapter Box COVID | COVID-19. 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. 1067–1070.

Cross-Chapter Box MIGRATE | Climate-Related Migration
Wrathall, D., R. McLeman, H. Adams, I. Adelekan, E. Gilmore, F. Gemenne, N. Hilmi, B. Orlove, R. Basu, H. Buhaug, E. Castellanos, D. Dodman, F.K. Kalaba, R. Mukerji, K. Patel, C. Singh, P. Thornton, C.H. Trisos, O. Warrick, and V. Pandey, 2022: Cross-Chapter Box MIGRATE | Climate-Related Migration. 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. 1080–1083.

Cross-Chapter Box HEALTH | Co-benefits of Climate Actions for Human Health, Wellbeing and Equity
Tirado, M.C., R. Biesbroek, M. Pelling, J. Hess, F. Creutzig, R. Bezner Kerr, S. Eriksen, D. Campbell-Lendrum, E. Gilmore, M. Figueroa, N. Hilmi, P. Newman, S. Mirasgedis, S. Rohit, Y. Saheb, G. Sanchez Martinez, P. Smith, A. Leip, D. Subash, C.H. Trisos, M. Bustamante, L. Cabeza, and D. Urge-Vorsatz, 2022: Cross-Chapter Box HEALTH | Co-benefits of Climate Actions for Human Health, Wellbeing and Equity. 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. 1124–1125.

Cross-Chapter Box INTEREG | Inter-regional Flows of Risks and Responses to Risk
Bednar-Friedl, B., C.H. Trisos, L. Astigarraga, M. Benzie, A. Mukherji, and M. van Aalst, 2022: Cross-Chapter Box INTEREG | Inter-regional Flows of Risks and Responses to Risk. 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. 2441–2444.

Cross-Working Group Box SRM | Solar Radiation Modification
Trisos, C.H., O. Geden, S.I. Seneviratne, M. Sugiyama, M. van Aalst, G. Bala, K.J. Mach, V. Ginzburg, H. de Coninck, and A. Patt, 2022: Cross-Working Group Box SRM | Solar Radiation Modification. 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. 2473–2478.

Cross-Working Group Box ECONOMIC | Estimating Global Economic Impacts from Climate Change
Rose, S., D. Diaz, T. Carleton, L. Drouet, C. Guivarch, A. Méjean, and F. Piontek, 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 [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. 2495–2499.

Cross-Chapter Box LOSS | Loss and Damage
Mechler, R., A. Thomas, C. Huggel, E. Boyd, V. Muccione, I. Wallimann-Helmer, L. Bouwer, S. Juhola, C. Singh, C. Adler, K. Ebi, P. Pinho, R. Ara Begum, A. Gemeda, J. Nalau, K. Frieler, R. Jones, R. Djalante, R. Perez, T. Lissner, A. Wreford, M. Pelling, F. Gemenne, N. Simpson, and D. Stabinsky, 2022: Cross-Chapter Box LOSS | Loss and Damage. 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. 2563–2565.

Cross Chapter Box DEEP | Effective Adaptation and Decision-Making Under Deep Uncertainties
Adler, C., R. Lempert, A. Constable, M. Haasnoot, J. Lawrence, K.J. Mach, S. French, R. Kopp, C. Parmesan, M. Dominguez Aguilar, E.A. Gilmore, R. Bezner Kerr, A. Gemeda, M.C. Tirado von der Pahlen, D. Ley, and R. Mukerji, 2022: Cross Chapter Box DEEP | Effective Adaptation and Decision-Making Under Deep Uncertainties. 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. 2578–2580.

Cross-Chapter Box FINANCE | Finance for Adaptation and Resilience
New, M., M. Rawlins, D. Viner, C. Watson, L. Burge, L. Mok, L. Arendse, V. Karoblyte, L. Schalatek, N. Rai, B. Naran, S.-M. Cheong, and N. Giulivi, 2022: Cross-Chapter Box FINANCE | Finance for Adaptation and Resilience. 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. 2586–2593.

Cross-Chapter Box PROGRESS | Approaches and Challenges to Assess Adaptation Progress at the Global Level
Garschagen, M., T. Leiter, R. Biesbroek, A.K. Magnan, D. Reckien, M. New, L. Berrang-Ford, S.-M. Cheong, L. Schipper, and R. Lempert, 2022: Cross-Chapter Box PROGRESS | Approaches and Challenges to Assess Adaptation Progress at the Global Level. 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. 2610–2613.

Cross-Chapter Box GENDER | Gender, Climate Justice and Transformative Pathways
Prakash, A., C. Conde, A. Ayanlade, R. Bezner Kerr, E. Boyd, M.A Caretta, S. Clayton, M.G. Rivera Ferre, L.R. Gallardo, S.A. Halim, N. Lansbury, O. Lipka, R. Morgan, J. Roy, Diana Reckien, E.L.F. Schipper, C. Singh, M.C. Tirado von der Pahlen, E. Totin, K. Vasant, M. Wairiu, Z. Zaiton Ibrahim, 2022: Cross-Chapter Box GENDER | Gender, Climate Justice and Transformative 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. 2700–2704.

Cross-Chapter Box INDIG | The Role of Indigenous Knowledge and Local Knowledge in Understanding and Adapting to Climate Change

Mustonen, M., S. Harper, G. Pecl, V. Castán Broto, N. Lansbury, A. Okem, A. Ayanlade, J. Dawson, P. Harris, P. Feodoroff, and D. McGregor, 2022: Cross-Chapter Box INDIG | The Role of Indigenous Knowledge and Local Knowledge in Understanding and Adapting to 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 [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. 2713–2716.

Cross-Chapter Box FEASIB | Feasibility Assessment of Adaptation Options: An Update of the SR1.5

Ley, D., H. Adams, M. Araos, R. Basu, A. Bazaz, L. Conte, K. Davis, C. Dockendorff, J. Ford, S. Fuss, E.A. Gilmore, T. Guillén Bolaños, O. Hoegh-Guldberg, M. Howden, B. Kalyan, L. Moro, A. Mosurska, R. Mechler, J. Portugal-Pereira, A. Revi, S. Sharma, A.J. Sietsma, C. Singh, A. Triacca, B. van Bavel, I. Villaverde Canosa, M. Babiker, P. Bertoldi, B. Cohen, A. Cowie, K. de Kleijne, J. Emmet-Booth, A. Garg, G.-J. Nabuurs, A.F. Pereira de Lucena, A. Leip, L.J. Nilsson, P. Smith, L. Steg, and M. Sugiyama, 2022: Cross-Chapter Box FEASIB | Feasibility Assessment of Adaptation Options: An Update of the SR1.5. 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. 2769–2807.

Cross-Chapter Box CLIMATE | Climate Reference Periods, Global Warming Levels and Common Climate Dimensions

Authors: Steven Rose (USA), Richard Betts (UK), Philippus Wester (Nepal/the Netherlands), Aris Koutroulis (Greece)

This Cross-Chapter Box sets out common climate dimensions to contextualise and facilitate AR6 WGII analyses, presentation, synthesis and communication of assessed, observed and projected climate change impacts across WGII chapters and cross-chapter papers. 'Common climate dimensions' are defined as common global warming levels (GWLs), time periods and levels of other variables, as needed by WGII authors for consistent communications. The set of climate variable ranges given below was derived from the AR6 WGI report and supporting resources, and helps to contextualise and inform the projection of potential future climate impacts and key risks. The information enables the mapping of climate variable levels to climate projections and vice versa, with ranges of results provided to characterise the physical uncertainties relevant to assessing climate impacts risk.

AR6 WGI Reference Periods, Climate Projections and Global Warming Levels

AR6 WGI adopts a common set of reference years and time periods to assess observed and projected climate change, namely the pre-industrial period, the current 'modern' period and future reference time periods. The IPCC Glossary (2021b) defines the pre-industrial period as 'the multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial global mean surface temperature (GMST).' The 'modern' period is defined as 1995 to 2014 in AR6, while three future reference periods are used for presenting climate change projections, namely near term (2021–2040), mid-term (2041–2060) and long term (2081–2100), in both the AR6 WGI and WGII reports. Importantly, the historical rate of warming assessed by WGI in AR6 is different to that assessed in AR5 and Special Report on Global Warming of 1.5°C (SR1.5, IPCC, 2018b), due to methodological updates (see WGI Cross-Chapter Box 2.3 in Chapter 2 for details (Gulev, 2021)). This means that the 'modern' period is assessed as slightly warmer compared to 1850–1900 than it would have been with AR5-era methods. This also has implications for the projected timing of reaching policy-relevant levels of global warming, which need to be understood.

To explore and investigate climate futures, climate change projections are developed using sets of different input projections. These consist of sets of projections of GHG emissions, aerosols or aerosol precursor emissions, land use change, and concentrations designed to facilitate evaluation of a large climate space and enable climate modelling experiments. For AR5 (and the Coupled Model Intercomparison Project (CMIP) 5 climate model experiments), the input projections were referred to as representative concentration pathways (RCPs). For AR6 (and the CMIP6 climate model experiments), new sets of inputs are used and referred to as SSP scenarios, where SSP refers to socioeconomic assumptions called the shared socioeconomic pathways (SSPs).

The RCPs are a set of four trajectories that span a large radiative forcing range, defined as increased energy input at surface level in Watts per square metre, ranging from 2.6 W m^{-2} (RCP2.6) to 8.5 W m^{-2} (RCP8.5) by the end of the 21st century, with RCP4.5 and RCP6.0 as intermediate scenarios, and RCP2.6 a peak and decline scenario reaching 3 W m^{-2} before 2100. A range of emissions scenarios compatible with each specific RCP was also assessed in AR5 (Ciais et al., 2013).

A core set of five SSP scenarios, namely SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, was selected in the AR6 WGI report to fill certain gaps identified in the RCPs (see WGI Cross-Chapter Box 1.4 in Chapter 1 (Chen et al., 2021)). The first number in the label is the particular set of socioeconomic assumptions driving the emissions and other climate forcing inputs taken up by climate models and the second number is the radiative forcing level reached in 2100. WG1 Cross-Chapter Box 1.4 in Chapter 1 provides a comparison of this core set of SSP scenarios with scenarios used in previous reports, with SSP1–1.9 a low overshoot scenario consistent with limiting global average warming to 1.5°C, and SSP1-2.6 a scenario consistent with limiting warming to 2°C.

Also of importance to the impact literature and the WGII report are SSP-RCP combinations, that is, studies that employ climate outcomes based on RCPs and socio-economic assumptions based on SSPs. SSPs can be paired with a range of different RCPs because SSPs can be combined with mitigation policy assumptions to produce a range of emissions pathways. In addition to the SSPs, there are many other emissions pathways and societies consistent with any global mean temperature outcome. These represent uncertainty and broad ranges of possibilities that affect climate change exposure and vulnerability (Rose and and M. Scott, 2020; Rose and Scott, 2018). Furthermore, there are large uncertainties in translating emissions scenarios into concentration pathways due to uncertainties in climate-carbon cycle feedbacks (Jones et al., 2013; Booth et al., 2017).

The plausibility of emissions levels as high as the emissions scenario conventionally associated with the RCP8.5 and SSP5-8.5 concentration pathways has been called into question since AR5, as has the emissions pathway feasibility of the low scenarios (Hausfather and Peters, 2020; Rose and and Scott, 2020). However, these views are contested (Schwalm et al., 2020, for RCP8.5) It is important to realise that emissions

Cross-Chapter Box CLIMATE (continued)

scenarios and concentration pathways are not the same thing and higher concentration pathways, such as RCP8.5 could arise from lower emissions scenarios if carbon cycle feedbacks are stronger than assumed in the integrated assessment models (IAMs) used to create the standard scenarios (Booth et al., 2017). In the majority of full-complexity Earth System Models, these feedbacks are stronger than in the IAMs (Jones et al., 2013), so the RCP8.5 concentration pathway cannot be ruled out purely through consideration of the economic aspects of emissions scenarios. Nonetheless, the likelihood of a climate outcome, and the overall distribution of climate outcomes, are a function of the emissions scenario's likelihood. Note that the original RCPs were created explicitly to facilitate a broad range of climate modelling experiments, with the expectation that other issues, such as socioeconomic uncertainty, could be subsequently explored (Moss et al., 2010).

An important feature of the AR6 cycle is a stronger emphasis on the use of future GWLs to support consistency and comparability across the three IPCC Working Groups' contributions to the AR6 and improve communication. The common range of GWLs relative to the 1850 to 1900 period, termed the 'Tier 1' range by WGI, are 1.5, 2.0, 3.0 and 4.0°C. The use of GWLs assists in the comparison of climate states across climate change scenarios (projections) and in assessing the broader literature, as well as for cross-chapter and cross-working group comparisons. They facilitate the integration of climate projections, impacts, adaptation challenges and mitigation challenges within and across the three Working Groups as there is a close connection between the level of global warming and climate change impacts. Of particular interest is the timing of when the 'Tier 1' GWLs are reached, relative to the period 1850–1900, under the five SSP x–y scenarios, as well as RCP scenarios. For climate change impacts and adaptation responses, linking GWLs to RCP and SSP climate projections using a climate information translation resource is of great relevance for the WGII contribution to AR6.

AR6 WGII Common Climate Dimensions

WGII's common climate dimensions include (a) a common range of GWLs from WGI, (b) common ranges for other climate variables, (c) information for translating climate variable levels to climate projections and vice versa. See Table Cross-Chapter Box CLIMATE.1 for global warming level ranges by time periods for RCP and SSP climate projections, and Table Cross-Chapter Box CLIMATE.2 for information regarding the timing for when GWLs are reached in climate projections. The common GWL range is based on WGI's 'Tier 1' dimensions of integration range: 1.5°C, 2°C, 3°C and 4°C. The first table illustrates the greater levels of projected global warming with higher emissions pathways, as well as the increasing uncertainty in the climate response over time for a given pathway. The second table illustrates significant uncertainty in the timing for passing GWL thresholds which can narrow for a given GWL, the higher the emissions pathway. Finally, given the importance of geographic heterogeneity in projected changes in future climate, Table Cross-Chapter Box CLIMATE.3a and 3b are provided with ranges for select climate variables (temperature, precipitation, ocean) by GWL and continent (or ocean biome). The ranges illustrate spatial heterogeneity in potential physical changes in levels and uncertainty that are relevant to assessing climate impacts risk. There is significantly more spatial heterogeneity than represented in the table that is relevant to local decision makers (see, for instance, WGI Interactive Atlas).

The common climate dimensions can be used as a dimension of integration for impact studies in WGII, for example by providing a common framework for comparison of projected impacts for different studies (Figure Cross-Chapter Box CLIMATE.1). Moreover, GWL bands are needed in WGII to map the diverse temperature levels found across WGII's literature. The GWL's also facilitate integration with WGIII's global emissions projections categorisation by global mean temperature (WGIII Chapter 3).

Table Cross-Chapter Box CLIMATE.1 | GWL ranges by time periods for CMIP5 (RCP) and CMIP6 (SSP) climate projections (20-year averages). Temperature anomalies relative to 1850–1900. Full ranges for CMIP raw results (across all models and ensemble runs) and WGI AR6 assessed *very likely* (5–95%) ranges. *Sources: Hauser et al. (2019); WGI SPM (IPCC, 2021a); Table SPM.1*

	Full ranges									WGI AR6 assessed *very likely* (5–95%) ranges								
Projection	**2021–2040**			**2041–2060**			**2081–2100**			**2021–2040**			**2041–2060**			**2081–2100**		
RCP2.6	1.0	to	2.2	1.0	to	2.3	0.9	to	2.3	n/a			n/a			n/a		
RCP4.5	1.1	to	2.2	1.4	to	2.7	1.8	to	3.3	n/a			n/a			n/a		
RCP6.0	1.0	to	2.0	1.3	to	2.5	2.3	to	3.6	n/a			n/a			n/a		
RCP8.5	1.1	to	2.6	1.7	to	3.7	3.0	to	6.2	n/a			n/a			n/a		
SSP1–1.9	1.0	to	2.4	1.1	to	2.7	1.0	to	2.5	1.2	to	1.7	1.2	to	2.0	1.0	to	1.8
SSP1–2.6	1.0	to	2.4	1.2	to	2.9	1.3	to	3.1	1.2	to	1.8	1.3	to	2.2	1.3	to	2.4
SSP2–4.5	0.9	to	2.5	1.3	to	3.3	1.9	to	4.4	1.2	to	1.8	1.6	to	2.5	2.1	to	3.5
SSP3–7.0	1.0	to	2.6	1.5	to	3.7	2.7	to	6.2	1.2	to	1.8	1.7	to	2.6	2.8	to	4.6
SSP5–8.5	1.0	to	2.7	1.6	to	4.0	3.1	to	7.2	1.3	to	1.9	1.9	to	3.0	3.3	to	5.7

Cross-Chapter Box CLIMATE (continued)

Table Cross-Chapter Box CLIMATE.2 | Timing for when 20-year average GWLs are reached in CMIP5 (RCP) and CMIP6 (SSP) climate projections. GWL anomalies relative to 1850–1900. Ranges based on CMIP raw results (all models and ensemble runs), and WGI AR6 assessed results. For each GWL and RCP/SSP, the earliest and latest 20-year window when a 20-year average GWL is reached across the CMIP models and ensemble members is reported, or the *very likely* (5–95%) assessed range is reported. 'n.c.' means the GWL is not reached during the period 2021–2100. ***Sources: Hauser et al. (2019); WGI TS Cross-Section Box Table TS.1(Arias et al., 2021)***

	CMIP5 full ranges			
GWL	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.5**
4°C	n.c.	n.c.	n.c.	2047–2066 to 2080–2099
3°C	n.c.	2054–2073 to 2070–2089	2062–2081 to 2080–2099	2030–2049 to 2077–2096
2°C	2015–2034 to 2079–2098	2014–2033 to 2075–2094	2023–2042 to 2068–2087	2004–2023 to 2048–2067
1.5°C	1998–2017 to 2075–2094	1998–2017 to 2051–2070	2001–2020 to 2050–2069	1990–2009 to 2035–2054

	CMIP6 full ranges				
GWL	**SSP1–1.9**	**SSP1–2.6**	**SSP2–4.5**	**SSP3–7.0**	**SSP5–8.5**
4°C	n.c.	n.c.	2061–2080 to 2081–2100	2046–2065 to 2081–2100	2042–2061 to 2081–2100
3°C	n.c.	2050–2069 to 2068–2087	2034–2053 to 2081–2100	2030–2049 to 2081–2100	2027–2046 to 2079–2098
2°C	2009–2028 to 2063–2082	2008–2027 to 2075–2094	2009–2028 to 2080–2099	2008–2027 to 2060–2079	2008 - 2027 to 2055 - 2074
1.5°C	1997–2016 to 2058–2077	1997–2016 to 2073–2092	1997–2016 to 2051–2070	1997–2016 to 2042–2061	1997 - 2016 to 2038 - 2057

	WGI AR6 assessed *very likely* (5–95%) ranges				
GWL	**SSP1–1.9**	**SSP1–2.6**	**SSP2–4.5**	**SSP3–7.0**	**SSP5–8.5**
4°C	n.c.	n.c.	n.c.	2070–2089 to n.c.	2058–2077 to n.c.
3°C	n.c.	n.c.	2061–2080 to n.c.	2050–2069 to n.c.	2042–2061 to 2074–2093
2°C	n.c.	2031–2050 to n.c.	2028–2047 to 2075–2094	2026–2045 to 2053–2072	2023–2042 to 2044–2063
1.5°C	2013–2032 to n.c.	2012–2031 to n.c.	2012–2031 to 2037–2056	2013–2032 to 2033–2052	2011–2030 to 2029–2048

Cross-Chapter Box CLIMATE (continued)

Table Cross-Chapter Box CLIMATE.3a | Projected continental level result ranges for select temperature and precipitation climate change variables by global warming level. Ranges are 5th and 95th percentiles from SSP5–8.5 WGI CMIP6 ensemble results. There is little variation in the 5th and 95th percentile values by GWL across the SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5 projections. ***Source: WGI AR6 Interactive Atlas*** *(*https://interactive-atlas.ipcc.Chapter/*).*

Climate variable	Global warming level	All regions			North America			Europe			Asia			Centra-South America			Africa			Australia			Antarctica		
Mean temperature (°C)	4°C	12	to	15	8	to	11	5	to	9	12	to	14	24	to	27	26	to	29	24	to	27	–33	to	–27
	3°C	11	to	14	6	to	11	4	to	7	10	to	14	23	to	26	25	to	28	23	to	26	–35	to	–26
	2°C	10	to	13	5	to	9	3	to	6	8	to	12	22	to	25	24	to	27	22	to	25	–36	to	–27
	1.5°C	9	to	12	4	to	8	2	to	5	8	to	12	22	to	24	24	to	26	22	to	24	–36	to	–27
Mean daily minimum temperature (°C)	4°C	8	to	11	4	to	8	1	to	6	6	to	11	19	to	24	21	to	25	18	to	23	–38	to	–29
	3°C	6	to	11	2	to	8	0	to	5	4	to	10	19	to	22	19	to	23	17	to	21	–39	to	–30
	2°C	5	to	10	0	to	6	–2	to	4	3	to	9	17	to	21	18	to	22	16	to	20	–40	to	–31
	1.5°C	4	to	9	–1	to	5	–2	to	3	2	to	8	17	to	21	17	to	22	16	to	19	–41	to	–32
Minimum of daily minimum temperatures (°C)	4°C	–12	to	–5	–25	to	–15	–22	to	–14	–18	to	–9	11	to	15	10	to	14	5	to	10	–64	to	–48
	3°C	–13	to	–6	–27	to	–15	–24	to	–15	–20	to	–11	10	to	15	8	to	14	4	to	10	–64	to	–50
	2°C	–15	to	–8	–30	to	–18	–27	to	–17	–22	to	–13	9	to	14	7	to	13	3	to	9	–65	to	–51
	1.5°C	–16	to	–9	–32	to	–20	–28	to	–19	–23	to	–14	8	to	14	6	to	12	3	to	9	–66	to	–51
Mean maximum daily temperature (°C)	4°C	16	to	19	12	to	15	8	to	11	15	to	18	27	to	32	30	to	35	28	to	33	–31	to	–25
	3°C	15	to	19	11	to	15	7	to	11	14	to	18	27	to	32	30	to	37	27	to	34	–32	to	–25
	2°C	14	to	18	9	to	13	6	to	9	13	to	17	26	to	31	29	to	36	27	to	33	–33	to	–25
	1.5°C	13	to	17	8	to	12	5	to	9	12	to	16	25	to	30	28	to	35	26	to	33	–33	to	–26
Maximum of daily maximum temperatures (°C)	4°C	32	to	37	32	to	38	28	to	33	35	to	40	36	to	43	40	to	47	41	to	49	–12	to	–5
	3°C	31	to	39	31	to	38	28	to	34	35	to	41	35	to	44	39	to	51	41	to	54	–12	to	–3
	2°C	30	to	37	30	to	36	26	to	33	33	to	39	34	to	43	38	to	50	39	to	53	–13	to	–4
	1.5°C	29	to	36	29	to	35	25	to	31	32	to	39	33	to	42	38	to	49	39	to	52	–14	to	–5
Number of days with maximum temperature above 35°C—bias adjusted	4°C	81	to	106	36	to	50	11	to	22	57	to	77	138	to	194	153	to	210	140	to	168	0	to	0
	3°C	66	to	87	27	to	40	6	to	15	44	to	59	100	to	153	131	to	183	124	to	147	0	to	0
	2°C	52	to	68	19	to	29	4	to	8	33	to	45	61	to	106	116	to	151	102	to	124	0	to	0
	1.5°C	45	to	58	16	to	24	2	to	5	30	to	39	43	to	85	107	to	133	94	to	115	0	to	0
Number of days with maximum temperature above 40°C—bias adjusted	4°C	28	to	40	9	to	16	1	to	5	19	to	26	21	to	68	69	to	92	53	to	83	0	to	0
	3°C	20	to	30	5	to	11	1	to	2	14	to	21	9	to	32	56	to	77	41	to	64	0	to	0
	2°C	14	to	21	2	to	6	0	to	1	9	to	15	3	to	13	41	to	57	27	to	45	0	to	0
	1.5°C	11	to	17	2	to	4	0	to	0	8	to	12	1	to	8	35	to	47	22	to	38	0	to	0

Cross-Chapter Box CLIMATE (continued)

Climate variable	Global warming level	All regions			North America			Europe			Asia			Centra-South America			Africa			Australia			Antarctica		
Near-surface total precipitation (mm d–1)	**4°C**	2	to	3	2	to	3	2	to	2	2	to	3	4	to	5	2	to	3	1	to	2	1	to	1
	3°C	2	to	3	2	to	3	2	to	2	2	to	3	3	to	5	2	to	3	1	to	2	1	to	1
	2°C	2	to	3	2	to	3	2	to	2	2	to	3	3	to	5	2	to	3	1	to	2	1	to	1
	1.5°C	2	to	3	2	to	3	2	to	2	2	to	3	3	to	5	2	to	3	1	to	2	1	to	1
Maximum 1-day precipitation amount (mm)	**4°C**	35	to	55	40	to	53	27	to	35	36	to	52	47	to	90	29	to	67	43	to	68	9	to	13
	3°C	31	to	52	34	to	50	23	to	33	30	to	50	37	to	88	25	to	66	38	to	69	8	to	12
	2°C	29	to	50	32	to	48	22	to	32	28	to	47	37	to	85	22	to	59	36	to	66	8	to	11
	1.5°C	28	to	48	31	to	47	21	to	31	27	to	45	35	to	84	21	to	58	36	to	64	8	to	11
Maximum 5-day precipitation amount (mm)	**4°C**	79	to	99	75	to	93	53	to	71	81	to	105	118	to	168	68	to	113	81	to	124	20	to	29
	3°C	66	to	99	68	to	87	48	to	68	70	to	101	97	to	165	60	to	118	76	to	129	19	to	27
	2°C	64	to	93	65	to	84	47	to	65	66	to	95	93	to	162	55	to	107	73	to	122	18	to	26
	1.5°C	63	to	91	63	to	83	46	to	64	64	to	93	92	to	160	52	to	105	74	to	119	18	to	25
Consecutive dry days (precipitation < 1 mm)	**4°C**	36	to	80	23	to	31	26	to	38	35	to	68	31	to	88	48	to	146	45	to	109	44	to	99
	3°C	36	to	88	21	to	33	25	to	43	35	to	76	29	to	82	49	to	160	40	to	127	45	to	120
	2°C	37	to	88	21	to	32	24	to	40	36	to	74	29	to	77	49	to	161	38	to	128	45	to	127
	1.5°C	36	to	87	22	to	31	25	to	37	36	to	74	28	to	77	49	to	159	40	to	125	46	to	131

Table Cross-Chapter Box CLIMATE.3b | Projected sea surface temperature change ranges by global warming level and ocean biome (degrees Celsius). Ranges are 5th and 95th percentiles from SSP5–8.5 WGI CMIP6 ensemble results. There is little variation in the 5th and 95th percentile values by GWL across the SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5 projections. ***Source: WGI Interactive Atlas (***https://interactive-atlas.ipcc.Chapter/***).***

Global warming level	All ocean biomes			Northern Hemi-sphere—high latitudes			Northern Hemisphere—subtropics			Equatorial			Southern Hemisphere—subtropics			Southern Hem-isphere—high latitudes			Gulf of Mexico			Eastern boundaries			Amazon River			Arabian Sea			Indonesian Flowthrough		
4°C	1.9	to	2.4	2.0	to	3.3	2.2	to	2.8	2.1	to	3.0	1.8	to	2.4	1.3	to	2.0	2.1	to	2.8	2.1	to	2.7	1.7	to	2.5	2.3	to	2.9	1.9	to	2.7
3°C	1.3	to	1.7	1.2	to	2.2	1.4	to	2.4	1.4	to	2.2	1.2	to	1.7	0.7	to	1.4	1.5	to	2.3	1.4	to	2.1	1.2	to	2.0	1.6	to	2.2	1.3	to	1.9
2°C	0.6	to	1.0	0.5	to	1.4	0.7	to	1.4	0.7	to	1.3	0.5	to	1	0.3	to	0.8	0.6	to	1.4	0.6	to	1.3	0.6	to	1.3	0.6	to	1.3	0.5	to	1.2
1.5°C	0.2	to	0.7	0.1	to	0.9	0.2	to	1.0	0.2	to	0.8	0.2	to	0.6	0.1	to	0.5	0.2	to	1.0	0.2	to	0.9	0.2	to	0.9	0.2	to	0.9	0.1	To	0.8

Cross-Chapter Box CLIMATE (continued)

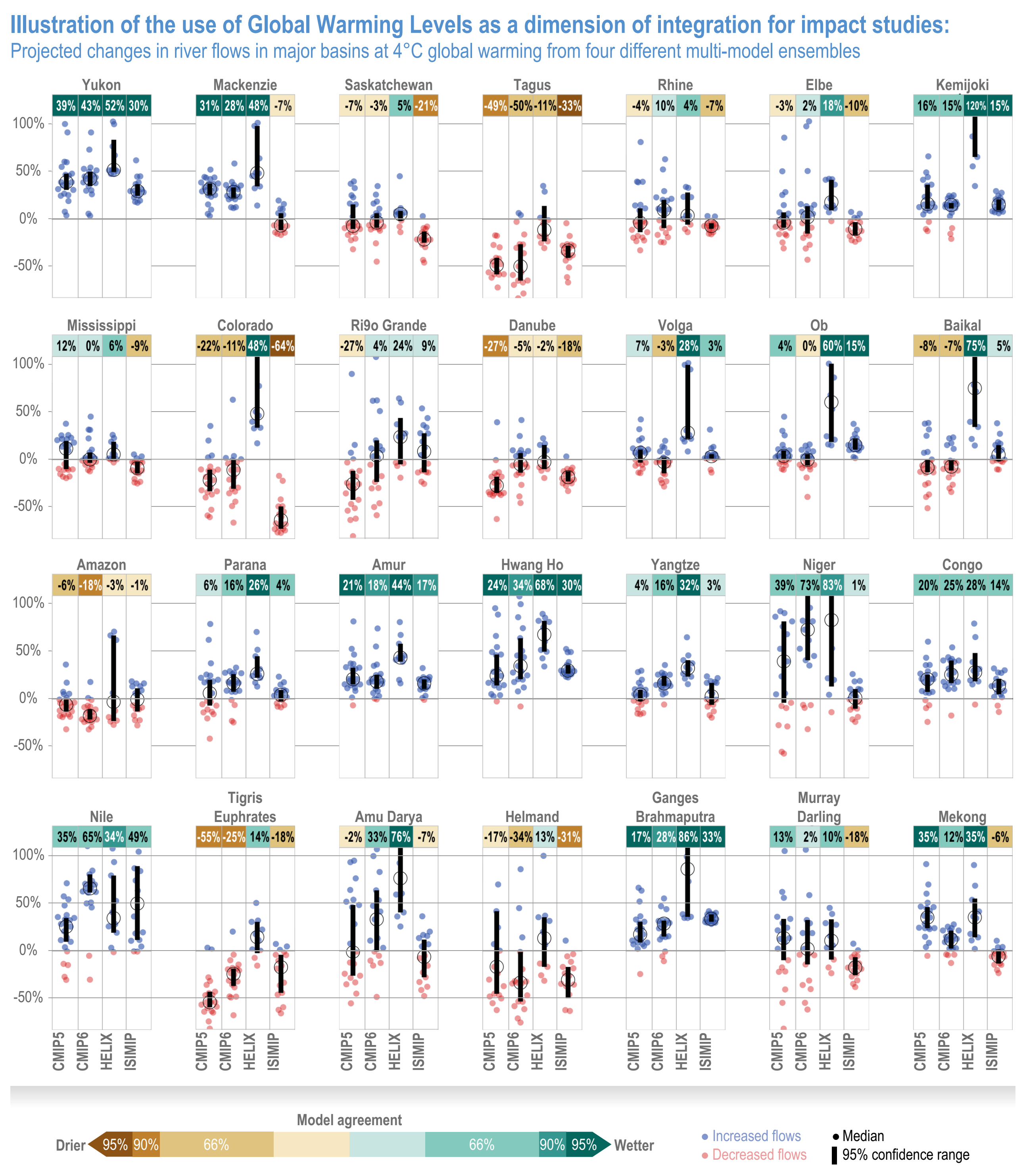


Figure Cross-Chapter Box CLIMATE.1 | Illustration of the use of global warming levels (GWLs) as a dimension of integration for impact studies: projected changes in river flows in major basins at 4°C global warming from four different multi-model ensembles. Results are shown for projected flow changes direct from Earth System Models (ESMs) in CMIP5 and CMIP6, for the Joint UK Land Environment Simulator (JULES) land surface model driven by meteorological outputs of the HadGEM3 and EC-Earth model in the High-End cLimate Impacts and eXtremes (HELIX) ensemble (Betts et al., 2018; Koutroulis et al., 2019), and nine hydrological models driven by a subset of five CMIP5 ESMs in the Inter-Sectoral Impacts Model Intercomparison Project (ISIMIP; Warszawski et al., 2014). Dots show results from individual models, blue for increased flows and red for decreased flows, black circles show the median for each ensemble, and black bars show the 95% confidence range in the median. See Figure 4.11 for further details.

Cross-Chapter Box CLIMATE (continued)

To contextualise reported impacts by warming level for the influence of other determinants of risk, where appropriate and feasible (e.g., level of exposure/vulnerability, level of adaptation, time period), common time periods for the past and future can be aligned with WGI's historical and projected time windows. Given differences in available literature, WGII chapters and CCPs (cross-chapter papers) contextualise impacts with respect to exposure, vulnerability and adaptation as appropriate.

Common ranges for other 'climate' variables, such as minimum and maximum temperatures and regional climates, are available based on WGI projections. They are based on feasible combinations with GWLs taken into consideration using the WGI Interactive Atlas. Climate information translation may have been necessary within chapters for mapping the WGII literature and assessments of the common climate dimensions. WGII's climate impacts literature is based primarily on climate projections around AR5 and earlier or assumed temperature levels, though some recent impacts literature uses newer climate projections based on the CMIP6 exercise. Thus, it was important to be able to map climate variable levels to climate projections of different vintages and vice versa and adjust variables, when possible, to a common reference year. WGII chapters and CCPs only provide climate impact information for the common climate dimensions that their literature supports and where there is sufficient evidence.

Interpretation of the update in projected time of reaching 1.5°C global warming from SR1.5 to AR6

In an assessment using multiple lines of evidence, including models, observational constraints and improved understanding of climate sensitivity, WGI project a central estimate of the 20-year average warming crossing the 1.5°C GWL in the early 2030s in all scenarios assessed, except SSP5–8.5 (Lee et al., 2021). This is about 10 years earlier than the midpoint of the likely range (2030–2052) assessed in SR1.5, which assumed continuation of the observed warming rate reported at that time. However, this does not imply that the projected impacts of 1.5°C will be reached 10 years earlier, because roughly half of the 10-year difference is a result of updating the diagnosed historical rate of warming due to methodological advances, new datasets and other improvements (Gulev et al., 2021). The other half of the 10-year difference arises because, for central estimates of climate sensitivity, most scenarios show stronger warming over the near term than was assessed as 'current' in SR1.5 (*medium confidence*).

The revised historical warming rate does not necessarily contribute to a change in timing of estimated impacts. It depends on how impacts are calculated relative to climate. Because the revised historical warming results in a redefinition of the 1.5°C GWL relative to the modern time period (1995–2014) rather than a different level of overall change (Figure Cross-Chapter Box CLIMATE.2 in Chapter 1), impacts assessed relative to the modern time period are unaffected. There are, in effect 'old' and 'new' definitions of the 1.5°C GWL with different levels of impacts, and the impacts assessed for the 'old' 1.5°C GWL now apply to a different level of global warming. However, the timing of impacts assessed relative to pre-industrial (e.g., aggregate economic impact estimates), are affected and we are closer to impact levels associated with 1.5°C and 2°C.

To illustrate with a worked example: in SR1.5, the historical warming between 1850–1900 and the modern period of 2006–2015 was assessed as 0.87°C, implying that the 1.5°C GWL would be accompanied by impacts associated with 0.63°C warming from the modern period. However, AR6 WGI (Gulev et al., 2021) revised the assessment of warming between 1850–1900 and 2006–2015 to 0.94°C, implying that the 1.5°C GWL would be accompanied by a slightly lower level of impacts associated with only 0.56°C warming from the modern period. So, while the redefined 1.5°C GWL would be reached earlier, it would also be accompanied by a lower level of impacts (Figure Cross-Chapter Box CLIMATE.2 in Chapter 1). The impacts associated with the 'old' 1.5°C GWL would now be seen at 1.57°C global warming relative to 1850–1900, reached at the time of the 'old' 1.5°C GWL, if the same future level of warming were to be used as in SR1.5.

However, in addition to this redefinition of the historical warming rate, the assessed future warming in AR6 is also slightly faster than the continuation of reported recent warming used in SR1.5. This means that both the 'old' and 'new' 1.5°C GWLs are projected to be reached earlier than they would have been using the SR1.5 method. This and the revised historical warming diagnosis contribute approximately equally to the assessment of 1.5°C global warming being reached about 10 years earlier than projected in SR1.5.

Central estimates of impacts associated with a specifically defined 1.5°C GWL could therefore be considered to be projected to be reached approximately 5 years earlier than implied by SR1.5. However, uncertainties in regional climate responses at a given GWL are large (Cross-Chapter Box CLIMATE in Chapter 1, Table CLIMATE.3a) and natural climate variability occurs in parallel with ongoing warming, so the potential for impacts higher than central estimates could be a more urgent consideration for risk assessments and adaptation planning than the earlier projected timing of reaching 1.5°C (*high confidence*). It should also be noted that individual years may exceed 1.5°C above 1850–1900 sooner, but this is not the same as exceedance of the 1.5°C GWL which refers to the 20-year mean.

Cross-Chapter Box CLIMATE (continued)

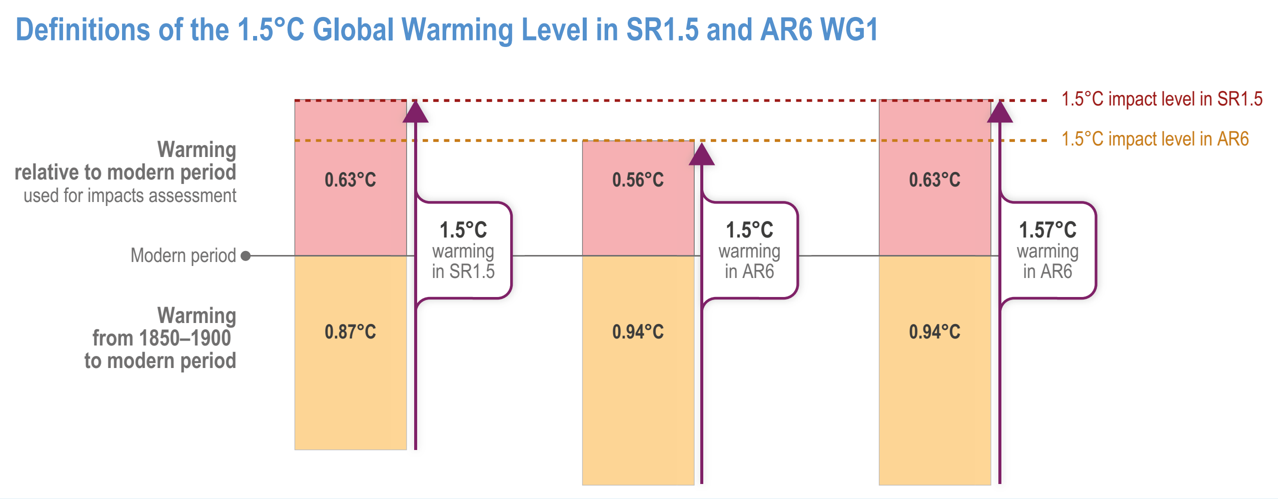


Figure Cross-Chapter Box CLIMATE.2 | Definitions of the 1.5°C global warming level (GWL) in SR1.5 (IPCC, 2018b) and AR6 WGI (IPCC, 2021a). GWLs are defined relative to 1850–1900 but impacts at the GWL are typically assessed in association with warming relative to a modern period 1995–2014, which in SR1.5 was 2006–2015. Revised assessment of the historical warming between 1850–1900 and the modern period (0.87°C in SR1.5 to 0.94°C in AR6) has the effect of slightly reducing the warming between the modern period and the 1.5°C GWL (0.63°C in SR1.5 to 0.56°C in AR6), and the impacts at the GWL previously defined as 1.5°C in SR1.5 now occur at 1.57°C global warming with the AR6 definition. Warming values are central estimates. Heights of the bars are not to scale.

Cross-Working Group Box ATTRIBUTION | Attribution in the IPCC Sixth Assessment Report

Authors: Pandora Hope (Australia), Wolfgang Cramer (France/Germany), Maarten van Aalst (Netherlands), Greg Flato (Canada), Katja Frieler (Germany), Nathan Gillett (Canada/UK), Christian Huggel (Switzerland), Jan Minx (Germany), Friederike Otto (UK /Germany), Camille Parmesan (France/ UK /USA), Joeri Rogelj (UK /Belgium), Maisa Rojas (Chile), Sonia I. Seneviratne (Switzerland), Aimee Slangen (the Netherlands), Daithi Stone (New Zealand), Laurent Terray (France), Robert Vautard (France), Xuebin Zhang (Canada)

Introduction

Changes in the climate system are becoming increasingly apparent, as are the climate-related impacts on natural and human systems. Attribution is the process of evaluating the contribution of one or more causal factors to such observed changes or events. Typical questions addressed by the IPCC are, for example: 'To what degree is an observed change in global temperature induced by anthropogenic GHG and aerosol concentration changes or influenced by natural variability?' or 'What is the contribution of climate change to observed changes in crop yields that are also influenced by changes in agricultural management?' Changes in the occurrence and intensity of extreme events can also be attributed, addressing questions such as: 'Have human GHG emissions increased the likelihood or intensity of an observed heat wave?'

This Cross-Working Group Box briefly describes why attribution studies are important. It also describes some new developments in the methods used and provides recommendations for interpretation.

Attribution studies serve to evaluate and communicate linkages associated with climate change, for example: between the human-induced increase in GHG concentrations and the observed increase in air temperature or extreme weather events (WGI Chapters 3, 10 and 11); or between observed changes in climate and changing species distributions and food production (e.g., Verschuur et al., 2021; WGII Chapter 2 and others, summarised in Chapter 16) or between climate change mitigation policies and atmospheric GHG concentrations (WGI Chapter 5; WGIII Chapter 14). As such, they support numerous statements made by the IPCC (IPCC, 2013; IPCC, 2014c; WGI Section 1.3, Appendix 1A).

Attribution assessments can also serve to monitor mitigation and assess the efficacy of applied climate protection policies (e.g., Nauels et al., 2019; Banerjee et al., 2020; WGI Section 4.6.3), inform and constrain projections (Gillett et al., 2021; Ribes et al., 2021; WGI Section 4.2.3) or inform loss and damages estimates and potential climate litigation cases by estimating the costs of climate change (Huggel et al., 2015; Marjanac et al., 2017; Frame et al., 2020). These findings can thus inform mitigation decisions, as well as risk management and adaptation planning (e.g., Climate & Development Knowledge Network, 2017).

Steps towards an attribution assessment

The unambiguous framing of what is being attributed to what is a crucial first step for an assessment (Easterling et al., 2016; Hansen et al., 2016; Stone et al., 2021), followed by the identification of the possible and plausible drivers of change and the development of a hypothesis or theory for the linkage (see Figure ATTRIBUTION.1 in Chapter 1). The next step is to clearly define the indicators of the observed change or event and note the quality of the observations. There has been significant progress in the compilation of fragmented and distributed observational data, broadening and deepening the data basis for attribution research (Poloczanska et al., 2013; Ray et al., 2015; Cohen et al., 2018; WGI Section 1.5). The quality of the observational record of drivers should also be considered (e.g., volcanic eruptions: WGI Section 2.2.2). Impacted systems also change in the absence of climate change. This baseline and its associated modifiers such as agricultural developments or population growth need to be considered, alongside the exposure and vulnerability of people depending on these systems.

There are many attribution approaches, and several methods are detailed below. In physical and biological systems, attribution often builds on the understanding of the mechanisms behind the observed changes and numerical models are used, while in human systems other methods of evidence-building are employed. Confidence in the attribution can be increased if more than one approach is used and the model is evaluated as fit for purpose (Hegerl et al., 2010; Vautard et al., 2019; Otto et al., 2020a; Philip et al., 2020; WGI Section 1.5). Finally, appropriate communication of the attribution assessment and the accompanying confidence in the result is needed (e.g., Lewis et al., 2019).

Attribution methods

Attribution of changes in atmospheric GHG concentrations to anthropogenic activity

AR6 WGI Chapter 5 (Canadell et al., 2021) presents multiple lines of evidence that unequivocally establish the dominant role of human activities in the growth of atmospheric CO_2, including through analysing changes in atmospheric carbon isotope ratios and the atmospheric

Cross-Working Group Box ATTRIBUTION (continued)

O_2:N_2 ratio (WGI Section 5.2.1.1, Canadell et al., 2021). Decomposition approaches can be used to attribute emissions underlying those changes to various drivers such as population, energy efficiency, consumption or carbon intensity (Hoekstra and van den Bergh, 2003; Raupach et al., 2007; Rosa and Dietz, 2012). Combined with attribution of their climate outcomes, the attribution of the sources of GHG emissions can inform the attribution of anthropogenic climate change to specific countries or actors (Matthews, 2016; Otto et al., 2017; Skeie et al., 2017; Nauels et al., 2019) and, in turn, inform discussions on fairness and burden sharing (WGIII Chapter 14).

Attribution of observed climate change to anthropogenic forcing

Changes in large-scale climate variables (e.g., global mean temperature) have been reliably attributed to anthropogenic and natural forcings (e.g., Hegerl et al., 2010; Bindoff and et al., 2014; WGI Section 1.3.4). The most established method is to identify the 'fingerprint' of the expected space–time response to a particular climate forcing agent such as the concentration of anthropogenically induced GHGs or aerosols, or natural variation of solar radiation. This technique disentangles the contribution of individual forcing agents to an observed change (e.g., Gillett et al., 2021). New statistical approaches have been applied to better account for internal climate variability and the uncertainties in models and observations (e.g., Naveau et al., 2018; Santer et al., 2019; WGI Section 3.2). There are many other approaches, for example, global mean sea level change has been attributed to anthropogenic climate forcing by attributing the individual contributions from, for example, glacier melt or thermal expansion, while also examining which aspects of the observed change are inconsistent with internal variability (WGI Sections 3.5.2; 9.6.1.4).

Specific regional conditions and responses may simplify or complicate attribution on those scales. For example, some human forcings, such as regional land use change or aerosols, may enhance or reduce regional signals of change (Lejeune et al., 2018; Undorf et al., 2018; Boé et al., 2020; Thiery et al., 2020; see also WGI Sections 10.4.2; 11.1.6; 11.2.2). In general, regional climate variations are larger than the variations in global mean climate, adding additional uncertainty to attribution (e.g., in regional sea level change, WGI Section 9.6.1). These statistical limitations may be reduced by 'process-based attribution', focusing on the physical processes known to influence the response to external forcing and internal variability (WGI Section 10.4.2).

Attribution of weather and climate events to anthropogenic forcing

New methods have emerged since AR5 to attribute the change in likelihood or characteristics of weather or climate events or classes of events to underlying drivers (National Academies of Sciences, 2016; Stott et al., 2016; Jézéquel et al., 2018; Wehner et al., 2019; Wang et al., 2020; WGI Sections 10.4.1; 11.2.2). Typically, historical changes, simulated under observed forcings, are compared to a counterfactual climate simulated in the absence of anthropogenic forcing. Another approach examines facets of the weather and thermodynamic status of an event through process-based attribution (Hauser et al., 2016; Shepherd et al., 2018; Grose et al., 2020; WGI Section 10.4.1; WGI Chapter 11). Events where attributable human influences have been found include hot and cold temperature extremes (including some with widespread impacts), heavy precipitation, and certain types of droughts and tropical cyclones (e.g., Vogel et al., 2019; Herring et al., 2021; WGI Section 11.9). Event attribution techniques have sometimes been extended to 'end-to-end' assessments from climate forcing to the impacts of events on natural or human systems (Otto et al., 2017; examples in Table 16.1; Section 16.2).

Attribution of observed changes in natural or human systems to climate-related drivers

The attribution of observed changes to climate-related drivers across a diverse set of sectors, regions and systems is part of each chapter in the WGII contribution to the AR6 and is synthesised in WGII Chapter 16 (Section 16.2). The number of attribution studies on climate change impacts has grown substantially since AR5, generally leading to higher confidence levels in attributing the causes of specific impacts. New studies include the attribution of changes in socioeconomic indicators, such as economic damages due to river floods (e.g., Schaller et al., 2016; Sauer et al., 2021), the occurrence of heat-related human mortality (e.g., Vicedo-Cabrera et al., 2018; Sera et al., 2020) or economic inequality (e.g., Diffenbaugh and Burke, 2019).

Impact attribution covers a diverse set of qualitative and quantitative approaches, building on experimental approaches, observations from remote sensing, long-term *in situ* observations and monitoring efforts, teamed with LK, process understanding and empirical or dynamical modelling (Section 16.2; Stone et al., 2013; Cramer et al., 2014). The attribution of a change in a natural or human system (e.g., wild species, natural ecosystems, crop yields, economic development, infrastructure or human health) to changes in climate-related systems (i.e., climate and ocean acidification, permafrost thawing or sea level rise) requires accounting for other potential drivers of change, such as technological

Cross-Working Group Box ATTRIBUTION (continued)

and economic changes in agriculture affecting crop production (Hochman et al., 2017; Butler et al., 2018), changes in human population patterns and vulnerability affecting flood or wildfire induced damages (Huggel et al., 2015; Sauer et al., 2021), or habitat loss driving declines in wild species (IPBES, 2019b). These drivers are accounted for by estimating a baseline condition that would exist in the absence of climate change. The baseline might be stationary and be approximated by observations from the past, or it may change over time and be simulated by statistical or process-based impact models (Section 16.2; Cramer et al., 2014). Assessment of multiple independent lines of evidence, taken together, can provide rigorous attribution when more quantitative approaches are not available (Parmesan et al., 2013). These include palaeodata, physiological and ecological experiments, natural 'experiments' from very long-term datasets indicating consistent responses to the same climate trend/event and 'fingerprints' in species' responses that are uniquely expected from climate change (e.g., poleward range boundaries expanding and equatorial range boundaries contracting in a coherent pattern worldwide, Parmesan and Yohe, 2003). Meta-analyses of species/ecosystem responses, when conducted with wide geographic coverage, also provide a globally coherent signal of climate change at an appropriate scale for attribution to anthropogenic climate change (Parmesan and Yohe, 2003; Parmesan et al., 2013).

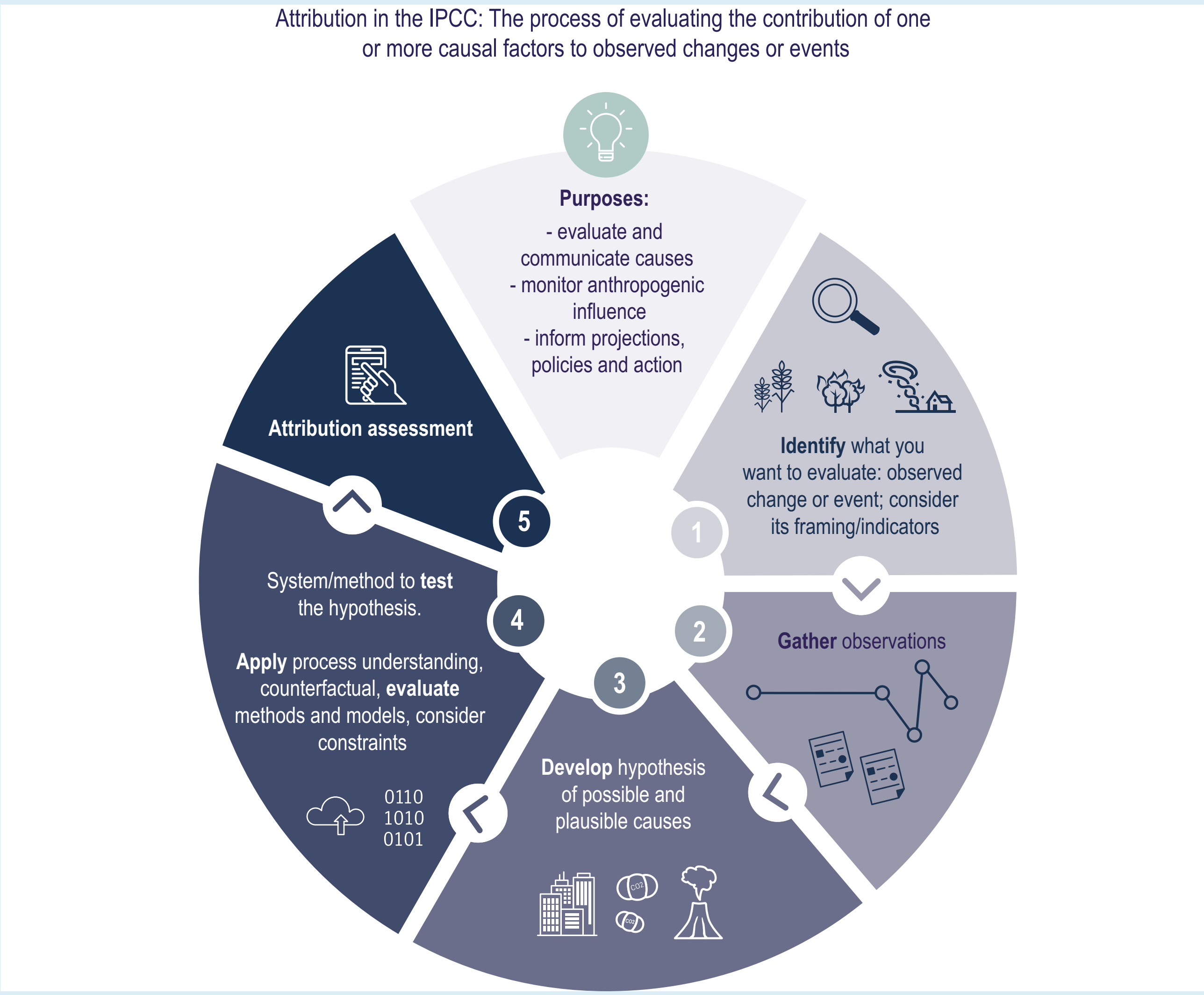


Figure Cross-Working Group Box ATTRIBUTION.1 | Schematic of the steps to develop an attribution assessment, and the purposes of such assessments. Methods and systems used to test the attribution hypothesis or theory include model-based fingerprinting, other model-based methods, evidence-based fingerprinting, process-based approaches, empirical or decomposition methods and the use of multiple lines of evidence. Many of the methods are based on the comparison of the observed state of a system to a hypothetical counterfactual world that does not include the driver of interest to help estimate the causes of the observed response.

Impact attribution does not always involve attribution to anthropogenic climate forcing. However, a growing number of studies include this aspect (e.g., Diffenbaugh and Burke, 2019, for the attribution of economic inequality between countries; Frame et al., 2020, for the attribution of damages induced by Hurricane Harvey; or Schaller et al., 2016, for flood damages).

Cross-Chapter Box PALEO | Vulnerability and Adaptation to Past Climate Changes

Authors: Wolfgang Kiessling (Germany, Chapter 3, Cross-Chapter Paper 1), Timothy A. Kohler (USA, Chapter 14), Wolfgang Cramer (France, Chapter 1, Cross-Chapter Paper 4), Gusti Anshari (Indonesia, Chapter 2), Jo Skeie Hermansen (Norway, CA Chapter 1), Darrell S. Kaufman (USA, WG 1, Chapter 2), Guy Midgley (South Africa, Chapter 16), Nussaïbah Raja (Mauritius, CA Chapter 3), Daniela N. Schmidt (UK/ Germany, Chapter 13), Nils Chr. Stenseth (Norway, Chapter 1), Sukumar Raman (India, Chapter 1)

Understanding how Earth's biota have responded to past climate dynamics is essential to understanding current and future climate-related risks, as well as the adaptive capacity and vulnerabilities of ecosystems and the human livelihoods depending on them. Here we assess climate impacts on long geological time scales (Cross-Chapter Box PALEO in Chapter 1, Figure PALEO.1), as well as for the last 70 kyr of *Homo sapiens*' existence (Cross-Chapter Box PALEO in Chapter 1, Figure PALEO.2). Climate responses of natural and human systems are intertwined through the physiological limits of wild animals, livestock, plants and humans, subject to a slow evolutionary dynamic (Pörtner, 2021; Sections 2.6.1; 3.3).

Climate has always changed, often with severe effects on nature, including species loss

Observations provided by the historical, archaeological, and palaeontological records, together with paleoclimatic data, demonstrate that climatic variability has high potential to affect biodiversity and human society (*high confidence*). The evolution of the Earth's biota has been punctuated by global biodiversity crises often triggered by rapid warming (*high confidence*) (Figure PALEO.1; Bond and Grasby, 2017; Benton, 2018; Foster et al., 2018;). These so-called hyperthermal events were marked by rapid warming of >1°C, which coincided with global disturbances of the carbon and water cycles, and by reduced oxygen and pH in seawater (Foster et al., 2018; Clapham and Renne, 2019). Magnitudes of global temperature shifts in hyperthermal events were sometimes greater than those predicted for the current century but extended over longer periods of time. Rates inferred from paleo records that are coarsely resolved are inevitably lower than those from direct observations during recent decades, and caution must be exercised when describing the rate of recent temperature changes as unprecedented (Kemp et al., 2015). Mass extinctions, each with greater than 70% marine species extinctions, occurred when the magnitude of temperature change exceeded 5.2°C (Song et al., 2021), albeit species extinctions occurred at lower magnitudes of warming (*medium confidence*).

Adaptation options to rapid climate change are limited

Responses of biota to rapid climate change have included range shifts (*very high confidence*), phenotypic plasticity (*high confidence*), evolutionary adaptation (*medium confidence*), and species extinctions, including mass extinctions (*very high confidence*). While knowledge about the relative roles of these processes in promoting survival during times of climate change is still limited (Nogués-Bravo et al., 2018), they have influenced the evolutionary trajectories of species and entire ecosystems (*high confidence*), and also the course of human history (*medium confidence*). The combined ecological and evolutionary responses to ancient rapid warming events ranged from extinction of 81% of marine animal species and 70% of terrestrial tetrapod species on land at the end of the Permian period (~ 252 million years ago, Ma) (Smith and Botha, 2005; Stanley, 2016) to low rates of species extinctions but biome- and range shifts on land and in the ocean at the Palaeocene-Eocene Thermal Maximum (PETM, ~ 56 Ma) (Figure PALEO.1; Ivany et al., 2018; Fraser and Lyons, 2020; Huurdeman et al., 2021). Temperature and deoxygenation were key drivers of past biotic responses in the oceans (Gibbs et al., 2016; Penn et al., 2018; Section 3.3) (*high confidence*), whereas on land the interplay between temperature and precipitation is less well established in ancient hyperthermals (Frank et al., 2021) (*medium confidence*). Climate-driven extinction risk increased by up to 40% when a short-term climate change added to a long-term trend in the same direction, for example when a long-term warming trend was followed by rapid warming (Mathes et al., 2021).

Organismic traits associated with extinctions during ancient climate changes help identify present-day vulnerabilities and conservation priorities (Barnosky et al., 2017; Calosi et al., 2019; Reddin et al., 2020; Chapters 2; 3; Cross-Chapter Paper 1). Marine invertebrates and fishes are at greater extinction risk in response to warming than terrestrial ones because of reduced availability of thermal refugia in the sea (Pinsky et al., 2019) (*high confidence*). Terrestrial plants showed reduced extinction during past rapid warming compared to animals (*high confidence*), although they readily adjusted their ranges and reorganised vegetation types (Yu et al., 2015; Lindström, 2016; Heimhofer et al., 2018; Slater et al., 2019; Huurdeman et al., 2021).

Cross-Chapter Box PALEO (continued)

Population range shifts including migrations are common adaptations to climate changes across multiple time scales and ecological systems in the past and in response to current warming (*high confidence*). Poleward expansions and retractions (Reddin et al., 2018; Williams et al., 2018; Fordham et al., 2020) as well as migration upslope and downslope in response to warming and cooling were common adaptations (Ortega-Rosas et al., 2008; Iglesias et al., 2018;). During warming periods, diversity loss was common near the equator (*medium confidence*)(Kiessling et al., 2012; Kröger, 2017; Yasuhara et al., 2020), while diversity gains and forest expansion occurred in high latitudes (Brovkin et al., 2021). Comparison of contemporary shells and skeletons with historical collections in museums (Barnes et al., 2011) and the analysis of skeletons of long-lived organisms (Cantin et al., 2010) indicate significant climate-induced change in organismic growth rates today (*high agreement, medium confidence*).

Humankind has responded to regional climate variability within a narrow Holocene climatic envelope

Early human evolution (beginning ~2.1 Ma) occurred in a highly variable climate characterised by glacial-interglacial cycles. This variability may have favoured key hominin adaptations such as bipedality, increased brain size, complex sociality, and more diverse tools (Potts, 1998; Potts et al., 2020) (*medium confidence*), but extinctions of five species of *Homo* have also been attributed partly to climate change (Raia et al., 2020) (*low confidence*). The 'out-of-Africa' dispersal of anatomically modern humans may have been driven by climate variability (Timmermann and Friedrich, 2016; Tierney et al., 2017) (*medium confidence, low agreement*). Most late Pleistocene megafaunal extinctions are attributed to direct and indirect human impacts (Sandom et al., 2014), although some were likely accelerated by climate change (Wan and Zhang, 2017; Westaway et al., 2017; Carotenuto et al., 2018; Saltré et al., 2019) (*low confidence*).

The emergence of agriculture (~10.2 ka) in southwest Asia was associated with stable (within ±1°C global mean annual on multi-century time scale; WGI Chapter 2) warm and moist conditions (Richerson et al., 2001; Rohling et al., 2019; Palmisano et al., 2021). Variability in resource availability and agricultural production, entrained by climatic variability, is implicated in the disruption and decline of numerous past human societies (*medium confidence*) (d'Alpoim Guedes and Bocinsky, 2018; Cookson et al., 2019; Jones, 2019; Park et al., 2019). These crises are partially caused by regional climate anomalies including Holocene 'Rapid Climate Change Events' (Rohling et al., 2019) not visible in the globally averaged conditions shown in Figure PALAEO.2. Such anomalies affected human population size (Clark et al., 2019; Kuil et al., 2019; Riris and Arroyo-Kalin, 2019), health (Campbell and Ludlow, 2020) and social stability/conflict (Büntgen et al., 2011; Kohler et al., 2014), and triggered migrations (D'Andrea et al., 2011; Schwindt et al., 2016; Chiotis, 2018; Pei et al., 2018) or retarded them (Betti et al., 2020; FAQ 14.2). Populations have also been impacted by sea level change in coastal areas (Turney and Brown, 2007; Cross-Chapter Box SLR in Chapter 3).

Evidence for widespread droughts ~4.2 ka, lasting for several centuries in some regions, has been tentatively linked to declines of the Akkadian Empire (Weiss, 2017; Carolin et al., 2019), the Indus Valley (Giosan et al., 2018; Sengupta et al., 2020), and the Egyptian Old Kingdom and Yangtze River Valley (Ran and Chen, 2019). Deteriorating climates often exacerbate accumulating weaknesses in social systems to which population growth and urban expansion contribute (Knapp and Manning, 2016; Lawrence et al., 2021; Scheffer et al., 2021). The rather narrow climatic niche favoured by human societies over the last 6000 years is poised to move on the Earth's surface at speeds unprecedented in this time span (IPCC, 2021a), with consequences for human well-being and migration that could be profound under high-emission scenarios (Xu et al., 2020). This will overturn the long-lasting stability of interactions between humans and domesticated plants and animals as well as challenge the habitability for humans in several world regions (Horton et al., 2021) (*medium confidence*).

Cross-Chapter Box PALEO (continued)

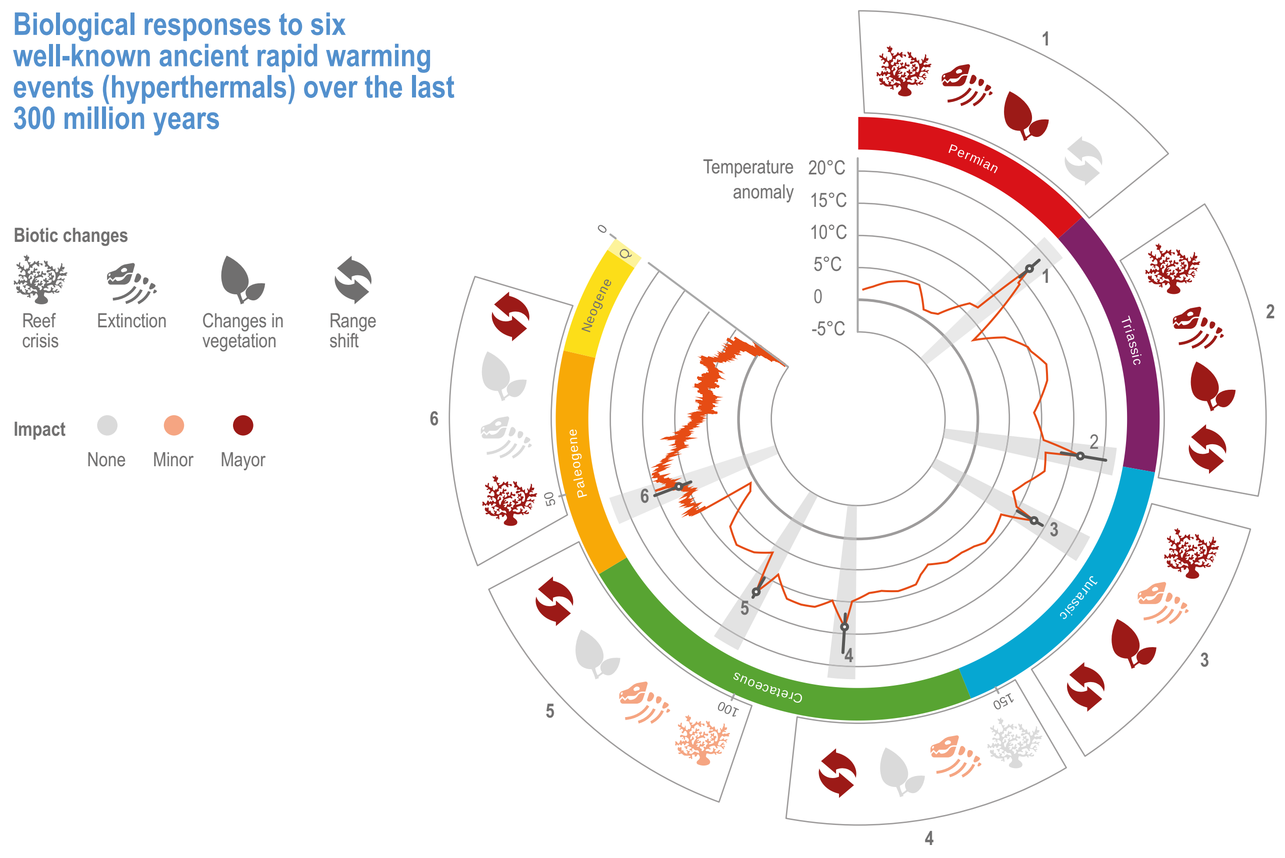


Figure Cross-Chapter Box PALEO.1 | Biological responses to six well-known ancient rapid warming events (hyperthermals) over the last 300 million years. Temperature anomalies (mean temperature difference to pre-industrial 1850–1900, solid orange curve) derived from climate modelling (300–66 Ma) (Haywood et al., 2019) and deep-sea proxy data (66–0.1 Ma) (Hansen et al., 2013). Temperature peaks underneath the grey bars indicate well-known hyperthermals with temperature anomalies derived from temperature-sensitive proxy data (Foster et al., 2018). Error bars indicate uncertainties in peak warming events (ranges in the literature). Insets show observed impacts to the biosphere. Q, Quaternary.

Climate change destroys unique natural archives and important cultural heritage sites

Climate change not only impacts past ecosystems and societies but also the remains they have left. The progressive loss of archaeological and historical sites and natural archives of paleo environmental data (WGI Chapter 2) constitutes often-overlooked impacts of climate change (Cross-Chapter Box SLR in Chapter 3; Anderson et al., 2017; Hollesen et al., 2018; Climate Change Cultural Heritage Working Group International, 2019). These archives include peat bogs and coastal archives lost to sea level rise, droughts and fires, degradation through permafrost thaw, and dissolution. The ancient cultural diversity documented by such sites is an important resource for future adaptation (Rockman and Hritz, 2020; Burke et al., 2021). Since many of these sites constitute anchors for IK, their loss is not just data lost to science, it also interrupts intergenerational transmission of knowledge (Green et al., 2009).

Cross-Chapter Box PALEO (continued)

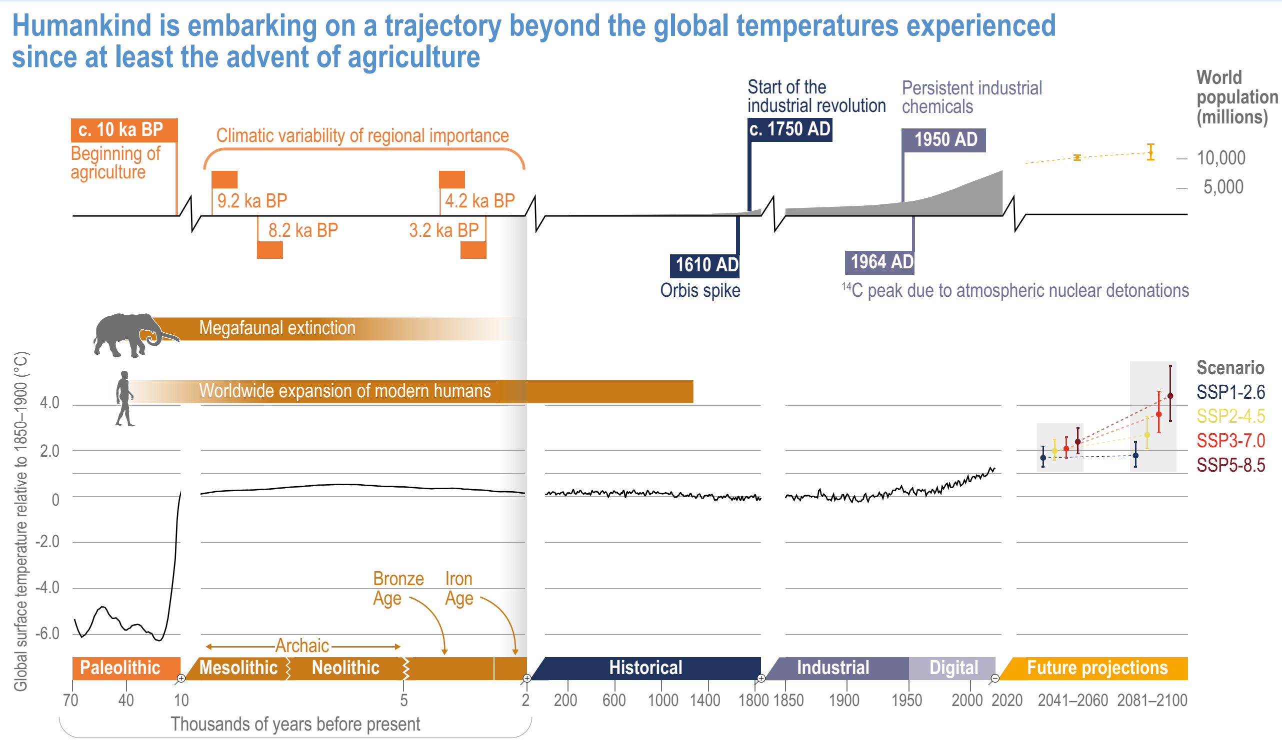


Figure Cross-Chapter Box PALEO.2 | Humankind is embarking on a trajectory beyond the global temperatures experienced since at least the advent of agriculture. Global surface temperature change for the last 70,000 years (relative to 1850–1900; data from WGI Chapter 2) alongside projections (with 5–95% range; WGI Chapter 4) and major events in human societies. Global climatic parameters do not always capture regional variability of importance to specific societies. The 'Orbis Spike' represents a pronounced dip in atmospheric CO_2 from the Law Dome ice core (Antarctica) (MacFarling Meure et al., 2006) marking the globalisation in biota and trade of the Columbian Exchange and population declines and afforestation in the Americas. This, and the 1964 ^{14}C peak, have been suggested as possible markers for the onset of the Anthropocene (Lewis and Maslin, 2015). Population trends from United Nations (2019).

Cross-Chapter Box ADAPT | Adaptation science

Authors: Johanna Nalau (Australia/Finland), Lauren Rickards (Australia), Tabea Lissner (Germany), Katharine J. Mach (USA), Lisa Schipper (Sweden/UK), Chandni Singh (India), William Solecki (USA), Adelle Thomas (Bahamas) and Edmond Totin (Benin)

High-level statements:

- Adaptation knowledge consists of a diverse set of sources including academic research, applied analysis, and practice and experience with projects and policy on the ground.
- Adaptation science encompasses both research 'on adaptation', documenting and analysing experiences of adaptation, and 'for adaptation', aiming to advance the planning and implementation of adaptation.

- The nature of adaptation research is diversifying and examines different approaches from local case studies to more global, transboundary, comparative and interactive perspectives, although critical conceptual and empirical gaps remain in defining effectiveness in adaptation and measuring adaptation progress.

This cross-chapter box complements the reviews of specific adaptation knowledge, content and progress described throughout WGII by providing a higher-level analysis of the shifting characteristics of and trends in **adaptation research** and its evolution over time.

The characteristics and diversity of adaptation knowledge

The knowledge base on adaptation has matured significantly since AR5. Whereas adaptation research was primarily academic during the 1990s and 2000s, it now includes a proliferation of on-the-ground experience of how to adapt to climate change, increasingly documented in reports and papers. Furthermore, academic research on adaptation has diversified significantly. Understanding the characteristics and diversity of this knowledge base is key for it to effectively inform decision making and action on adaptation.

Academic work on adaptation now spans an increasing number of disciplines and countries and is published across diverse academic outlets and disciplines, with 28.5% annual average increase in adaptation specific publications (Nalau and Verrall, 2021). This expands the range of considerations and perspectives within adaptation research and increases the challenge of identifying and synthesising all relevant research on adaptation in reviews or assessments (Berrang-Ford et al., 2015; Webber, 2016; Singh et al., 2020; Sietsma et al., 2021). Also, large bodies of research and knowledge exist that support climate adaptation ideas, theoretical development and practical implementation, but are not explicitly framed as climate change adaptation (Dupuis and Biesbroek, 2013; Biesbroek et al., 2018; Keskitalo and Preston, 2019a). Therefore, debates still emerge about what actually counts as 'adaptation' (Dupuis and Biesbroek, 2013), and what knowledge is being assessed and measured for this purpose.

IPCC assessment reports combine two complementary approaches to adaptation research: that which is 'on' or 'about' adaptation and that which is 'for adaptation'. Both are needed because research 'on adaptation' helpfully investigates the phenomenon and processes of adaptation (e.g., via analyses of others' adaptation practices and efforts), while research 'for adaptation' generates knowledge that can enable the planning and implementation of adaptation (e.g., action research as part of an adaptive capacity-building process) (Swart et al., 2014).

One of the contributions of research 'on adaptation' is to track and debate the broader trends, core characteristics and overall assumptions embedded in adaptation knowledge. This reflexive turn about the foundational assumptions is itself one emerging trend in adaptation research (e.g., Preston et al., 2013; Nalau et al., 2015; Juhola, 2016; Atteridge and Remling, 2017). This signals the influence of more social science in adaptation research and increased awareness of the practical value of being transparent and critically reflective about the content, topics, frames and approaches that researchers use (Lacey et al., 2015; Nalau et al., 2021; Singh et al., 2021). For example, different conceptions of adaptation contribute to different definitions of 'adaptation success', different ideas about what 'effective' adaptation practice looks like and, thus, different conclusions about what is and is not working well (Berrang-Ford et al., 2019; Dilling et al., 2019; Magnan et al., 2020; Owen, 2020; Eriksen et al., 2021; Singh et al., 2021; Section 17.5.1.1). This diversity adds richness and options, but also poses challenges in constructing a conventional evidence base for decision and policymaking. Adaptation researchers are increasingly expected to offer clear and confident advice on adaptation success, yet are also increasingly aware of how context-specific and contested success is (see also Lacey et al., 2015 on ethics).

Grey literature on adaptation is also proliferating, typically authored by organisations funding and implementing adaptation. This literature often documents a range of adaptation strategies (Sections 9.8.3; 10.4.6.4; 14.4.3.3; 17.2.1.) and lived experiences of adaptation efforts, including helping give voice to marginalised groups, and highlighting the importance of IK and LK (Sections 4.7.5.4; 15.6.4; Box 9.2; Cross-

Cross-Chapter Box ADAPT (continued)

Chapter Box INDIG in Chapter 18; Nunn et al., 2016; Petzold et al., 2020). However, most of the lessons learned through implementation of adaptation projects and programmes are still not captured in academic or even grey literature and thus remain less systematically analysed. Crucially, the large gaps in documentation of adaptation knowledge mean that a lack of published evidence about a given issue does not necessarily reflect its absence in real life—a qualification about adaptation research that readers of AR6 should appreciate.

The evolution of adaptation research trends

In the 1990s, climate change adaptation was constrained as a specific topic of inquiry by the dominant focus on mitigation of GHG emissions and the related assumption that successful mitigation would render unnecessary the need for adaptation beyond what human and natural systems could inherently manage (Pielke, 1998; Schipper, 2006; Schipper and Burton, 2009). Several key developments in the 1990s included IPCC's 2nd report (1996) and the establishment of several key journals including *Climatic Change* (1978), *Mitigation and Adaptation Strategies to Global Change* (1996) and the *Global Environmental Change* journal that strengthened more dedicated focus on climate change related research.

Many foundational papers on key concepts central to adaptation were published in the 1990s and early 2000s onwards (Burton, 1992; Smit, 1993; Smithers and Smit, 1997; Parry and Carter, 1998; Fankhauser et al., 1999; Smit et al., 1999; Pittock and Jones, 2000; Klein, 2003; Adger et al., 2005), while adaptation began to gain more prominence in IPCC's 3rd assessment (2001) and 4th assessment (2007). For example, the Canada Climate Programme report (Smit, 1993) set out many of the principles of adaptation and was highly influential charting these concepts in IPCC's 3rd Assessment Report (Schipper and Burton, 2009). These papers and IPCC reports remain key foundations of climate adaptation science literature (Nalau and Verrall, 2021).

Helping to differentiate adaptation from mitigation during this period was a focus on theoretical principles and a framing of adaptation as local and context specific, in contrast to mitigation's global character (Nalau et al., 2015; Westoby et al., 2020), leading to locally oriented adaptation research and practice, including the rise of community-based adaptation (Kirkby et al., 2017). Since AR5, however, adaptation has extended beyond the local, recognising the 'borderless' character of many climate change risks and vulnerabilities (Benzie and Persson, 2019) and framing adaptation and global adaptation governance as a global public good (Persson, 2019). Encompassing this expanded scale is challenging for adaptation research compared to treating adaptation as a local issue, which fits more easily with social research methods. Adaptation now works across scales (Biesbroek et al., 2013; Dzebo and Stripple, 2015; Keskitalo and Preston, 2019a) and attends simultaneously to both the opportunities and risks arising from climate change (Juhola, 2016; Keskitalo and Preston, 2019a). This suggests that empirical adaptation research should incorporate multi-scalar research designs and methods.

A strong focus has been and remains on case studies of adaptation practice, but adaptation science literature reviews have become common. Recent systematic reviews cover topics such as adaptation effectiveness (Owen, 2020), public participation and engagement (Hügel and Davies, 2020), the role of LK (Klenk et al., 2017), adaptive capacity (Mortreux and Barnett, 2017; Siders, 2019a; Mortreux et al., 2020), evolution of adaptation science (Nalau and Verrall, 2021), empirical adaptation research in the Global South (Vincent and Cundill, 2021), how cities are adapting (Reckien et al., 2018), how decisions can be made (Siders and Pierce, 2021), IK (Petzold et al., 2020) and SIDS (Robinson, 2020). Review papers have developed common methodologies for how to undertake robust reviews in adaptation research (Berrang-Ford et al., 2015; Biesbroek et al., 2018; Lesnikowski et al., 2019a; Singh et al., 2020), and noted an existing imbalance as the majority of the literature still originates from the Global North compared to Global South (Robinson, 2020; Nalau and Verrall, 2021; Sietsma et al., 2021).

At the same time, adaptation research is also challenged by increasing attention to transformational adaptation, which refers to fundamental changes going beyond existing practices, including new approaches to adaptation decision making (Section 1.5). Whereas AR5 noted transformational adaptation as an area of future research (Klein et al., 2014b), it has continued to grow in profile since then. Rather than a future or fringe consideration—for example, an extreme action necessitated by the limits of incremental adaptation— transformational adaptation is increasingly an option that decision makers are considering today. This increasing attention to transformational adaptation is driven by a growing recognition of climate risks and impacts, as well as the need for urgent, systemic action as laid out in the IPCC's recent special reports (IPCC, 2018c). Yet what incremental and transformational adaptation look like, how they relate in practice and how to appropriately choose incremental or transformational options is uncertain and increasingly debated (Section 17.2.2.3; Termeer et al., 2016; Few et al., 2017; Vermeulen et al., 2018; Magnan et al., 2020; Wilson et al., 2020). One of the main challenges is now to generate empirical evidence and policy relevant insights on transformational adaptation (e.g., Jakku et al., 2016). Transformative approaches are especially being discussed in the context of COVID-19 (Schipper et al., 2020; Cross-Chapter Box COVID in Chapter 7).

Cross-Chapter Box ADAPT (continued)

Increasingly reflective adaptation research

Another characteristic of recent adaptation research is a stronger focus on ethics, justice and power (Byskov et al., 2021; Coggins et al., 2021; Eriksen et al., 2021; Singh et al., 2021). Researchers and practitioners are increasingly impatient to address the root causes of vulnerability and use inclusive climate adaptation processes to generate effective adaptation responses for marginalised and misrecognised groups (Tschakert et al., 2013; Eriksen et al., 2015; Scoones et al., 2015; Gillard et al., 2016; Wisner, 2016). Increasingly ambitious, normative adaptation research often challenges technological solutions that simply reinforce the existing *status quo* (Nightingale et al., 2019, p. 2) and calls for 'socially just pathways for change'. Here work on adaptation overlaps with mitigation, transitions and other large-scale social change, encouraging the move towards more systemic, integrated approaches that discern between options according to multiple criteria (Goldman et al., 2018).

Fundamental questions about equity and justice in adaptation include gender and intersectionality (see Cross-Chapter Box GENDER in Chapter 18; Section 1.4.1.1; Chapter 18;) and broader critiques of who participates in processes of adaptation planning and implementation, who receives investments, who and what benefits from them, who makes key decisions regarding adjustments through time (Taylor et al., 2014; Boeckmann and Zeeb, 2016; Nightingale et al., 2019; Pelling and Garschagen, 2019; Byskov et al., 2021; Eriksen et al., 2021) and how climate justice intersects with other justice agendas. Attention is also turning to relations and tensions between different adaptation approaches, scales, constraints, limits, losses, enablers and outcomes (Barnett et al., 2015; Pelling et al., 2015; Mechler and Schinko, 2016; Crichton and Esteban, 2017; Gharbaoui and Blocher, 2017; Deshpande et al., 2018; McNamara and Jackson, 2019). Evident here is an ongoing, serious knowledge gap around the long-term repercussions of adaptation interventions. There is growing awareness of the need to address the potential for maladaptation (Sections 1.4.2.4; 5.13.3; 15.5.1; 17.5.2; Chapter 4). Concerns about maladaptation have led to renewed calls to open the 'black box' of decision making to examine the influence of power relationships, politics and institutional culture (Biesbroek et al., 2013; Eriksen et al., 2015; Goldman et al., 2018), including the power–adaptation linkage itself (Woroniecki et al., 2019), external factors outside the decision-making process (Eisenack et al., 2014) and the influence of leadership on adaptation processes and outcomes (Meijerink et al., 2014; Vignola et al., 2017).

All of these developments indicate that adaptation research is not only more reflexive about some of its central assumptions, methodologies and tools (Biesbroek et al., 2013; Conway and Mustelin, 2014; Nalau et al., 2015; Nightingale, 2015a; Porter et al., 2015; Eriksen et al., 2015; Lubell and Niles, 2019; Woroniecki et al., 2019; Singh et al., 2021), but also cognisant of the need to critically consider its underpinning goals, purpose and impact in the world.

Cross-Chapter Box EXTREMES | Ramifications of Climatic Extremes for Marine, Terrestrial, Freshwater and Polar Natural Systems

Authors: Rebecca Harris (Australia, Chapter 2, CCP3), Philip Boyd (Australia, Chapter 3), Rita Adrian (Germany, Chapter 2), Jörn Birkmann (Germany, Chapter 8), Sarah Cooley (USA, Chapter 3), Simon Donner (Canada, Chapter 3), Mette Mauritzen (Norway, Chapter 3), Guy Midgley (South Africa, Chapter 16); Camille Parmesan (France/USA/UK, Chapter 2), Dieter Piepenburg (Germany, Chapter 13, CCP6), Marie-Fanny Racault (UK/France, Chapter 3), Björn Rost (Germany, Chapter 3, CCP6), David Schoeman (Australia, Chapter 3), Stavana E. Strutz (USA/Chapter 2), Maarten van Aalst (the Netherlands, Chapter 16).

Introduction

Increases in the frequency and magnitudes of extreme events, attributed to anthropogenic climate change by WGI (IPCC, 2021a), are now causing profound negative effects across all realms of the world (marine, terrestrial, freshwater and polar) (*medium confidence*) (Fox-Kemper et al., 2021; Seneviratne et al., 2021) (Sections 2.3.1, 2.3.2, 2.3.3.5, 2.4.2.2, Chapter 3, Chapters 9–12, this report). Changes to population abundance, species distributions, local extirpations, and global extinctions are leading to long-term, potentially irreversible shifts in the composition, structure and function of natural systems (*medium confidence*) (Frolicher and Laufkotter, 2018; Harris et al., 2018a; Maxwell et al., 2019; Smale et al., 2019). These effects have widespread ramifications for ecosystems and the services they provide—physical habitat, erosion control, carbon storage, nutrient cycling and water quality—with knock-on effects for tourism, fisheries, forestry and other natural resources (2.4.3, 2.4.4, 2.5.1, 2.5.2, 2.5.3, 2.5.4) (Kaushal et al., 2018; Heinze et al., 2021; Pörtner et al., 2021).

Increasingly, the magnitude of extreme events is exceeding the values projected for mean conditions for 2100, regardless of emissions scenario (Figure Cross-Chapter Box EXTREMES.1). This has collapsed the timeline that organisms and natural communities have to acclimate or adapt to climate change (*medium confidence)*. Consequently, rather than having decades to identify, develop and adopt solutions, actions to build resilience and assist recovery following extreme events are required quickly if they are to be effective.

Recent extremes highlight the characteristics that enable natural systems to resist or recover from events, helping natural resource managers to develop solutions to improve the resilience of natural communities and identify the limits to adaptation (Bergstrom et al., 2021).

Marine Heat Waves

Consensus is emerging that anthropogenic climate change has significantly increased the likelihood of recent marine heat waves (MHWs) (*medium confidence*) (Oliver et al., 2018; Fox-Kemper et al., 2021). A widespread MHW occurred in the northeast Pacific in 2013–2015, with upper ocean temperature anomalies of up to 6.2°C relative to 2002–2012 (Gentemann et al., 2017). This event, termed the 'Blob', enhanced surface water stratification, decreasing nutrient supply, primary and community production and leading to widespread changes to open ocean and coastal ecosystems, with geographical shifts of key species across trophic levels, mass strandings of marine mammals, seabird mortalities and the closure of commercially important fisheries (Cavole et al., 2016; Piatt et al., 2020). The MHW reappeared in 2019 ('Blob 2.0') (Amaya et al., 2020), with similarly high temperature anomalies extending from Alaska to California, but the ecological effects of this event are expected to differ because the Blob originated in winter, and Blob2.0 intensified in summer (Amaya et al., 2020). Modelling suggests rapid shifts in the geographic distributions of important fish species in response to MHWs (Cheung and Frolicher, 2020), with projected decreased biomass and distributional shifts of fish at least four times faster and larger than the effects of decadal-scale mean changes throughout the 21st century under RCP8.5 (*high confidence*) (Cheung and Frolicher, 2020). MHWs can also dramatically increase CH_4 emissions from oceans, a significant positive feedback to global warming (see also Chapter 3, this report) (Borges et al., 2019).

The Arctic region is warming more than twice as fast as the global mean, and polar organisms and ecosystems are likely to be particularly vulnerable to heat waves due to their specific thermal niches and physiological thresholds and also the lack of poleward 'refugia' (*high confidence*). The consequences of MHWs are exacerbated by concomitant sea ice melting and the freshening of surface waters, leading to secondary effects due to osmotic stress and failing pH homeostasis. Since sea ice-associated organisms are often critical components of polar food chains, cascading effects up to the top predators are expected. In 2015–2016, a MHW occurred in the Gulf of Alaska/Bering Sea (Walsh et al., 2018) which was unprecedented in terms of surface temperatures and ocean heat content, geographical extent, depth range and persistence, impacting the entire marine food web. Persistent warming favoured some phytoplankton species and triggered one of the largest algal blooms recorded in this region, with concomitant oyster farm closures due to uncommon paralytic shellfish-poisoning events (Walsh et al., 2018). There were also massive die-offs of common guillemots (*Uria aalge*) and puffins (*Fratercula cirrhata)*, attributed to starvation resulting from warming-induced effects on food supply (Jones et al., 2019). A 2017 survey found a 71% decline in the abundance of Pacific cod (*Gadus macrocephalus*) since 2015, likely due to an increase in metabolic demand and reduced prey supply during the MHWs (Barbeaux et al., 2020).

Cross-Chapter Box EXTREMES (continued)

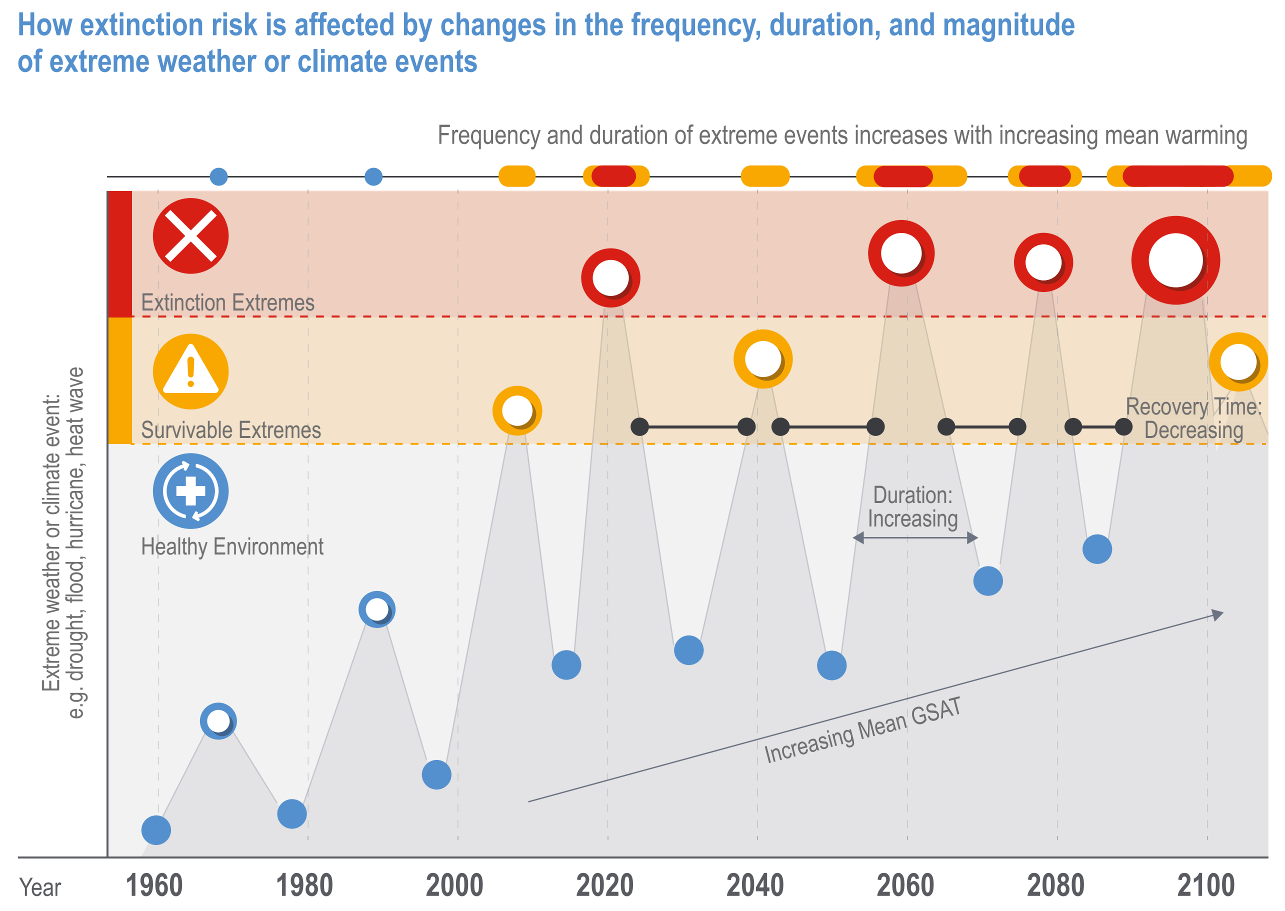


Figure Cross-Chapter Box EXTREMES.1 | A conceptual illustration of how extinction risk is affected by changes in the frequency, duration and magnitude of extreme weather or climate events (e.g,. drought, fire, flood and heat waves). Many organisms have adapted to cope with long- and short-term climate variability, but as the magnitude and frequency of extreme events increases, superimposed on the long-term climate trend, the threshold between survivable extreme weather events (yellow) and extremes that carry a high risk of causing population or species extinctions (red) is crossed more frequently. This can lead to local extinction events with insufficient time between to enable recovery, resulting in long-term, irreversible changes to the composition, structure and function of natural systems. When the extreme event occurs over a large area relative to the distribution of a species (e.g., a hurricane impacting an island which is the only place a given species occurs), a single extreme event can drive the global extinction of a species.

Terrestrial Heat Waves

Heat waves are now regularly occurring that exceed the physiological thresholds of some species, including birds and other small endotherms such as flying foxes (*high confidence*) (Sections 2.4.2.2, 2.4.2.6). Heat waves in Australia, North America and southern Africa have caused mass mortality events due to lethal hyperthermia and dehydration (Saunders et al., 2011; Conradie et al., 2020; McKechnie et al., 2021), reducing fitness (du Plessis et al., 2012; Andrew et al., 2017; Sharpe et al., 2019; van de Ven et al., 2019; van de Ven et al., 2020), breeding success, and recruitment (Kennedy et al., 2013; Wiley and Ridley, 2016; Ratnayake et al., 2019) and affecting daily activity and geographic distributions (Albright et al., 2017). They also place enormous demands on wildlife management agencies and pose risks to human health (Welbergen et al., 2008).

Recent mortality events affected 14 species of bird and fruit bats (*Epomophorus wahlbergi*) in South Africa when maximum air temperatures exceeded 43–45°C in 2020 (McKechnie et al., 2021). Passerine birds seem more vulnerable to lethal hyperthermia, due to the relative inefficiency of panting to lose heat (McKechnie et al., 2021) and also their small size, as heat tolerance generally increases with body mass (McKechnie et al., 2021). Several mass mortality events of flying foxes (*Pteropus poliocephalus, P. alecto*) have occurred in eastern Australia when maximum air temperatures exceeded 42° (Welbergen et al., 2008). Nineteen such events occurred between 1994 and 2008, compared to three events prior to 1994. In January 2002, maximum temperatures exceeded the 30-year average mean daily maximum by up to 16.5° and killed >3500 individuals (Welbergen et al., 2008). In 2014, an estimated 45,500 flying foxes died in

Cross-Chapter Box EXTREMES (continued)

a single day, when average maximum temperatures were ≥8°C above average (Bureau of Meteorology, 2014). Drought compounds the impacts, as mortality increases when water availability is low (Welbergen et al., 2008; Mo and Roache, 2020; McKechnie et al., 2021).

Antarctica encountered its first recorded heat wave in 2020. Record high temperatures occurred in East Antarctica (Robinson et al., 2020), with a maximum (9.2°) temperature ~7° above the mean maximum, and minimum temperatures > 0°. Record high temperatures (18.3°) were also recorded in West Antarctica (Robinson et al., 2020). It is too soon to know the impact on polar life, but such abrupt heating is expected to have wide-ranging effects on biota, from flash-flooding and dislodgement of plants, to excess meltwater supplying moisture to arid polar ecosystems (Cross-Chapter Paper 6 Polar). Heat waves in Siberia in 2016, 2018 and 2020, with air temperature anomalies >6°, were associated with extensive wildfires, pest infestations and melting permafrost (Overland and Wang, 2021).

Freshwater Extremes

Heat waves, storms and floods affect the thermal regime and biogeochemical functioning of lakes and rivers (Woolway and Merchant, 2017; Vicente-Serrano et al., 2020). Extreme heat waves lead to abnormally high water temperatures (Till et al., 2019) and reduce the mixing of lakes (Woolway et al., 2021), causing a decrease in oxygen and deep-water oxygen renewal (Zhang et al., 2015). Ectotherms such as fish and invertebrates are particularly susceptible to such temperature and oxygen stress (Stoks et al., 2014). Their metabolic demands increase with rising temperature and a suitable habitat is eroded due to both high temperatures and lower oxygen concentrations in lakes and rivers. Till et al. (2019) attributed 502 fish kill events in the Wisconsin lakes (USA) to warmer summers in lakes that experienced abnormally high water temperatures. Such events are predicted to double by 2041–2059 and increase four-fold by 2081–2099 compared to historical levels (Till et al., 2019). This anticipated increase in die-offs may facilitate warm-water fish species displacing cool-water species (Hansen et al., 2017; Jennings et al., 2021). Floods mobilise nutrients and sediment, and aid dispersal of invasive species in rivers (Death et al., 2015), while drought extremes reduce river connectivity, threatening biodiversity in rivers (section 2.3.3.5) (Tickner et al., 2020).

Learnings from Recent Extremes

These examples show that the impact of an extreme event is a function of its characteristics and those of the exposed ecosystem. The timing, frequency, absolute magnitude and geographic extent of the extreme event, relative to antecedent conditions and the life cycle, resistance and resilience of the natural community, all determine the biological response (Figure Cross-Chapter Box Extremes.1) (Hillebrand et al., 2018; Gruber et al., 2021). The impact appears to be greater when extreme events occur more frequently, particularly when the interval between events is insufficient to allow recovery to previous population sizes (e.g., frequent fires and coral bleaching) or coincides with vulnerable life-cycle stages, even when populations are adapted to cope with such disturbances. Events occurring over large spatial areas reduce the potential for recolonisation from nearby populations (e.g., regional droughts causing widespread declines). Often the magnitude of extreme events exceeds historical levels, so organisms are less likely to be adapted to them, particularly when several extremes coincide (e.g., high water temperature and drought) (Duke et al., 2017). When hazards occur simultaneously (compound events), the impacts of extremes can be substantially aggravated, triggering a cascade of effects in ecosystems (Gruber et al., 2021).

Several characteristics of natural systems are associated with greater vulnerability to extreme events (Figure Cross-Chapter Box EXTREMES.2), knowledge of which can inform solutions to build resilience and aid recovery (Robinson et al., 2020). Resilience can be built prior to an event by minimising additional disturbances, such as water extraction from river systems, pollution of aquatic systems, fragmentation of land and LULCCs. Managing landscapes to reduce fragmentation and increase habitat extent, connectivity and heterogeneity, by increasing the number and extent of reserves, may provide local refugia from extreme events and enhance post-event recolonisation, but may be less effective for marine systems (Section 3.6). Maintaining taxonomic, phylogenetic and functional diversity is important, as more diverse systems may be more stable in the face of disturbances (Pimm, 1984; García-Palacios et al., 2018).

Several characteristics increase vulnerability: low or narrow thermal tolerance, high habitat specificity, low dispersal ability, long generation times, low competitive ability and life-cycle constraints that limit recovery or recolonisation. Populations living close to one or more limiting factors near range edges are also vulnerable (Arafeh-Dalmau et al., 2019). Understanding these characteristics can inform management intervention to aid recovery following an extreme event. For instance, knowledge of the flying fox's physiological temperature threshold led to successful interventions, including misting populations to reduce mortality (Mo and Roache, 2020), and the development of a 'heat stress forecaster', an online tool which uses weather forecasts to identify roosts at risk of extreme heat events (Ratnayake et al., 2019). This early warning system increases the preparedness of wildlife management and conservation agencies, enabling efficient allocation of management resources towards the locations that are likely to be the most affected.

Monitoring following extreme events can help identify immediate impacts and the potential for cascading interactions, such as changes to competitive interactions following range shifts, impacts on freshwater ecosystems following wildfires and the spread of invasive species. Ongoing monitoring of recovery and effectiveness of management intervention is important, focussing on habitat-forming species (e.g.,

Cross-Chapter Box EXTREMES (continued)

kelp, corals and dominant tree species) and keystone species (e.g., filter-feeders, macrophytes and top predators), as the loss of these species can lead to ecosystem tipping points, beyond which the system may not recover (Collins et al., 2019) (Sections 2.5.3; 3.4.4.1; 3.4.4.1.4; chapters 9–15, this report).

The acute impacts of extreme events, in addition to the chronic stress of changing mean conditions, are accelerating and amplifying the biological effects of climate change. This amplification is being observed globally and in all realms where life exists. Extreme events are compressing the timeline available for natural systems to adapt, and impeding our ability to identify, develop and adopt solutions. Recent events highlight the urgent need to mitigate global GHG emissions and identify solutions to halt accelerating impacts on natural systems (Díaz et al., 2020).

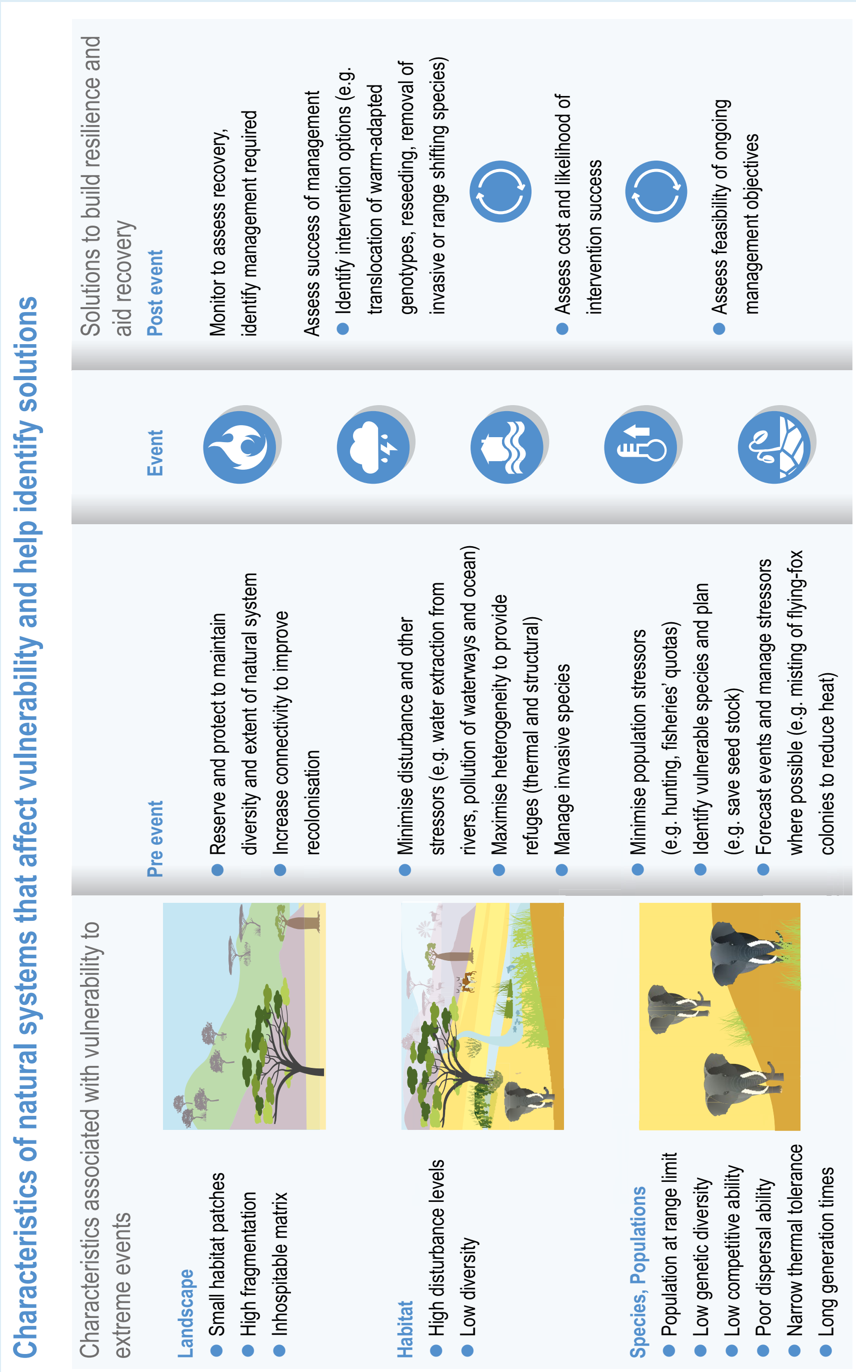


Figure Cross-Chapter Box EXTREMES.2 | Characteristics of natural systems that affect vulnerability and help identify solutions—both prior to and after extreme events—to build resistance, resilience and recovery.

Cross-Chapter Box ILLNESS | Infectious Diseases, Biodiversity and Climate: Serious Risks Posed by Vector- and Water-Borne Diseases

Authors: Marie-Fanny Racault (UK/France, Chapter 3), Stavana E. Strutz (USA, Chapter 2), Camille Parmesan (France/UK/USA, Chapter 2), Rita Adrian (Germany, Chapter 2), Guéladio Cissé (Mauritania/Switzerland/France, Chapter 7), Sarah Cooley (USA, Chapter 3), Meghnath Dhimal (Nepal), Luis E. Escobar (Guatemala/USA), Adugna Gemeda (Ethiopia, Chapter 9), Nathalie Jeanne Marie Hilmi (Monaco/France, Chapter 18), Salvador E. Lluch-Cota (Mexico, Chapter 5), Erin Mordecai (USA), Gretta Pecl (Australia, Chapter 11), A. Townsend Peterson (USA), Joacim Rocklöv (Germany/Sweden), Marina Romanello (UK/Argentina/Italy), David Schoeman (Australia, Chapter 3), Jan C. Semenza (Italy, Chapter 7), Maria Cristina Tirado (USA/Spain, Chapter 7), Gautam Hirak Talukdar (India, Chapter 2), Yongyut Trisurat (Thailand, Chapter 2)

*Climate change is altering the life cycles of many pathogenic organisms and changing the risk of transmission of vector- and water-borne infectious diseases to humans (*high confidence*). The rearrangement and emergence of some diseases are already observed in temperate-zone and high-elevation areas and coastal areas (*medium confidence to high confidence, depending upon region*). Shifts in the geographic and seasonal range suitability of pathogens and vectors are related to climatic-impact drivers (warming, extreme events, precipitation and humidity) (*very high confidence*), but there are substantial non-climatic drivers (LUC, wildlife exploitation, habitat degradation, public health and socioeconomic conditions) that affect the attribution of the overall impacts on the prevalence or severity of some vector- and water-borne infectious diseases over recent decades (*high confidence*). Adaptation options that involve sustained and rapid surveillance systems as well as the preservation and restoration of natural habitats with their associated higher levels of biodiversity, both marine and terrestrial, will be key to reducing the risk of epidemics and the large-scale transmission of diseases (*medium confidence*).*

Since AR5, further evidence is showing that climate-related changes in the geographic and seasonal range suitability of pathogens and vectors and the prevalence or new emergence of vector- and water-borne infectious diseases have continued across many regions worldwide and are sustained over decadal timescales (*low confidence to high confidence*, depending upon region)(Sections 2.4.2.5, 3.5.5.3, 7.2, 7.3, 9.10.1.2.1) (Harvell et al., 2009; Garrett et al., 2013; Burge et al., 2014; Guzman and Harris, 2015; Baker-Austin et al., 2018; Watts et al., 2019; Semenza, 2020; Watts et al., 2021). Ecosystem-mediated infectious diseases at risk of increase from climate change include water-borne diseases associated with pathogenic *Vibrio* spp. (e.g., those causing cholera and vibriosis) and harmful algal blooms (e.g., ciguatera fish poisoning) (Sections 3.5, 5.12, Table SM3.3) (Bindoff et al., 2019); (Baker-Austin et al., 2013; Levy, 2015; Trtanj et al., 2016; Ebi et al., 2017; Mantzouki et al., 2018; Nichols et al., 2018), and VBDs associated with arthropods (e.g., malaria, dengue, chikungunya, Zika virus, West Nile virus and Lyme disease), helminths (e.g., schistosomiasis) and zoonotic diseases associated with cattle and wildlife (e.g., leptospirosis) (*low confidence to very high confidence*, depending upon disease and region) (Sections 2.4.2.7, 3.5, 7.2, 7.3, 9.10.1.1.1, 13.7.1.2, 14.4.6, Cross-Chapter Box COVID in Chapter 7; Table Cross-Chapter Box ILLNESS.1) (Hoegh-Guldberg et al., 2018; Ebi et al., 2021).

The attribution of observed changes in disease incidence, partly or fully, to climatic-impact drivers remains challenging because of the difficulty of accurately capturing the contributions of multiple, interacting and often nonlinear underlying responses of host, pathogen and vector, which can be influenced further by non-climate stressors and the long history of anthropogenic disturbance. Disease emergence in new areas requires independent drivers to coincide (i.e., increasing climate suitability for pathogen or vector survival and competence/capacity, and introduction of the pathogen, that is often via the mobility of human populations). Furthermore, the extent to which changes in ecosystem-mediated diseases impact human health is highly dependent on local socioeconomic status, sanitation, medical systems and practices (Section 2.4.2.5, Figure FAQ2.3.1) (Gething et al., 2010; Lindgren et al., 2012; Mordecai et al., 2013; Liu-Helmersson et al., 2014; Bhatt et al., 2015; Morin et al., 2015; Ryan et al., 2015; Wesolowski et al., 2015; Stanaway et al., 2016; Yamana et al., 2016; Mordecai et al., 2017; Tesla et al., 2018; Ryan et al., 2019; Shah et al., 2019; Iwamura et al., 2020; Mordecai et al., 2020; Colón-González et al., 2021; Ryan et al., 2021).Thus, risk reduction is more effective when links between climate change, ecosystem change, health and adaptation are considered concurrently (Sections 2.4, 3.5.3, 7.2, 7.3, 4.3.3, 6.2.2.3, Table SM2.1).

Cross-Chapter Box ILLNESS (continued)

Table Cross-Chapter Box ILLNESS.1 | Observed climate change impacts on cholera, dengue and malaria incidence. (1) Cholera: endemicity based on (Ali et al., 2015). Changes (2003–2018) in suitability for coastal ***Vibrio cholerae*** estimated from model observations driven by sea-surface temperature (SST) and chlorophyll ***a*** (CHL) concentration (Escobar et al., 2015; Watts et al., 2019); vulnerabilities based on Sigudu et al. (2015) Agtini et al. (2005) and Sack et al. (2003). (2) Dengue: endemicity based on Guzman and Harris (2015). (3) Malaria: endemicity based on Phillips et al. (2017) and the WHO Global Malaria Programme. Impacts of climate change on diseases and their vectors are most evident at the margins of current distributions. However, it is difficult to implicate climate change in areas with extensive existing transmission and vector/pathogen abundance, and it is particularly difficult to distinguish from concurrent directional trends in disease control, changes in land use, water access, socioeconomic and public health conditions. As a result, while many studies indicate increasing climate suitability of some areas for cholera, and changes in disease incidence for dengue and malaria, the degree to which these changes can be attributed to climate change remains challenging. Uncertainty statements for malaria and dengue reflect the degree to which observed trends in disease incidence can be related to observed climate change in the given region. For cholera, confidence statements reflect the degree to which observed trends in disease or pathogen incidence and coastal area suitability for outbreaks can be linked to observed climate change drivers in the given region. Acronyms: ONI (Oceanic Niño Index), Tmin (minimum temperature), SPI (Standardised Precipitation Index), LST (land surface temperature). Full references for this table can be found in Table SM2.6.

	Cholera	Dengue	Malaria
Africa			
Endemicity	Endemic	Endemic in sub-Saharan Africa but not South Africa	Endemic
Climate drivers	Disease incidence: northeast Africa, Central Africa and Madagascar: rainfall (*medium confidence*) Southeast Africa: rainfall, LST, SST, Plankton (*medium confidence*) eastern South Africa: SST, CHL (*low confidence* due to *limited evidence*) West Africa: rainfall (floods), LST, SST (*medium confidence*)		West Africa: temperature (*medium confidence*) East Africa: temperature (*medium confidence*)
Direction of Change	Area of coastline suitable for outbreak: northandwest Africa: increase (*low confidence*) Central and East Africa: no change (*low confidence*) South Africa: decrease (*low confidence*)	Potentially expanding (*low confidence*) Dengue and *A. aegypti* present but underdetected in climatically suitable areas	East Africa: upward shift and increase in malaria and *Anopheles* spp. in highland areas (*medium confidence*) Widespread decreases due to malaria control (*medium confidence*) and warming climate (*low confidence*)
Vulnerabilities	Eastern South Africa: women of all ages more affected than men by outbreaks		
Asia			
Endemicity	Endemic	Endemic in South Asia, Southeast Asia and East Asia	Endemic in South Asia, Southeast Asia, partially endemic in East Asia
Climate drivers	Disease incidence: East Asia: SST, CHL, SLR (*medium confidence*) South Asia: SST, CHL, LST, rainfall (floods) (*high confidence*)	South Asia: rainfall, temperature, Humidity *(medium confidence)* Southeast Asia: rainfall, temperature (*medium confidence)* East Asia: rainfall, temperature, Typhoons (*low confidence*)	South Asia: rainfall, temperature (*medium confidence*) Southeast Asia: rainfall, temperature (*medium confidence*)
Direction of Change	Area of coastline suitable for outbreak: increase (*low confidence*)	Southeast Asia: increase (*low confidence*) South Asia: increase (*medium confidence*) East Asia: increase (*low confidence*)	South Asia: increase (*medium confidence*)
Vulnerabilities	Southeast Asia: infants (<9 years) with highest incidences of cholera South Asia: older children and young adults (aged 16–20 years) more frequently reported with cholera than non-cholera diarrhoea		
Australasia			
Endemicity	Not endemic	Partially endemic in northern Australia	Not endemic
Climate drivers	No evidence for disease incidence	Rainfall, temperature (*low confidence*)	
Direction of Change	Area of coastline suitable for outbreak: no change (*low confidence*)	Increase in sporadic outbreaks due to climate change (*low confidence*)	No change
Central America			
Endemicity	Not endemic	Endemic	Partially endemic
Climate drivers	No evidence for disease incidence	ONI, SST, Tmin, temperature, rainfall, drought (*low confidence*)	

Cross-Chapter Box ILLNESS (continued)

	Cholera	Dengue	Malaria
Direction of Change	Areas of coastline suitable for outbreak: decrease (*low confidence)*	Increasing due to climate (*low confidence*) Upward expansion of *A. aegypti* (*low confidence*)	Overall decrease not linked to climate change. Focal increases due to human activities.
South America			
Endemicity	Epidemic	Endemic in all regions except southern South America	Endemic
Climate drivers	Abundance of coastal *V. cholerae*: northwestern South America: SST, Plankton (*low confidence*)	Temperature, precipitation, drought	Northern South America: temperature (*low confidence*) northern and southeastern South America: Tmax, Tmin, humidity (*low confidence*)
Direction of Change	Area of coastline suitable for outbreak: no change (*low confidence*)	Increasing due to urbanisation and decreased vector control programmes, not strongly linked to climate	Higher elevation regions: Increase (*low confidence*)
Europe			
Endemicity	Not endemic	Southern Europe: focal outbreaks	Not endemic
Climate drivers	No evidence for disease incidence Abundance of coastal *V. cholerae*: northern Europe: SST, Plankton (*medium confidence*)		
Direction of Change	Area of coastline suitable for outbreak: increase (*low confidence*)	Mediterranean regions of southern Europe: outbreaks (*low confidence*)	No change
North America			
Endemicity	Not endemic	Partially endemic in southern North America	Not endemic
Climate drivers	No evidence for disease incidence Abundance of coastal V. cholerae: eastern North America: SST (*low confidence* due to *limited evidence*)	Winter Tmin (*low confidence*)	
Direction of Change	Area of coastline suitable for outbreak: increase (*low confidence*)	Declining	No change
Small Islands			
Endemicity	Epidemic	Endemic on many small islands in the Tropics	Endemic on many small islands in the Tropics
Climate drivers	Disease incidence: Caribbean: SST, LST, rainfall (*low* to *medium confidence*)	Caribbean: SPI, Tmin (*low confidence*)	
Direction of Change	Area of coastline suitable for outbreak: Caribbean and Pacific small islands: Decrease (*low confidence*)	Increasing (*low confidence*)	Decrease in Caribbean not linked to climate

Observed and projected changes

In aquatic systems, at least 30 human pathogens with water infection routes (freshwater and marine) are affected by climate change (Section 3.5.3, Table SM3.G) (Nichols et al., 2018) . Warming, acidification, hypoxia, SLR and increases in extreme weather and climate events (e.g., MHWs, storm surges, flooding and drought), which are projected to intensify in the 21st century (*high confidence*) (IPCC, 2021b), are driving species' geographic range shifts and global rearrangements in the location and extent of areas with suitable conditions for many harmful pathogens, including viruses, bacteria, algae, protozoa and helminths (*high confidence*) (Sections 2.3, 2.4.2.7, 3.5.5.3) (Trtanj et al., 2016; Ebi et al., 2017; Manning and Nobles, 2017; Pecl et al., 2017; Mantzouki et al., 2018; Nichols et al., 2018; Bindoff et al., 2019; IPCC, 2019b; Kubickova et al., 2019; Watts et al., 2019; Watts et al., 2020; Watts et al., 2021).

The incidence of cholera and *Vibrio*-related disease outbreaks have been shown to originate primarily in coastal regions, and then spread inland via human transportation. Our understanding of the impacts of climate-change drivers on the dynamics of *Vibrio* pathogens and related infections has been strengthened through improved observations from long-term monitoring programmes (Vezzulli et al., 2016) and statistical modelling supported by large-scale and high-resolution satellite observations (*high confidence*) ((Baker-Austin et al., 2013; Escobar et al., 2015; Jutla et al., 2015; Martinez et al., 2017; Semenza et al., 2017; Racault et al., 2019; Campbell et al., 2020).

Cross-Chapter Box ILLNESS (continued)

The poleward expansion of the distribution of *Vibrio* spp. has increased the risk of vibriosis outbreaks from multiple species in northern latitudes. Specifically, the coastal area suitable for *Vibrio* infections in the past 5 years has increased by 50.6% compared with a 1980s baseline at latitudes of 40°N–70°N; in the Baltic region, the highest-risk season has been extended by 6.5 weeks over the same periods (Watts et al., 2021). Already, studies have noted greater numbers of *Vibrio*-related human infections and, most notably, disease outbreaks linked to extreme weather events such as heat waves in temperate regions such as Northern Europe (Baker-Austin et al., 2013; Baker-Austin et al., 2017; Baker-Austin et al., 2018) (*high confidence*). By the end of the 21st century, under RCP6.0, the number of months of risk of *Vibrio* illness is projected to increase in Chesapeake Bay by 10.4 ± 2.4%, with largest increases during May and September, which are the months of strong recreational and occupational use, compared to a 1985–2000 baseline (Jacobs et al., 2015; Davis et al., 2019a). In the Gulf of Alaska, the coastal area suitable for *Vibrio* spp. is projected to increase on average by 58 ± 17.2% in summer under RCP6.0 by the 2090s, compared to a 1971–2000 baseline (*low to medium confidence*) (Jacobs et al., 2015).

The coastal area suitable for *V. cholerae* (the causative agent for cholera) has increased by 9.9% globally compared to a 2000s baseline (Escobar et al., 2015; Watts et al., 2019). However, in the case of *V. cholerae* and cholera disease incidence, climate change is more difficult to implicate because outbreaks require independent drivers to coincide (i.e., introduction of pathogenic strains of *V. cholerae* in the waters via mobility of human-infected populations) and observed trends are difficult to separate from concurrent directional trends in disease control, sanitation and water access, socioeconomic and public health conditions.

On land, increased global connectivity and mobility, unsustainable exploitation of wild areas and species and land conversion (agricultural expansion, intensification of farming, deforestation and infrastructure development), together with climate change-driven range shifts of species and human migration (Cross-Chapter Box MOVING PLATE in Chapter 5), have modified the interfaces between people and natural systems (IPBES, 2018a). Climate-driven increase in temperature, the frequency and intensity of extreme events as well as changes in precipitation and relative humidity have provided opportunities for rearrangements of disease geography and seasonality, and emergence into new areas (*high confidence*) (Section 2.4.2.7). In particular, malaria has expanded into higher elevations in recent decades and, although attributing this to climate change remains challenging (Hay et al., 2002; Pascual et al., 2006; Alonso et al., 2011; Campbell et al., 2019c), evidence that the elevational distribution of malaria has tracked warmer temperatures is compelling for some regions (Siraj et al., 2014). Models based on both empirical relationships between temperature and the *Anopheles* mosquito and *Plasmodium* parasite traits that drive transmission (Mordecai et al., 2013; Yamana and Eltahir, 2013; Johnson et al., 2015) and existing mosquito distributions (Peterson, 2009) predict that warming will increase the risk of malaria in highland East Africa and Southern Africa, while decreasing the risk in some lowland areas of Africa, as temperatures exceed the thermal optimum and upper thermal limit for transmission (Peterson, 2009; Yamana and Eltahir, 2013; Ryan et al., 2015; Watts et al., 2021).

In contrast to malaria, dengue has expanded globally since 1990, particularly in Latin America and the Caribbean, South Asia and sub-Saharan Africa (Stanaway et al., 2016). While urbanisation, changes in vector control and human mobility play roles in this expansion (Gubler, 2002; Åström et al., 2012; Wesolowski et al., 2015), the physiological suitability of temperatures for dengue transmission is also expected to have increased as climates have warmed (Colón-González et al., 2013; Liu-Helmersson et al., 2014; Mordecai et al., 2017; Rocklöv and Tozan, 2019). Models predict that dengue transmission risk will expand across many tropical, subtropical and seasonal temperate environments with future warming (Åström et al., 2012; Colón-González et al., 2013; Ryan et al., 2019; Iwamura et al., 2020; Watts et al., 2021)).

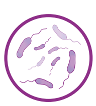
Adaptation options

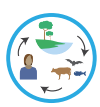
During the 21st century, public health adaptation measures (Figure Cross-Chapter Box ILLNESS.2) have been put in place in attempts to control or eradicate a variety of infectious diseases by improving surveillance and early detection systems; constraining pathogen, vector, and/or reservoir host distributions and abundances; reducing the likelihood of transmission to humans; and improving treatment and vaccination programmes and strategies (*robust evidence*, *high agreement*) (Chinain et al., 2014; Adrian et al., 2016; Friedman et al., 2017; Konrad et al., 2017; Semenza et al., 2017; Borbor-Córdova et al., 2018; Rocklöv and Dubrow, 2020). In addition, the effective management and treatment of domestic and waste-water effluent, through better infrastructure and preservation of aquatic systems acting as natural water purifiers, have been key to securing the integrity of the surrounding water bodies, such as groundwater, reservoirs and lakes, and agricultural watersheds as well as protecting public health (*high confidence*) (Okeyo et al., 2018; Guerrero-Latorre et al., 2020; Kitajima et al., 2020; Sunkari et al., 2021). The preservation and restoration of natural ecosystems, with their associated higher levels of biodiversity, have been reported as significant buffers against epidemics and large-scale pathogen transmission (*medium confidence*) (Johnson and Thieltges, 2010; Ostfeld and Keesing, 2017; Keesing and Ostfeld, 2021). Furthermore, the timely allocation of financial resources and sufficient political will in support of a 'One Health' scientific research approach, recognising the health of humans, animals and ecosystems as interconnected (Rubin et al., 2014; Whitmee et al., 2015; Zinsstag et al., 2018), holds potential for improving surveillance and prevention strategies that may help to reduce the risks of further spread and new emergence of pathogens and vectors (*medium confidence*) (Destoumieux-Garzón et al., 2018; Hockings et al., 2020; Volpato et al., 2020; Hopkins et al., 2021; Pörtner et al., 2021).

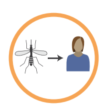
Cross-Chapter Box ILLNESS (continued)

Adaptation measures to reduce risks of ecosystem-mediated diseases under climate change

Type	Description of adaptation options			Climate impact	Confidence
Warning systems	Build & maintain early surveillance systems of pathogens affecting humans, wildlife & farm animals	Establish seasonal & dynamic forecasts of disease outbreaks with detailed risk mapping	Create early warning systems targeted to the appropriate scale (local, regional, and international)		+++
Diagnostic abilities	Increase technological & lab capacity & train personnel to rapidly diagnose & raise case awareness	Report cases in near-real time for efficient response & resource mobilization to mitigate outbreaks	Respond rapidly to disease emergence events with adequate public health & medical resources		+++
Capacity building	Train health & environmental officials to rapidly respond to newly emerging disease risks	Increase public awareness of the health risks from pathogens & vectors	Invest in robust healthcare systems with good facilities, access & epidemic protocols		++
Public policy	Increase international cooperation and build policies within a One Health/One Biosecurity framework	Promote large-scale public health programs for disease/vector eradication	Reach herd-level immunity via vaccination for pathogens with few host species		++
Financing	Use Green recovery funds to tackle biodiversity loss & climate change	Use national funds for Nature-based Solution projects to conserve habitats & improve water services	Provide funds to tribal/local groups engaging in sustainable agricultural, forest & water management		+
Technology	Priotitize using non-insecticide based control for vectors	Utilize control alternatives (avoiding use of antibiotics, synthetic chemicals & drugs when possible)	Build robust vector/pathogen genetic surveillance & control programmes		++
Management	Align planning with Sustainable Development Goals & climate targets	Build sustainabile long-term observation & monitoring systems	Institute environmental regulations & sustainable agriculture, livestock & fisheries' farming practices		++
Infrastructure	Create urban forests & green spaces with vector control integrated into the design	Improve & maintain drinking water access, & sewage/drainage systems	Build and outfit homes/buildings with high quality materials to prevent vectors from entering		+++
Nature-based Solutions	Restore and conserve natural habitats (e.g., reforestation)	Decrease habitat fragmentation & limit human proximity to risky environments	Use ecosystem-based management to regulate pathogen & vector populations		++
Changes in practices	Diversify diets & create more resilient food systems	Reduce the wildlife trade	Decrease reliance on bushmeat and wild animal products		++
Co-benefits from mitigation	Reductions in local emissions from energy systems	Promotion of clean transport systems	Improved access to food, water & energy		++


Pathogen, host/vector distributions & abundance


Pathogen-host transmission cycle occurrence and efficiency


Likelihood of transmission to humans

Evidence: Low --------- High

Agreement: + Low --------- High +++

Figure Cross-Chapter Box ILLNESS.1 | Adaptation measures to reduce risks of climate change impact on water- and vector-borne diseases. Impacts are identified at three levels: (1) on pathogen, host/vector distributions and abundance; (2) on pathogen-host transmission cycle occurrence and efficiency; and (3) on the likelihood of transmission to humans. Adaptation typology is based on (Biagini et al., 2014; Pecl et al., 2019). For each type of adaptation, examples are provided with their level of evidence and agreement.

Cross-Chapter Box NATURAL | Nature-Based Solutions for Climate Change Mitigation and Adaptation

Authors: Camille Parmesan (France/USA/UK, Chapter 2), Gusti Anshari (Indonesia, Chapter 2, CCP7), Polly Buotte (USA, Chapter 4), Donovan Campbell (Jamaica, Chapter 15), Edwin Castellanos (Guatemala, Chapter 12), Annette Cowie (Australia, WGIII Chapter 12), Marta Rivera Ferre (Spain, Chapter 8), Patrick Gonzalez (USA, Chapter 2, CCP3), Elena López Gunn (Spain, Chapter 4), Rebecca Harris (Australia, Chapter 2, CCP3), Jeff Hicke (USA, Chapter 14), Rachel Bezner Kerr (USA/Canada, Chapter 5), Rodel Lasco (Philippines, Chapter 5), Robert Lempert (USA, Chapter 1), Brendan Mackey (Australia, Chapter 11), Paulina Martinetto (Argentina, Chapter 3), Robert Matthews (UK, WGIII, Chapter 3), Timon McPhearson (USA, Chapter 6), Mike Morecroft (UK, Chapter 2, CCP5), Aditi Mukherji (India, Chapter 4), Gert-Jan Nabuurs (the Netherlands, WGIII Chapter 7), Henry Neufeldt (Denmark/Germany, Chapter 5), Roque Pedace (Argentina, WGIII Chapter 3), Julio Postigo (USA/Peru, Chapter 12), Jeff Price (UK, Chapter 2, CCP1), Juan Pulhin (Philippines, Chapter 10), Joeri Rogelj (UK/Belgium, WGI Chapter 5), Daniela Schmidt (UK/Germany, Chapter 13), Dave Schoeman (Australia, Chapter 3), Pramod Kumar Singh (India, Chapter 18), Pete Smith (UK, WGIII Chapter 12), Nicola Stevens (South Africa, Chapter 2, CCP3), Stavana E. Strutz (USA, Chapter 2), Raman Sukumar (India, Chapter 1), Gautam Hirak Talukdar (India, Chapter 2, CCP1), Maria Cristina Tirado (USA/Spain, Chapter 7), Christopher Trisos (South Africa, Chapter 9)

Nature-based solutions provide adaptation and mitigation benefits for climate change as well as contributing to other sustainable development goals (**high confidence*****). Effective nature-based climate change mitigation stems from inclusive decision-making and adaptive management pathways that deliver climate-resilient systems serving multiple sustainable development goals. Robust decision-making adjusts management pathways as systems are impacted by ongoing climate change. Poorly conceived and poorly designed nature-based mitigation efforts have the potential for multiple negative impacts, including competing for land and water with other sectors, reducing human well-being and failing to provide mitigation that is sustainable in the long term (*****high confidence*****).***

The concept of Nature-based Solutions (NbS) is broad and under debate, but has become prominent in both the scientific literature and policy since AR5, and includes earlier concepts like EbA. The key point is that these are actions benefitting both people and biodiversity (IUCN, 2020) (WGII Glossary). In the context of climate change, NbS provide adaptation and mitigation benefits in ways that support wild species and habitats, often contributing to other sustainable development goals (*robust evidence*, *high agreement*) (Griscom et al., 2017; Keesstra et al., 2018; Hoegh-Guldberg et al., 2019; IPCC, 2019a; Lewis et al., 2019; Lavorel et al., 2020; Malhi et al., 2020; Seddon et al., 2020b) (AR6 WGIII Chapter 12; Sections 2.2, 2.5.4, 2.6.3, 2.6.5, 2.6.7). Well-designed and implemented NbS mitigation schemes can increase carbon uptake or reduce GHG emissions at the same time as protecting or restoring biodiversity and incorporating elements of food provisioning (Mehrabi et al., 2018). A variety of measures can be part of NbS, ranging from the protection of natural terrestrial, freshwater and marine ecosystems to the restoration of degraded ones (this Cross-Chapter Box; Section 13.3) and more sustainable management of naturally regenerating ecosystems used for food, fibre and energy production (Figure Cross-Chapter Box NATURAL.1, Chapter 5 in this report, Cross-Working Group Box BIOECONOMY in Chapter 5). Agro-ecological practices mitigate and adapt to climate change and can promote native biodiversity (*high confidence*) (Sinclair et al., 2019; Snapp et al., 2021).

The Role of Restoration in Nature-Based Solutions

Where natural ecosystems have been degraded or destroyed, re-establishing them and restoring natural processes can be a key action for adaptation and mitigation, and the science of restoration is well established (de los Santos et al., 2019; Duarte et al., 2020) (Section 13.4.1). Such restoration activities need to adapt to ongoing climate change risks for the landscape and oceans and the species composition of biological communities. Indeed, the impacts of climate change may overwhelm attempts at restoration/conservation of previous or existing ecosystems, particularly when the ecosystem is already near its tipping point, as is the case with tropical coral reefs (Bates et al., 2019; Bruno et al., 2019).

Land (e.g., forests) and oceans (e.g., fisheries) managed for products using sustainable practices (whether applied by individuals, states or Indigenous Peoples) can also be carbon- and biodiversity-rich, and thus considered effective NbS (Paneque-Gálvez et al., 2018; Soto-Navarro et al., 2020). Indigenous Peoples and private forest owners manage, use or occupy at least one-quarter of the global land area, over one-third of which overlaps with protected areas, thus combining both protection and production (Jepsen et al., 2015; Garnett et al., 2018; IPBES, 2019; Santopuoli et al., 2019).

The protection/restoration of natural systems including reducing non-climate stressors, and the sustainable management of semi-natural areas emerge as necessary actions for adaptation to minimise extinctions of species, the reaching of tipping points that cause regime shifts in natural system and the loss of whole ecosystems and their associated benefits for humans (Scheffer et al., 2001; Folke et al., 2005; Luther et al., 2020) (Chapters 2 and 3 in this report; AR6 WGIII Chapter 7). Such measures are critical for the conservation of biodiversity

Cross-Chapter Box NATURAL (continued)

and the provision of ecosystem goods and services in the face of projected climate change (Duarte et al., 2020). Supporting local livelihoods and providing benefits to indigenous local communities and millions of private landowners, together with their active engagement in decision-making, are critical to ensuring support for NbS and their successful delivery (*high confidence*) (Chapter 5 in this report; Figure Cross-Chapter Box NATURAL.1)(Ceddia et al., 2015; Blackman et al., 2017; Nabuurs et al., 2017; Smith et al., 2019a; Smith et al., 2019b; Jones et al., 2020a; McElwee et al., 2020; Cao et al., 2021).

Forests

Intact natural forest ecosystems are major stores of carbon and support large numbers of species that cannot survive in degraded habitats (*very high confidence*). Extensive areas of natural forest ecosystems remain in tropical, boreal and (to a lesser extent) temperate biome regions, but in many regions they are managed (sustainably and unsustainably) or have been degraded or cleared. Deforestation and land degradation continue to be a source of global GHG emissions (*very high confidence*) (Friedlingstein et al., 2019). Protection of existing natural forests and sustainable management of semi-natural forests that continue to provide goods and services are highly effective NbS (Bauhus et al., 2009) (*high confidence*).

Natural forests and sustainably managed biodiverse forests play important roles in climate change mitigation and adaptation while providing many other ecosystem goods and services (*very high confidence*) (Bradshaw and Warkentin, 2015; Favero et al., 2020; Mackey et al., 2020). Contributions of natural forests to climate change mitigation are estimated at a median of 5–7 $GtCO_2$ yr^{-1} (Roe et al., 2019). Forests influence the water cycle on a local, regional and global scale (Creed and van Noordwijk, 2018), reducing surface runoff, increasing infiltration to groundwater and improving water quality (Bruijnzeel, 2004; Zhou et al., 2015a; Ellison et al., 2017; Alvarez-Garreton et al., 2019). Recent evidence shows that downwind precipitation is also influenced by evapotranspiration from forests (Keys et al., 2016; Ellison et al., 2017). Protecting existing natural forests and sustainably managing production forests in a holistic manner can optimise the provision of the many functions forests fulfil for owners, conservation, mitigation and for society as a whole (Bauhus et al., 2009; Nabuurs et al., 2013).

Reforestation of previously forested land can help to protect and recover biodiversity and is one of the most practical and cost-effective ways of sequestering and storing carbon (*high confidence*) (Nabuurs et al., 2017; Hoegh-Guldberg et al., 2018; Paneque-Gálvez et al., 2018; Smith et al., 2018; Cook-Patton et al., 2020; Cowie et al., 2021; Drever et al., 2021). This can be achieved through planting or by allowing natural colonisation by tree and shrub species. The most effective method to deploy depends upon local circumstances (e.g., the presence of remnant forest cover) or socio-cultural and management objectives. Reforestation with climate-resilient native or geographically-near species restores biodiversity at the same time as sequestering large amounts of carbon (Lewis et al., 2019; Rozendaal et al., 2019). It can also restore hydrological processes, thereby improving water supply and quality (Ellison et al., 2017) and reducing the risk of soil erosion and floods (*high confidence*) (Locatelli et al., 2015).

Climate change may mean that, in any given location, different species will be able to survive and become dominant and restoring the former composition of forests may not be possible (Sections 2.4, 2.5). Severe disturbances such as insect/pathogen outbreaks, wildfires and droughts, which are an increasing risk, can cause widespread tree mortality resulting in sequestered forest carbon being returned to the atmosphere (Anderegg et al., 2020; Senf and Seidl, 2021), suggesting that we need to adapt (Sections 2.4, 2.5, 13.3 14.4.1, Box 14.1). Adaptation measures, such as increasing the diversity of forest stands through ecological restoration rather than monoculture plantations can help to reduce these risks (*high confidence*). When plantations are established without effective landscape planning and meaningful engagement including free prior and informed consent, they can present risks to biodiversity and the rights, well-being and livelihoods of indigenous and local communities as well as being less climate-resilient than natural forests (*very high confidence*) (Section 5.6) (Corbera et al., 2017; Mori et al., 2021).

Afforesting areas such as savannas and temperate peatlands, which would not naturally be forested, damages biodiversity and increases vulnerability to climate change (*high confidence*), so cannot be considered a nature-based solution and can even exacerbate GHG emissions (Sections 2.4.3.5, 2.5.2.5, Box 2.2 in this chapter). Remote sensing-based assessments of the suitability of land for planting trees can overestimate potential, due to their failure to adequately distinguish between degraded forest and naturally open areas (Bastin et al., 2019; Veldman et al., 2019; Bastin et al., 2020; Sullivan et al., 2020).

Peatlands

Peatlands are naturally high-carbon ecosystems, which have built up over millennia. Draining, cutting and burning peat lead to oxidation and the release of CO_2 (*very high confidence*). Re-wetting by blocking drainage and preventing cutting and burning can reverse this process on temperate peatlands (*medium confidence*) but takes many years (Bonn et al., 2016). Trees are naturally found on many tropical

Cross-Chapter Box NATURAL (continued)

peatlands and restoration can involve removing non-native species like the oil palm and re-establishing natural forest. However, peatland tropical forest is difficult to fully restore, and native pond-fish, vital as a local food, often do not return. Protecting intact peat forests, rather than attempting to restore cleared forest, is by far the more effective pathway, in terms of cost, CO_2 mitigation and the protection of food sources (Kreft and Jetz, 2007). Naturally treeless temperate and boreal peatlands have, in some cases, been drained to enable trees to be planted, which then leads to CO_2 emissions, and restoration requires the removal of trees as well as re-blocking drainage (*high confidence*) (Sections 2.4.3.8, 2.5.2.8, 2.6.5.10).

Blue Carbon

Blue carbon ecosystems (mangroves, saltmarshes and seagrass meadows; see Glossary Appendix II) often have high local rates of carbon accumulation and sequestration (Section 3.5.5.5) (Macreadie et al., 2019). However, quantification of their overall mitigation value is difficult due to the variable production of CH_4 and N_2O (Adams et al., 2012; Rosentreter et al., 2018; MacLean et al., 2019b), uncertainties regarding the provenance of the carbon accumulated (Macreadie et al., 2019) and the release of CO_2 by biogenic carbonate formation in seagrass ecosystems (Saderne et al., 2019). Therefore, blue carbon strategies, referring to climate change mitigation and adaptation actions based on the conservation and restoration of blue carbon ecosystems, can be effective NbS, with evidence of the recovery of carbon stocks following restoration, although their global or regional carbon sequestration potential and net mitigation potential may be limited (*medium confidence*) (Sections 3.6.3.1.6, 13.4.3) (section 5.6.2.2.2 in (Canadell et al., 2021)) (Duarte et al., 2020).

They can also significantly attenuate wave energy, raise the seafloor (thereby counteracting the effects of SLR) and buffer storm surges and erosion from flooding (*high confidence*) (Sections 13.2.2, 13.10.2). Additionally, they provide a suite of cultural (e.g., tourism and the livelihoods and well-being of native and local communities), provision (e.g., mangrove wood, edible fish and shellfish) and regulation (e.g., nutrient cycling) services (*high confidence*) (Section 3.5.5.5). These services have motivated the implementation of management and conservation strategies of these ecosystems (Sections 3.6.3.1.6, 13.4.2). Blue carbon strategies are relatively new, with many of them experimental and small-scale; there is therefore only *limited evidence* of their long-term effectiveness. There is also limited information on the potential emission of other GHGs from restored blue carbon ecosystems, although reconnecting hydrological flow in mangroves and restoring saltmarshes are effective interventions to reduce CH_4 and CO_2 (*limited evidence*, *medium agreement*) (Kroeger et al., 2017; Al-Haj and Fulweiler, 2020).

Urban Nature-Based Solutions

NbS can be a key part of urban climate adaptation efforts. Direct human adaptation benefits may stem from the cooling effects of urban forests and green spaces (parks and green roofs), from coastal wetlands and mangroves reducing storm surges and flooding and from sustainable drainage systems designed to reduce surface flooding as a result of extreme rainfall as well as the general benefits to human health and well-being (*high confidence*) (Sections 2.2, 2.6, Chapter 6) (Kowarik, 2011; Frantzeskaki et al., 2019; Keeler et al., 2019). Not all green schemes are considered 'Nature-Based Solutions' if they do not benefit biodiversity, but carefully designed urban greening can be effective NbS. Careful planning also helps limit negative equity consequences such as benefitting wealthy neighbourhoods more than poor neighbourhoods (Geneletti et al., 2016; Pasimeni et al., 2019; Grafakos et al., 2020). Effective planning should also consider what is appropriate for the climate and conditions of each city. For example, some trees emit volatiles (e.g., isoprene) which, in the presence of certain atmospheric pollutants, can increase surface ozone which can, in turn, cause human respiratory problems (Kreft and Jetz, 2007). Wetland restoration close to human settlements needs to be paired with mosquito control to prevent negative impacts on human health and well-being (Stewart-Sinclair et al., 2020), but it has been shown to provide better filtration and toxicity reduction with a lower environmental impact than other forms of waste-water treatment (Vymazal et al., 2021), including 'green roofs' and 'green walls' (Chapter 6 in this report) (Addo-Bankas et al., 2021).

Agro-Ecological Farming

AF is a holistic approach that incorporates ecological and socioeconomic principles, many of which have been shown to have a positive impact on biodiversity and on the resilience of human and natural systems to climate change (chapter 5, this report). It strives to enhance biodiversity, soil health and synergies between agro-ecosystem components, reduces reliance on synthetic inputs (e.g., pesticides), builds on IKLK and fosters social equity (e.g., supporting fair, local markets) (HLPE, 2019; Wezel et al., 2020). AF practices include inter-cropping; the mobility of livestock grazing across landscapes; organic agriculture; and the integration of livestock, fish and cropping, cover crops and agro-forestry (Sections 5.14, FAQ 12.5, FAQ 13.5).

Agro-forestry, cover crops and other practices that increase vegetation cover and enhance soil organic matter, carefully managed and varying by agro-ecosystem, mitigate climate change (*high confidence*) (Zomer et al., 2016; Aryal et al., 2019; Nadège et al., 2019). Global meta-analyses demonstrate agro-forestry as storing 20–33% more soil carbon than conventional agriculture (De Stefano and Jacobson,

Cross-Chapter Box NATURAL (continued)

2018; Shi et al., 2018) and reducing the spread of fire (Sections 5.6, 13.5.2, 7.4.3, Box 7.7). Minimising synthetic inputs such as nitrogen-based fertilizers reduces emissions (Gerber et al., 2016). Cover crops can reduce N_2O emissions and increase soil organic carbon (Abdalla et al., 2019). Conservation farming (no-till with residue retention and crop rotation) increases soil organic carbon, particularly in arid regions (Sun et al., 2020). Silvo-pastoral systems (pastures with trees) and other practices that increase vegetation cover and enhance soil organic matter increase sequestered carbon in vegetation and soils (Zomer et al., 2016; Aryal et al., 2019; Nadège et al., 2019; Ryan, 2019). Agro-ecologically improved management of land for crops and grazing has significant mitigation potential, estimated at 2.8–4.1 $GtCO_2$-eq yr^{-1} (Smith et al., 2020) (Sections 5.10, 5.14, Box 5.10, Cross Working-Group Box BIOECONOMY in Chapter 5; WGIII 7.4.3, Box 7.7).

AF enhances adaptation to climate change, including resilience to extreme events. Building organic matter improves the water-holding capacity of soils and buffers against drought; increased perenniality and high levels of ground cover reduce soil erosion during storms; agro-forestry shelters livestock and crops during heat waves; landscape complexity and agro-biodiversity increase resilience to disease and pests and stabilise livestock production; and restoration of oyster reefs provides thermal refugia and storm surge protection (Henry et al., 2018; Kremen and Merenlender, 2018; Kuyah et al., 2019; Gilby et al., 2020; Niether et al., 2020; Richard et al., 2020; Howie and Bishop, 2021; Snapp et al., 2021). Livestock mobility enables adjustment to increased climatic variability while maintaining the productivity of pastoral systems (Turner and Schlecht, 2019; Scoones, 2020). The adoption of agro-ecology principles and practices will therefore be highly beneficial to maintaining healthy, productive food systems under climate change (*high confidence*) (Sections 5.4.4, 13.5.2, FAQ 12.4).

AF practices such as hedgerows and poly-cultures maintain habitat and connectivity for biodiversity, thus aiding the ability of wild species to respond to climate change via range shifts, and support ecosystem functioning under climate stress compared to conventional agriculture (*high confidence*) (Section 5.4.4.4) (Buechley et al., 2015; Kremen and Merenlender, 2018; Albrecht et al., 2020). Increasing farm biodiversity benefits pollination, pest control, nutrient cycling, water regulation and soil fertility (Beillouin et al., 2019; Tamburini et al., 2020; Snapp et al., 2021). Biodiverse agro-forestry systems increase ecosystem services and biodiversity benefits compared to simple agro-forestry and conventional agriculture (*high confidence*), with up to 45% more biodiversity and 65% more ecosystem services compared to conventional production of timber and crops and profits from livestock in the Atlantic Forest in Brazil (Santos et al., 2019), including benefits for birds and local tree species (Braga et al., 2019) and meaning there are fewer invasive exotic plants species (de Almeida Campos Cordeiro et al., 2018). AF includes the conservation of semi-natural woodlands, which can conserve bird predators of insect pests (Gonthier et al., 2019). The richness and abundance of insect species, including essential pollinators, are increased by organic farming (Sections 5.10, 12.6) (Kennedy et al., 2013; Haggar et al., 2015; Lichtenberg et al., 2017).

AF significantly improves food security and nutrition by increasing access to healthy, diverse diets and raising incomes for food producers, due to the increased biodiversity of crops, animals and landscapes (*high confidence*) (Garibaldi et al., 2016; D'Annolfo et al., 2017; Isbell et al., 2017; Dainese et al., 2019; Kerr et al., 2021). Livestock mobility improves the site-specific matching of animals' needs with food availability (Damonte et al., 2019; Mijiddorj et al., 2020; Postigo, 2021), and can generate a form of re-wilding that restores lost ecosystem functioning (Gordon et al., 2021). Conservation of crop wild relatives *in situ* supports the genetic diversity of crops for a range of future climate scenarios (Redden et al., 2015).

System-level agro-ecological transitions require policy support for experimentation and exchange of knowledge by farmers, community-based participatory methodologies and market and policy measures, for example, public procurement, local and regional market support, regulation or payments for environmental services (Mier y Terán Giménez Cacho et al., 2018; HLPE, 2019; Snapp et al., 2021). Scientific consensus about the food security and environmental implications of agro-ecological transitions on a global scale is lacking. Yields of agro-forestry and organic farming can be lower than high-input agricultural systems but, conversely, AF can boost productivity and profit, varying according to the time frame and the socioeconomic, political or ecosystem context (*medium confidence*) (Section 5.14) (Muller et al., 2017; Barbieri et al., 2019; Smith et al., 2019b; Smith et al., 2020). Such contrasting results and the limited investment in agro-ecological research to date mean it is paramount to assess the global and regional impacts of agro-ecological transitions on food production, ecosystems and economies in the context of climate change adaptation (Section 5.14) (DeLonge et al., 2016; Muller et al., 2017; Barbieri et al., 2019).

Cross-Chapter Box NATURAL (continued)

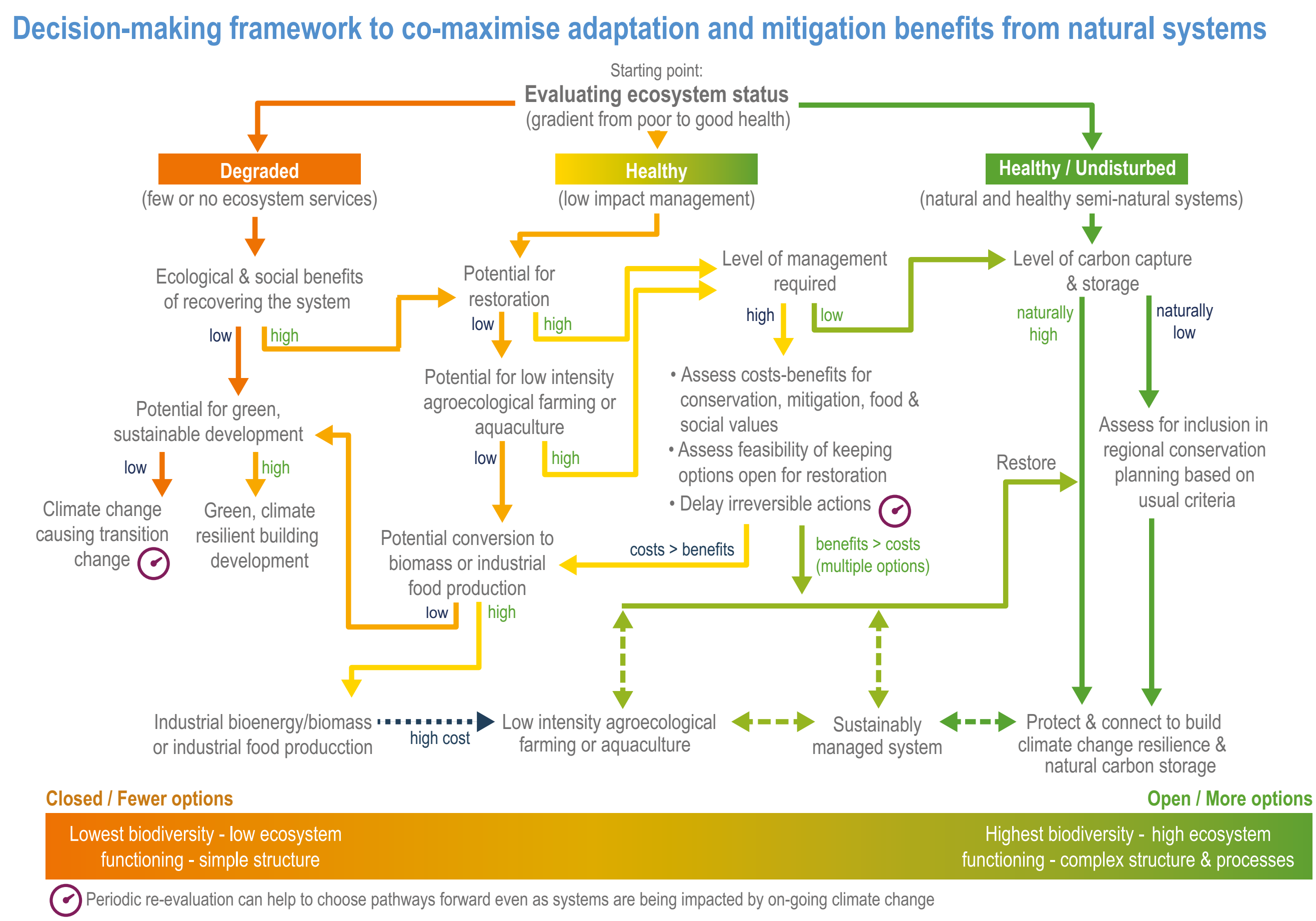


Figure Cross-Chapter Box NATURAL.1 | Decision-making framework to co-maximise adaptation and mitigation benefits from natural systems. Decision-making pathways are designed to add robustness in the face of uncertainties in future climate change and its impacts. Emphasis is on keeping open as many options as possible, for as long as possible, with periodic re-evaluation to aid in choosing pathways forward, even as systems are being impacted by ongoing climate change.

Conclusions

NbS provide adaptation and mitigation benefits for climate change as well as contributing to achieving other sustainable development goals (*high confidence*). NbS avoid further emissions and promote CO_2 removal, by using approaches that yield long-lasting mitigation benefits and avoid negative outcomes for other sustainable development goals. Poorly conceived and poorly designed mitigation efforts have the potential for multiple negative impacts: (1) cascading negative effects on long-term mitigation by promoting short-term sequestration over existing long-term accumulated carbon stocks; (2) being detrimental for biodiversity, undermining conservation adaptation; and (3) eroding other ecosystem services important for human health and well-being (*high confidence*). Conversely, well-designed and implemented mitigation efforts have the potential to provide co-benefits in terms of climate change adaptation as well as providing multiple goods and services, including the conservation of biodiversity, clean and abundant water resources, flood mitigation, sustainable livelihoods, food and fibre security and human health and well-being (*high confidence*). A key aspect of such 'smart' climate mitigation is the implementation of inclusive and adaptive management pathways (Section 1.4.2). These entail acceptance of the uncertainty inherent in projections of future climate change, especially at the regional or local level, and using decision-making processes that keep open as many options as possible for as long as possible, with periodic re-evaluation to aid in choosing pathways forward, even as systems are being impacted by ongoing climate change (Figure Cross-Chapter Box NATURAL.1; Cross-Chapter Box DEEP in Chapter 17; Section 1.4.2).

Cross-Chapter Box NATURAL (continued)

Table Cross-Chapter Box NATURAL.1 | Assessment of benefits and trade-offs between mitigation and strategies for both biodiversity and human adaptation to future climate change. Best practices highlight approaches that lead to maximal positive synergy between mitigation and adaptation; worst practices are those most likely to lead to negative trade-offs for adaptation. Many best practices have additional societal benefits beyond adaptation, such as food provisioning, recreation and improved water quality. Mitigation Potential (Mit. Pot.) and Restoration Potential (Rest. Pot.) are considered.

System	Mit. Pot.	Rest. Pot.	Best practices and adaptation benefits	Worst practices and negative adaptation trade-offs	Additional societal benefits	References
Forests						
Boreal forests	medium	medium	Maintain or restore species and structural diversity, reduce fire risk, spatially separate wood production and sustainably intensify management in some regions	Very large-scale clear cuts, aiming for one or few tree species, although boreal is characterised by few tree species and a natural fire risk	Providing goods and services, jobs and improved air quality and hydrology	(Drever et al., 2021)
Temperate forests	very high	high	Maintain or restore natural species and structural diversity, leading to more biodiverse and resilient systems	Planting large-scale non-native monocultures which would lead to loss of biodiversity and poor climate change resilience	Providing goods and services, jobs and improved hydrology and biodiversity	Sections 2.4.3; 2.5; Box 2.2 ; (Nabuurs et al., 2017; Roe et al., 2019; Favero et al., 2020)
Tropical wet forests	high	moderate	Maintain or restore natural species and structural diversity, high biodiversity, more resilient to climate change	Planting non-native monocultures, loss of biodiversity, poor climate change resilience, soil erosion	Indigenous foods, medicines and other forest products, including sustainable selective logging	Section 2.4.3 (Edwards et al., 2014)
Tropical dry forests	high	moderate	Integrated landscape management	Planting non-native monocultures, loss of biodiversity, poor climate change resilience, soil erosion		(Foli et al., 2018)
Tropical peatland forests	very high	low	Integrated landscape management	Cutting native rainforest and planting palm oil for biodiesel results in very high carbon emissions from exposed peat soils	Forest pond fish are a major food for local communities	Section 2.4.3; 2.5; (Smith et al., 2019b)
Blue carbon						AR6 WGI 5.6.2.2.2 (Canadell et al., 2021)
Mangroves	moderate	high	Conservation, restoration of hydrological flows, re-vegetation with native plants, livelihood diversification, landscape planning for landward and upstream migration	Potential NH_4 emissions	Improved fisheries and biodiversity, coastal protection against SLR and storm surges, recreation and cultural benefits	Sections 3.4.2.5; 3.5.5.5; 3.6.3.1; (Macreadie et al., 2019; Duarte et al., 2020; Sasmito et al., 2020)
Saltmarshes	moderate	high	Conservation, reduction of nutrient loads, restoration of hydrological flows and sediment delivery, re-vegetation with native plants, landscape planning for landward and upstream migration	Potential NH_4 emissions	Improved fisheries and biodiversity, protection against SLR and storm surges, recreational and cultural benefits	Sections 3.4.2.5; 3.5.5.5; 3.6.3.1; (Macreadie et al., 2019; Duarte et al., 2020)
Seagrasses	moderate	high	Conservation, restoration, improve water quality and reduce local stressors (reduction of industrial sewage, anchoring and trawling regulation)	Potential NH_4 emissions	Improved fisheries and biodiversity, protection from shoreline erosion, recreational benefits	Section 3.4.2.5; 3.5.5.5; 3.6.3.1; (de los Santos et al., 2019; Macreadie et al., 2019; Duarte et al., 2020)

Cross-Chapter Box NATURAL (continued)

System	Mit. Pot.	Rest. Pot.	Best practices and adaptation benefits	Worst practices and negative adaptation trade-offs	Additional societal benefits	References
Urban ecosystems						
Urban forests	moderate to high*	moderate	Integrated landscape management. Species richness (including exotics) can be high.	Monoculture of an exotic tree lowers resilience and reduces biodiversity	Recreation and aesthetics, stormwater absorption benefits, heat mitigation, air quality improvements	Chapter 6, this report
Urban wetlands	moderate*	moderate	Integrated landscape management		Recreation and aesthetics, stormwater absorption, heat mitigation, coastal flood protection	Chapter 6, this report
Urban grasslands	moderate*	moderate	Integrated landscape management	fertilised commercial grass monocultures often require irrigation and are less resilient to droughts than native, mixed grasses and forbs	Recreation and aesthetics, stormwater absorption, heat mitigation	Chapter 6, this report
Open grasslands and savanna						
Boreal and temperate peatlands	high	moderate	Block drainage channels, raise water levels to their natural condition, remove planted trees, re-vegetation of bare peat, no fires, increased biodiversity resilience, reduced flood risk	Inappropriate hydrological restoration, e.g., flood surface depth greater than natural depth leading to methane emissions	Improved water quality in some conditions	Sections 2.4.3; 2.5;(Bonn et al., 2016; Nugent, 2019; Taillardat et al., 2020)
Tropical savannas and grasslands (including rangelands)	moderate	high	Control of feral herbivores, reintroduce indigenous burning, reintroduce native herbivores and controlled grazing, strategic design of water holes, community-based natural resource management, grass reseeding, clearing of invasive and encroaching woody plants	Afforestation,over-grazing/stocking, no burning, inappropriate placement and design of watering points. All lead to loss of biodiversity and resilience, soil erosion and water insecurity.	Improved grazing potential for livestock and dairy production, sustainable wildlife harvests, increased water security, income from eco-tourism, medicinal plants, fuel wood, enhanced food security	Sections 2.4.3; 2.5; Box 2.1; (Stafford et al., 2017; Moura et al., 2019; Shackelford et al., 2021; Stringer et al., 2021; Wilsey, 2021)
Temperate grasslands and rangelands	moderate to high	moderate to high	Integrated landscape management, sustainable grazing, community-based natural resource management, native grassland species are more resistant to drought than introduced species	Monocultures (especially of introduced species), over-fertilising with chemical or organic amendments, failure to manage human–wildlife clashes, failure to distribute income equitably, inadequate enabling policy to facilitate integrated landscape management	Sustainable harvest of wildlife, livestock and dairy production, wild fruits, medicinal plants, construction material, fuel wood, income from ecotourism	Sections 2.4.3; 2.5, Box 2.1; (Farai, 2017; Baker et al., 2018; Homewood et al., 2020; Wilsey, 2021)
AF and aquaculture	high	high (context-specific)	Biodiverse systems on the landscape scale, participatory adaptation to context, short value chains, farmer incentives, biodiversity synergies, reduced climate risk	Poorly chosen species, practices and amendments can lead to low yields. Simplified agro-forestry systems and industrial-scale organic agriculture lack a holistic system-wide approach. Over-fertilising with organic amendments.	Food security, human health, livelihoods, socio-cultural benefits, e.g., culturally appropriate foods	Sections 5.4, 5.10, 5.12, 5.14 ; (Coulibaly et al., 2017; HLPE, 2019; Quandt et al., 2019; Sinclair et al., 2019; Smith et al., 2019b; Muchane et al., 2020; Reppin et al., 2020)

Cross-Chapter Box SLR | Sea Level Rise

Authors: Gonéri Le Cozannet (France, Chapter 13, CCP4), Judy Lawrence (New Zealand, Chapter 11), David S. Schoeman (Australia, Chapter 3), Ibidun Adelekan (Nigeria, Chapter 9), Sarah R. Cooley (USA, Chapter 3), Bruce Glavovic (New Zealand/South Africa, Chapter 18, CCP2), Marjolijn Haasnoot (The Netherlands, Chapter 13, CCP2), Rebecca Harris (Australia, Chapter 2), Wolfgang Kiessling (Germany, Chapter 3), Robert E. Kopp (USA, WGI), Aditi Mukherji (Nepal, Chapter 4), Patrick Nunn (Australia, Chapter 15), Dieter Piepenburg (Germany, Chapter 13), Daniela Schmidt (UK/Germany, Chapter 13), Craig T. Simmons (Australia), Chandni Singh (India, Chapter 10, CCP2), Aimée Slangen (The Netherlands, WGI), Seree Supratid (Thailand, Chapter 4).

Sea level rise is already impacting ecosystems, human livelihoods, infrastructure, food security and climate mitigation at the coast and beyond. Ultimately, it threatens the existence of cities and settlements in low-lying areas, and some island nations and their cultural heritage (Chapters 9–15; Cross-Chapter Papers 2, 4; Oppenheimer et al., 2019). The challenge can be addressed by mitigation of climate change and coastal adaptation.

Current impacts of sea level rise

The rate of global mean SLR was 1.35 mm yr^{-1} (0.78–1.92 mm yr^{-1}, *very likely* range) during 1901–1990, faster than during any century in at least 3000 years (*high confidence*) (WGI AR6 Chapter 9; Stanley and Warne, 1994; Woodroffe et al., 2016; Fox-Kemper et al., 2021). Global mean SLR has accelerated to 3.25 mm yr^{-1} (2.88–3.61 mm yr^{-1}, *very likely* range) during 1993–2018 (*high confidence*). Extreme sea levels have increased consistently across most regions (WGI AR6 Chapter 9; Fox-Kemper et al., 2021). The largest observed changes in coastal ecosystems are being caused by the concurrence of human activities, waves, current-induced sediment transport and extreme storm events (*medium confidence*) (Chapters 3, 15, 16; Takayabu et al., 2015; Mentaschi et al., 2018; Duvat, 2019; Murray et al., 2019; Oppenheimer et al., 2019). Early impacts of accelerating SLR detected at sheltered or subsiding coasts include chronic flooding at high tides, wetland salinisation and ecosystem transitions, increased erosion and coastal flood damage (Chapters 3, 11, 13–16; WGI AR6 Chapter 9; Sweet and Park, 2014; Moftakhari et al., 2015; Nunn et al., 2017; Oppenheimer et al., 2019; Sharples et al., 2020; Fox-Kemper et al., 2021; Strauss et al., 2021). The exposure of many coastal populations and ecosystems to SLR is high: economic development is disproportionately concentrated in and around coastal cities and settlements (*virtually certain*) (Chapters 3, 9–15; Cross-Chapter Papers 2, 4).

Projected risks to coastal communities, infrastructure and ecosystems

Risks from SLR are *very likely* to increase by one order of magnitude well before 2100 without adaptation and mitigation action as agreed by parties to the Paris Agreement (*very high confidence*). Global mean SLR is *likely* to continue accelerating under SSP1-2.6 and more strongly forced scenarios (Figure BoxSLR1; WGI AR6 Chapter 9; Oppenheimer et al., 2019; Fox-Kemper et al., 2021), increasing the risk of chronic coastal flooding at high tide, serious flooding during extreme events such as swells, storms and hurricanes, and erosion, and coastal ecosystem losses across many low-lying and erodible coasts (*very high confidence*) (Chapters 3, 9–15; Cross-Chapter Paper 2; Hinkel et al., 2014; McLachlan and Defeo, 2018; Kulp and Strauss, 2019; Vousdoukas et al., 2020b). The compounding of rainfall, river flooding, rising water tables, coastal surges and waves are projected to exacerbate SLR impacts on low-lying areas and rivers further inland (Chapters 4, 11–15; Bevacqua et al., 2020).

There is *high confidence* that coastal risks will increase by at least one order of magnitude over the 21st century due to committed SLR (Hinkel et al., 2013; Hinkel et al., 2014; IPCC, 2019b). Exposure of population and economic assets to coastal hazards is projected to increase over the next decades, particularly in coastal regions with fast-growing populations in Africa, Southeast Asia and Small Islands (*medium evidence*) (Chapters 9–15; Cross-Chapter Papers 2, 4; Neumann et al., 2015; Jones and O'Neill, 2016; Merkens et al., 2016; Merkens et al., 2018; Rasmussen et al., 2020). For RCP8.5, 2.5–9% of the global population and 12–20% of the global gross domestic product is projected to be exposed to coastal flooding by 2100 (Kulp and Strauss, 2019; Kirezci et al., 2020; Rohmer et al., 2021). Above 3°C global warming levels (GWL) and with low adaptation, SLR may cause disruptions to ports and coastal infrastructure (Camus et al., 2019; Christodoulou et al., 2019; Verschuur et al., 2020; Yesudian and Dawson, 2021), which in turn may cascade and amplify across sectors and regions, generating impacts to financial systems (Chapters 11, 13; Mandel et al., 2021). Depending on the hydrogeological context, SLR causes salinisation of groundwater, estuaries, wetlands and soils, adding constraints to water management and livelihoods in agriculture sectors, for example, in deltas (Chapters 9, 15; Cross-Chapter Paper 4; Oppenheimer et al., 2019; Nicholls et al., 2020).

Coastal ecosystems can migrate landward or grow vertically in response to SLR, but their resilience and capacity to keep up with SLR will be compromised by ocean warming and other drivers, depending on regions and species, for example, above 1.5°C for coral reefs (*high confidence*) (Chapters 3, 16; IPCC, 2018; Melbourne et al., 2018; Perry et al., 2018; IPCC, 2019b; Cornwall et al., 2021). Sediments and space for landward retreat are crucial for mangroves, salt marshes and beach ecosystems (*high confidence*) (Chapter 3; Peteet et al., 2018; Schuerch et al., 2018; FitzGerald and Hughes, 2019; Friess et al., 2019; Leo et al., 2019; Schuerch et al., 2019). Loss of habitat is accompanied by loss of associated ecosystem services, including wave-energy attenuation, habitat provision for biodiversity, food production and carbon storage (Chapter 3; Cross-Chapter Box NATURAL in Chapter 2).

Cross-Chapter Box SLR (continued)

Under a high-emissions, low-likelihood/high-impact scenario, where *low confidence* ice-sheet mass loss occurs, global mean SLR could exceed the *likely* range by more than one additional metre in 2100 (Figure BoxSLR1b; Cross-Chapter Box DEEP in Chapter 17; WGI AR6 Technical Summary and Chapter 9; Arias et al., 2021; Fox-Kemper et al., 2021). This is a reason for concern given that rapid SLR after the last glacial–interglacial transition caused a drowning of coral reefs (*high confidence*) (Camoin and Webster, 2015; Sanborn et al., 2017; Webster et al., 2018), extensive loss of coastal land and islands, habitats and associated biodiversity (*high confidence*) (AR6 WGI Chapter 9; Fruergaard et al., 2015; Fernández-Palacios et al., 2016; Hamilton et al., 2019; Helfensdorfer et al., 2019; Kane and Fletcher, 2020; Fox-Kemper et al., 2021), and triggered Neolithic migrations in Europe and Australia (*medium confidence*) (Cross-Chapter Box PALEO in Chapter 1; Turney and Brown, 2007; Brisset et al., 2018; Williams et al., 2018).

At centennial time scales, projected SLR represents an existential threat for island nations, low-lying coastal zones and the communities, infrastructure, and cultural heritage therein (Chapters 9–15; Cross-Chapter Paper 4). Even if climate warming is stabilised at 2°C to 2.5°C GWL, coastlines will continue to reshape over millennia, affecting at least 25 megacities and drowning low-lying areas where 0.6–1.3 billion people lived in 2010 (*medium confidence*) (WGI AR6 Chapter 9; Marzeion and Levermann, 2014; Clark et al., 2016; Kulp and Strauss, 2019; Fox-Kemper et al., 2021; Strauss et al., 2021).

Solutions, opportunities and limits to adaptation

The ability to adapt to current coastal impacts, to cope with future coastal risks and to prevent further acceleration of SLR beyond 2050 depends on immediate mitigation and adaptation actions (*very high confidence*). The most urgent adaptation challenge is chronic flooding at high tide (Chapters 10, 11, 13–15). Reducing the acceleration of SLR beyond 2050 will only be achieved with fast and profound mitigation of climate change (Nicholls et al., 2018; Oppenheimer et al., 2019). Until 2050, adaptation planning and implementation needs are projected to increase significantly in most inhabited coastal regions (see Figure BoxSLR1; WGI AR6 Chapter 9; IPCC, 2019b; Fox-Kemper et al., 2021). For SSP1-2.6 and more strongly forced scenarios, SLR rates continue to increase (WGI AR6 Chapter 9; Fox-Kemper et al., 2021), and so do the scale and frequency of adaptation interventions needed in coastal zones (Figure BoxSLR1; Haasnoot et al., 2020).

Risks can be anticipated, planned and decided upon, and adaptation interventions can be implemented over the coming decades considering their often long lead- and lifetimes, irrespective of the large uncertainty about SLR beyond 2050 (*high confidence*) (Figure BoxSLR1; Cross-Chapter Box DEEP in Chapter 17; Cross-Chapter Paper 2; Chapters 11, 13; Haasnoot et al., 2018; Stephens et al., 2018; Stammer et al., 2019). Adaptation capacity and governance to manage risks from projected SLR typically require decades to implement and institutionalise (*high confidence*) (Chapters 11, 13; Haasnoot et al., 2021). Without considering both short- and long-term adaptation needs, including beyond 2100, communities are increasingly confronted with a shrinking solution space, and adverse consequences are disproportionately borne by exposed and socially vulnerable people (Chapters 1, 8). Sea level rise is *likely* to compound social conflict in some settings (*high confidence*) (Oppenheimer et al., 2019).

Coastal impacts of SLR can be avoided by preventing new development in exposed coastal locations (Chapters 3, 9–15; Cross-Chapter Paper 2; Doberstein et al., 2019; Oppenheimer et al., 2019). For existing developments, a range of near-term adaptation options exists, including: (a) engineered, sediment- or ecosystem-based protection; (b) accommodation and land-use planning, to reduce the vulnerability of people and infrastructure; (c) advance through, for example, land reclamation; and (d) retreat through planned relocation or displacements and migrations due to SLR (Chapters 9–15; Cross-Chapter Paper 2; Oppenheimer et al., 2019). Only avoidance and relocation can remove coastal risks for the coming decades, while other measures only delay impacts for a time, have increasing residual risk or perpetuate risk and create ongoing legacy effects and *virtually certain* property and ecosystem losses (*high confidence*) (Cross-Chapter Paper 2; Siders et al., 2019). Large-scale relocation has immense cultural, political, social and economic costs, and equity implications, which can be reduced by fast implementation of climate mitigation and adaptation policies (Chapter 8; Cross-Chapter Paper 2; Gibbs, 2015; Haasnoot et al., 2021). While relocation may currently appear socially unacceptable, economically inefficient or technically infeasible today (Lincke and Hinkel, 2021), it becomes the only feasible option as protection costs become unaffordable and the limits to accommodation become obvious (Chapters 11, 13, 15; Hino et al., 2017; Siders et al., 2019; Strauss et al., 2021). Effective responses to rising sea level involve locally applicable combinations of decision analysis, land-use planning, public participation and conflict resolution approaches; together these can anticipate change and help to chart adaptation pathways, over time addressing the governance challenges due to rising sea level (*high confidence*) (Oppenheimer et al., 2019).

Ecosystem-based adaptation can reduce impacts on human settlements and bring substantial co-benefits, such as ecosystem services restoration and carbon storage, but they require space for sediment and ecosystems and have site-specific physical limits, at least above 1.5°C GWL (*high confidence*) (Cross-Chapter Box NATURAL in Chapter 2; Chapters 3, 9, 11, 15; Herbert et al., 2015; Brown et al., 2019; Van Coppenolle and Temmerman, 2019; Watanabe et al., 2019; Neijnens et al., 2021). For example, planting and conserving vegetation helps sediment accumulation by dissipating wave energy and reducing impacts of storms, at least at present-day sea levels (*high confidence*)

Cross-Chapter Box SLR (continued)

(Temmerman et al., 2013; Narayan et al., 2016; Romañach et al., 2018; Laengner et al., 2019; Leo et al., 2019). Coastal wetlands and ecosystems can be preserved by landward migration (Schuerch et al., 2018; Schuerch et al., 2019) or sediment supply (VanZomeren et al., 2018), but they can be seriously damaged by coastal defences designed to protect infrastructure (Chapters 3, 13; Cooper et al., 2020b). Sediment nourishment can prevent erosion, but it can also negatively impact beach amenities and ecosystems through ongoing dredging, pumping and deposition of sand and silts (VanZomeren et al., 2018; de Schipper et al., 2021; Harris et al., 2021).

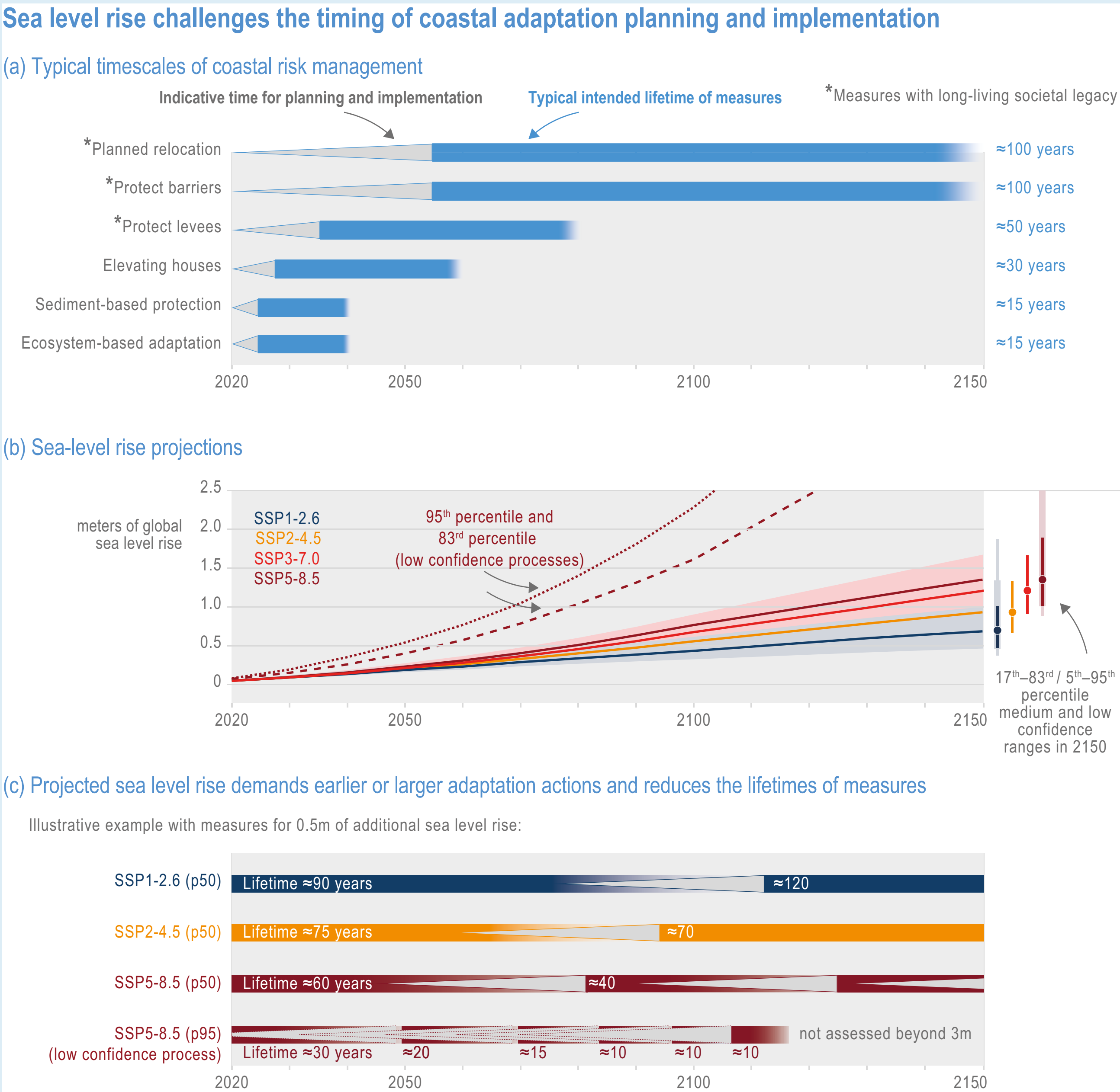


Figure Cross-Chapter BoxSLR.1 | The challenge of coastal adaptation in the era of sea level rise (SLR): (a) typical time scales for the planning, implementation (grey triangles) and operational lifetime of current coastal risk-management measures (blue bars); **(b)** global sea level projections, which are representative of relative SLR projected for 60–70% of global shorelines, within ±20% errors (WGI AR6 Chapter 9; Fox-Kemper et al., 2021); **(c)** frequency of illustrative adaptation decisions to +0.5 m of SLR under different SSP-RCP scenarios. In response to accelerated SLR, adaptation either occurs earlier and faster, or accounts for higher amounts of SLR (e.g., to +1 m instead of to +0.5 m). Adaptation to +0.5 m from today's sea levels have a lifetime of 90 years for SSP1-2.6, but lifetime is reduced to 60 years for SSP5-8.5 and 30 years for a high-end scenario involving *low confidence* processes. Adaptations to +0.5 m are comparable to, for example, the Thames Barrier in the United Kingdom or the Delta Works in the Netherlands, which primarily had an intended lifetime of 100–200 years. Adaptation measures to +0.2 m may include nourishment or wetland or setback zones.

Cross-Chapter Box SLR (continued)

There is increasing evidence that current governance and institutional arrangements are unable to address the escalating risks in low-lying coastal areas worldwide (*high confidence*). Barriers to adaptation, such as decision making driven by short-term thinking or vested interests, funding limitations and inadequate financial policies and insurance, can be addressed equitably and sustainably through implementation of suites of adaptation options and pathways (Chapters 11, 13, 17–18; Cross-Chapter Paper 2). Improved coastal adaptation governance can be supported by approaches that consider changing risks over time, such as 'dynamic adaptation pathways' planning (Chapters 11, 13, 18; Cross-Chapter Box DEEP in Chapter 17). Integrated coastal zone management and land-use and infrastructure planning are starting to consider SLR by, for example, monitoring early signals (Haasnoot et al., 2018; Stephens et al., 2018; Kool et al., 2020), updating sea level projections (Stephens et al., 2017; Hinkel et al., 2019; Kopp et al., 2019; Stammer et al., 2019), considering uncertainties of sea level projections and coastal impacts (e.g., Stephens et al., 2017; Jevrejeva et al., 2019; Rohmer et al., 2019), as well as engaging with communities, practitioners and scientists, recognising the values of current and future generations (e.g., Nicholls et al., 2014; Buchanan et al., 2016b). While there is *high agreement* that the majority of adaptation needs are not met yet, there is *robust evidence* of SLR increasingly being considered in coastal adaptation decision making and being embedded in national and local guidance and regulations (Nicholls et al., 2014; Le Cozannet et al., 2017; Lawrence et al., 2018; Kopp et al., 2019; McEvoy et al., 2021).

Cross-Chapter Box DISASTER | Disasters as the Public Face of Climate Change

Authors: Aditi Mukherji (India, Chapter 4), Guéladio Cissé (Mauritania/Switzerland/France, Chapter 7), Caroline Zickgraf (Contributing Author), Paulina Aldunce (Chile, Chapter 7), Liliana Raquel Miranda Sara (Peru, Chapter 12), William Solecki, (USA, Chapter 17), Friederike Otto (UK, WGI), François Gemenne (France, WGI), Martina Angela Caretta (Sweden, Chapter 4);, Richard Jones (UK, WGI); Richard Betts (UK, Chapter 4), Maarten van Aalst (the Netherlands, Chapter 16), Jakob Zscheischler (Switzerland), Kris Murray (UK), Mauro E. González (Chile).

Introduction

Some extreme weather events are increasing in frequency and (or) severity as a result of climate change (Seneviratne et al., 2021) (*high confidence*). These include extreme rainfall events (Roxy et al., 2017; Myhre et al., 2019; Tabari, 2020); extreme and prolonged heat leading to catastrophic fires (Bowman et al., 2017; Krikken et al., 2019; van Oldenborgh et al., 2020); and more frequent and stronger cyclones/ hurricanes and resulting extreme rainfall (Griego et al., 2020). These extreme events, coupled with high vulnerability and exposure in many parts of the world, turn into disasters and affect millions of people every year. New advances enable the detection and attribution of these extreme events to climate change (Otto et al., 2016; Seneviratne et al., 2021), with the most recent study saying that heavy rains leading to devastating floods in western Europe that captured the world's attention in July 2021 were made more likely due to climate change (Kreienkamp et al., 2021). Most WGII chapters (this volume) report various extreme event-induced disasters and their societal impacts. This cross-chapter box brings together authors from WGI and WGII to emphasise that disasters following extreme events have become the most visible and public face of climate change (Solecki and Rosenzweig, 2014). These disasters reflect immediate societal and political implications of rising risks (*high confidence*), but also provide windows of opportunity to raise awareness about climate change and to implement disaster-reduction policies and strategies (*high confidence*) (Albright, 2020; Boudet et al., 2020).

Here, we document eight catastrophic climate-related disasters that took place between 2017 and 2021. These disasters resulted in the loss of lives and livelihoods and had adverse impacts on biodiversity, health, infrastructure and the economy. These disasters provided important rallying points for discussions around climate change, equity and vulnerability in some cases. These disasters also offer valuable lessons about the role of effective climate change adaptation in managing disaster risks and the importance of Loss and Damage mechanisms in global negotiation processes (Jongman et al., 2014; Mechler et al., 2014; Cutter and Gall, 2015).

Case 1. Compounded events and impacts on human systems: Cyclones Idai and Kenneth in Mozambique in 2019

While individual events alone can lead to major disasters, when several events occur in close spatial and temporal proximity, impacts get compounded, with catastrophic results (Zscheischler et al., 2018; Zscheischler et al., 2020). In March 2019, Cyclone Idai (category 2) was the deadliest storm on record to strike the African continent, with the coastal city of Beira in Mozambique being particularly hard hit with at least 602 deaths (CRED, 2019; Zehra et al., 2019; Phiri et al., 2020). Nationally, Idai caused massive housing, water supply, drainage and sanitation destruction, but its impact extended to South Africa through disruption of the regional electricity grid (Yalew et al., 2020). In April 2019, amidst heightened vulnerabilities in the aftermath of cyclone Idai, cyclone Kenneth (category 4) hit the country, affecting 254,750 people and destroying more than 45,000 homes (Kahn et al., 2019). These circumstances caused the rapid spread of cholera, which triggered a massive vaccination programme to control the epidemic (Kahn et al., 2019; Lequechane et al., 2020). While there were no specific detection and attribution studies for Idai and Kenneth, overall, there is *high confidence* that the rainfall associated with tropical cyclones is more intense because of global warming. However, there remain significant uncertainties about the impact of climate change on the numbers and strength of tropical cyclones per se (Walsh et al., 2019; Zhang G. et al., 2020).

Case 2. COVID-19 as the compounding risk factor: Cyclone Amphan in India and Bangladesh, 2020

Cyclone Amphan hit coastal West Bengal and Bangladesh on 20 May 2020. It was the first supercyclone to form in the Bay of Bengal since 1999 and one of the fiercest to hit West Bengal, India, in the last 100 years. The cyclone intensified from a cyclonic storm (category 1) to a supercyclone (category 5) in less than 36 hours (Balasubramanian and Chalamalla, 2020). Several hours before and on 20 May, extreme rain events resulted in heavy cumulative rainfall, flash flooding and landslides in several adjoining districts (Mishra and Vanganuru, 2020). As per the initial estimates, about 1600 km^2 area in the mangrove forests of *Sundarbans* were damaged, and over 100 lives were lost. Earlier cyclones in the region have shown that impacts of these events are gendered (Roy, 2019). The cyclone damage was somewhat lessened due to the delta's mangroves (Sen, 2020). The estimated damage was USD 13.5 billion. Cyclone Amphan was the largest source of displacement in 2020, with 2.4 million displacements in India alone, of which 800,000 were pre-emptive evacuations by authorities

Cross-Chapter Box DISASTER (continued)

(IDMC, 2020). Because it happened amidst the COVID-19 crisis, evacuation plans were constrained due to social distancing norms (Baidya et al., 2020). Social media played an important role in disseminating pre-cyclone warnings and information on post-cyclone relief work (Crayton et al., 2020; Poddar et al., 2020).

Case 3. Further exacerbating inequities in human systems: Hurricane Harvey, USA, 2017

Hurricane Harvey, a category 4 hurricane, made landfall on Texas and Louisiana in August 2017, causing catastrophic flooding and 80 deaths and inflicting $125 billion (2017 USD) in damage, of which $67 billion (2017 USD) was attributable to climate change (Frame et al., 2020). Several studies estimated the return period of the rainfall associated with this event and assessed that human-induced climate change increased the likelihood by a factor of approximately three using a combination of observations and climate models (Risser and Wehner, 2017; van Oldenborgh et al., 2017b). The impacts of Hurricane Harvey were exacerbated by extensive residential development in flood-prone locations. A study showed that urbanisation increased the probability of such extreme flood events several folds (Zhang W. et al., 2018) through the alteration of ground cover and disruption and redirection of water flow. Water quality in cities also deteriorated (Horney et al., 2018; Landsman et al., 2019), and 85% of flooded land subsided at a rate of 5 mm yr^{-1} following the event (Miller and Shirzaei, 2019). Notably, the impacts of Harvey were unequally distributed along racial and social categories in the greater Houston area. Neighbourhoods with larger Black, Hispanic and disabled populations were the worst affected by the flooding following the storm and rainfall (Chakraborty et al., 2018; Chakraborty et al., 2019; Collins et al., 2019b). In addition, racial and ethnic disparities were shown to impact post-disaster needs, ranging from household damage to mental health and recovery (Collins et al., 2019b; Flores et al., 2020; Griego et al., 2020).

Case 4. Impacts worsened due to sociocultural and political conditions: The "Coastal Niño" in Peru, 2017

The Coastal Niño event of 2017 led to extreme rainfall in Peru, which was made more likely by at least 1.5 times as compared to pre-industrial times due to anthropogenic climate change and Coastal Niño (Christidis et al., 2019) and comparable to the El Niño events of 1982–1983 and 1997–1998 (Poveda et al., 2020). This event showed evidence of larger anomalies in flood exposure (Muis et al., 2018; Christidis et al., 2019; Rodríguez-Morata et al., 2019) and sediment transport (Morera et al., 2017). In Peru, this Niño event led to USD 6 to 9 billion of monetary losses, more than a million inhabitants were affected, 6614 km of roads were damaged, 326 bridges were destroyed, 41,632 homes were damaged or became uninhabitable and 2150 schools and 726 health posts were damaged (French and Mechler, 2017; French et al., 2020), leaving half of the country in a state of emergency (Christidis et al., 2019). Furthermore, institutional and systemic sociocultural and political conditions at multiple levels significantly worsened disaster risk management which hampered response and recovery (French et al., 2020). Citizens and zero-order responders proved to be more effective and quicker than national disaster risk management response (Briones et al., 2019).

Case 5. Triggering institutional response for future preparedness: Mega-fires of Chile, 2017

The mega-fire that occurred in Chile in January 2017 had the highest severity recorded on the planet (CONAF, 2017), burning in three weeks an area close to 350,000 hectares in south-central Chile. These events have been associated with the prolonged ongoing drought that has persisted for more than one decade and with the increase in heat waves (González et al., 2018; Miranda et al., 2020). This extreme drought and the total burned area of the last decades have been attributed to anthropogenic climate change in at least 25% and 20% of their severity, respectively (Boisier et al., 2016). The mega-fire of summer 2017 resulted in 11 deaths, more than 1500 houses burned and the destruction of the small town of Santa Olga. The smoke from these fires exposed 9.5 million people to air pollution, causing an estimated 76 premature deaths (Bowman et al., 2017; González et al., 2020). The direct costs incurred by the State exceeded USD 360 million (González et al., 2020). The 2017 mega-fires led to a series of institutional responses such as management plans that include preventive forestry techniques, regulatory plans containing rural–urban interface areas, an emergency forest fire plan, and promotion of native species (González et al., 2020).

Case 6. Loss of human lives and biodiversity: Bushfires in Australia, 2019/2020

In the summer of 2019/2020, bushfires in Australia killed 417 people due to smoke and killed between 0.5 and 1.5 billion wild animals and tens of thousands of livestock (van Oldenborgh et al., 2020). These fires also destroyed approximately 5900 buildings and burnt 97,000 km^2 of

Cross-Chapter Box DISASTER (continued)

vegetation, which provided habitat for 832 species of native vertebrate fauna. Seventy taxa had more than 30% of their habitat impacted, including 21 already identified as threatened with extinction (Ward et al., 2020). In addition, millions of people experienced levels of smoke 20 times higher than the government-identified safe level. The year 2019 had been Australia's warmest and driest year on record. In the summer of 2019/2020, the seasonal mean and mean maximum temperatures were the hottest by almost 1°C above the previous record. Eight of the 10 hottest days on record for national mean temperatures occurred in December 2019. While the prevailing weather conditions were strongly influenced by the Indian Ocean Dipole pressure pattern, with a contribution from weakly positive ENSO conditions in the Pacific, the fact that Australia is approximately 1°C warmer than the early 20th century demonstrates links to anthropogenic climate change. Eight climate models using event attribution methodologies (comparison of simulations with present-day and pre-industrial forcings) indicates that anthropogenic climate change made the heat conditions of December 2019 more than twice as likely (van Oldenborgh et al., 2020).

Case 7. Improved preparedness reduced mortality: Heatwave in Europe, 2019

In 2019, Europe experienced several record-breaking heatwaves. In June, the first one featured record heat for that time in early summer, with temperatures of 6°C–10°C above normal over most of France and Germany, northern Spain, northern Italy, Switzerland, Austria and the Czech Republic (Climate, 2019). The second heatwave also resulted in all-time records for Belgium, Germany, Luxembourg, the Netherlands and the UK in July. Attribution studies (Vautard et al., 2020) demonstrated that these would have had extremely small odds in the absence of human-induced climate change or would have been 1.5°C–3°C colder without human-induced climate change. This study concluded that state-of-the-art climate models underestimate the trends in local heat extremes compared to the observed trend. Since the 2003 heatwave, which resulted in tens of thousands of deaths across Europe, many European countries have adopted heatwave plans, including early warning systems. Therefore, mortality in 2019 was substantially lower than it might have been. Unfortunately, mortality is not registered systematically across Europe, and therefore, comprehensive analyses are missing. But even based on the countries that provide the numbers, more specifically France, Belgium and the Netherlands, the European heatwave of 2019 resulted in over 2500 deaths (CRED, 2019). Despite their deadliness and the fact that climate change increases the frequency, intensity and duration of heatwaves globally (Perkins-Kirkpatrick and Lewis, 2020), heatwaves are not consistently reported in many countries (Harrington and Otto, 2020), rendering it currently impossible to estimate climate change impacts on lives and livelihoods comprehensively.

Case 8. Loss of human lives and property: Floods in Europe in 2021

From 12 to 15 July 2021, extreme rainfall in Germany, Belgium, Luxembourg and neighbouring countries led to severe flooding. The severe flooding was caused by very heavy rainfall over a period of 1–2 d, wet conditions prior to the event and local hydrological factors. The observed rainfall amounts in the Ahr/Erft region and the Belgian part of the Meuse catchment substantially exceeded previous records for observed rainfall. An attribution study (Kreienkamp et al., 2021) focused on the heavy rainfall rather than river discharge and water levels, because sufficient hydrological data was not available, partly because hydrological monitoring systems were destroyed by the event. Considering a larger region of western Europe between the northern side of the Alps and the Netherlands, in any given location, one such event can be expected every 400 years on average in the current climate. The floods resulted in least 222 fatalities and substantial damage to houses, roads, communication infrastructure, motorways, railway lines and bridges.

Table Cross-Chapter Box DISASTER.1 | Summarising impacts, losses and damages, displacement and climate change detection and attribution of these seven disaster case studies.

Name of the disaster event	Impacts, losses and damages; and displacement	Climate change detection and attribution
Cyclones Idai and Kenneth, March and April 2019, Mozambique, Africa	254,750 affected people, and more than 45,000 houses were destroyed. Sparked cholera outbreaks that resulted in 6600 cases and over 200 deaths. More than 500,000 people were displaced in 2019. As of 31 December 2019, more than 132,000 people were internally displaced in Mozambique (IDMC, 2020).	There are no detection and attribution studies on Idai and Kenneth, but it is known that rainfall associated with tropical cyclones are now more intense because of global warming, but there remain significant uncertainties concerning changes in the number and strength of the cyclones themselves (Walsh et al., 2019; Zhang G. et al., 2020).
Cyclone Amphan, May 2020, West Bengal, India and Bangladesh	About 1600 km^2 area in the mangrove forests of Sundarbans were damaged. The city of Kolkata lost a substantial portion of its green cover due to Amphan. The estimated damage was USD 13.5 billion. Cyclone Amphan was the largest source of displacement in 2020, with 2.4 million displacements in India and a similar number in Bangladesh. Out of these 2.4 million, roughly 800,000 were pre-emptive evacuations or organised by the authorities (IDMC, 2020).	The combined decline of both aerosols (due to COVID-19-related lockdowns) and clouds may have contributed to the increased sea surface temperature, further compounding the climate change-related warming of the oceans (Vinoj and Swain, 2020). However, there are no attribution studies on tropical cyclones in the Indian Ocean.

Cross-Chapter Box DISASTER (continued)

Name of the disaster event	Impacts, losses and damages; and displacement	Climate change detection and attribution
Hurricane Harvey, 2017, USA	Catastrophic flooding and many deaths inflicted $125 billion (2017 USD). In addition, economic costs due to the rainfall are estimated at $90 billion, of which $67 billion are attributed to climate change (Frame et al., 2020).	Several attribution studies found that the rainfall associated with Harvey has increased by a factor of three, while intensity in rainfall and wind speed also increased due to human-induced climate change (Emanuel, 2017; Risser and Wehner, 2017; Patricola and Wehner, 2018; van Oldenborgh et al., 2020).
Coastal Niño 2017, Peru	USD 6–9 billion monetary losses with 114 deaths, 414 injuries and 1.08 million inhabitants affected. In addition, 6614 km of improved roads were damaged, 326 bridges destroyed, 41,632 homes destroyed or uninhabitable, and 242,433 homes, 2150 schools and 726 health centres damaged.	Clear anthropogenic climate change fingerprint detected. For example, while the anomalously warm ocean favoured extreme rainfall of March 2017 in Peru, the human influence was estimated to make such events at least 1.5 times more likely (Christidis et al., 2019).
Mega-fires in Chile, January 2017	The mega-fire that occurred in Chile in January 2017 burned in three weeks an area close to 3500 km^2 in south-central Chile. As a result, thousands of people were displaced.	There is no attribution study on the fires in Chile (yet). Still, there is an increasing number of attribution studies on wildfires worldwide, finding that because climate change has increased the likelihood of extreme heat, which is part of the fire weather, the likelihood of wildfire weather conditions has increased too (Krikken et al., 2019; van Oldenborgh et al., 2020).
Australian bushfires of 2019/2020	Killed 417 people due to smoke, and between 0.5 and 1.5 billion wild animals and tens of thousands of livestock. Destroyed ~5900 buildings and burnt 97,000 km^2 of vegetation that provided habitat for 832 species of native vertebrate fauna.	Anthropogenic climate change made the extreme heat condition of December 2019 more than twice as likely (van Oldenborgh et al., 2020).
Heatwaves of Europe, 2019	Record heat in several European countries, and deadliest global disaster of 2019, with over 2500 deaths (CRED, 2019)	There have been many attribution studies on heatwaves in Europe, finding that human-induced climate change is increasing the frequency and intensity of heatwaves. In the case of 2019, the observed heat would have been extremely unlikely without climate change. The studies also find that climate models underestimate the increase in heat waves in Europe compared to observed trends (Vautard et al., 2020).
Floods in western Europe (Germany, Belgium), July 2021	Severe flooding resulting in at least 222 fatalities and substantial damage to houses, roads, communication infrastructure, motorways, railway lines and bridges. Some communities were cut off for days due to road closures, inhibiting emergency responses, including evacuation.	Climate change was found to have increased the intensity of the maximum 1-d rainfall event in the summer season in this large region by about 3–19% compared to a global climate 1.2°C cooler than at the present day. The increase was similar for the 2-d event. The likelihood of such an event today was found to have increased by a factor between 1.2 and 9 for both the 1-d and 2-d events in the large region (Kreienkamp et al., 2021).

Disaster risk reduction needs to be a central component of adaptation and mitigation for meeting Sustainable Development Goals and for a climate-resilient future

Disasters resulting from extreme events are increasingly experienced by a large section of human population (Hoegh-Guldberg et al., 2018). Disasters expose inequalities in natural and managed systems and human systems as they disproportionately affect poor and marginalised communities like ethnic minorities, people of colour, Indigenous Peoples, women and children. Therefore, disaster risk reduction is fundamental for climate justice and climate resilient development (UNISDR, 2015). Far from being disconnected policy objectives, disaster risk reduction and climate change mitigation/adaptation are two sides of the same coin as recognised explicitly by the Paris Agreement and Sendai Framework of 2015. There can be no sustainable development without disaster risk reduction, as explicitly recognised by the SDGs of 2015. Furthermore, disaster events can increase awareness among citizens and provide a platform for all important stakeholders, including climate activists, to come together, and give a clarion call for the urgency of climate action.

In summary, disasters are a stark illustration of the potential for extreme weather events to impact people and other species. With the frequency, severity and (or) likelihood of several types of extreme weather increasing, disasters can increasingly be regarded as 'the public face of climate change' (*high confidence*). Detection and attribution studies make the climate change fingerprint of several types of disasters increasingly clear (*high confidence*). Moreover, existing vulnerabilities and exposures play an important role in turning extreme events into disasters, further exacerbating existing racial, gender and social inequalities (*high confidence*). Therefore, disaster risk reduction needs to be central to adaptation and mitigation efforts to meet the SDGs and the Paris Agreement for a climate-resilient future.

Cross-Chapter Box MOVING PLATE | Sourcing Food When Species Distributions Change

Authors: H. Gurney-Smith (Canada/UK), W. Cheung (Canada), S. Lluch Cota (Mexico), E. Ojea (Spain), C. Parmesan (France/UK/USA), J. Pinnegar (UK) P. Thornton (Kenya/UK), M-F. Racault (UK/France), G. Pecl (Australia), E.A. Nyboer (Canada), K. Holsman (USA), K. Miller (USA), J. Birkmann (Germany), G. Nelson (USA) and C. Möllmann (Germany)

This Cross-Chapter Box, the 'moving plate', addresses climate-induced shifts and domesticated production suitability of food species consumed by people. Marine, freshwater and terrestrial systems are already experiencing species shifts in response to climate change (*very high confidence*) (see also Sections 2.4.2.1. and 3.4.3., Figure MOVING PLATE.1 this chapter), with subsequent impacts on food provisioning services, pests and diseases (*high confidence*) (see Box 5.8 and Cross-Chapter Box ILLNESS in Chapter 2). This Box highlights food insecurity and malnutrition of vulnerable peoples under climate change for both wild and domesticated aquatic and terrestrial species, and discusses challenges for adaptation and the roles that management (transboundary and ecosystem-based) can play to enable food security, reduce conflicts and prevent resource over-extraction.

Range contractions, shifts or extirpations are projected for terrestrial and aquatic species under warming, with greater warming leading to larger shifts and losses, where mitigation would therefore benefit climate refugia and reduce projected biodiversity declines (Smith et al., 2018; Warren et al., 2018). Marine species are moving poleward faster than terrestrial and freshwater species, despite faster warming on land (Pecl et al., 2017; Lenoir et al., 2019; Woolway and Maberly, 2020), leading to new or exacerbated socioeconomic conflicts within and between countries (see Figure MOVING PLATE.1 this chapter, see Sections 13.5.2.2., 15.3.4.4., FAQ 15.3., Mendenhall et al., 2020). There is large variation in the magnitude and pattern of species shifts, even among similar species within a region, leading to changes in communities in a given region (Brown et al., 2016; Pecl et al., 2017). The number of extreme heat stress days are projected to increase for domesticated species like cattle (see Figure MOVING PLATE.1 this chapter), leading to shifts in suitable habitat for raising livestock in the open with associated impacts in animal productivity and the costs of adapting in Africa, Asia, and Central and South America (Thornton et al., 2021).

Nutritional dependency, cultural importance, livelihood, or economic reliance on shifting species will increase impacts of climate change, especially for small-scale fishers (marine and freshwater), farmers, women and communities highly dependent on local sources of food and nutrition (*high confidence*) (see Figures MOVING PLATE.1 and MOVING PLATE.3 this chapter, Sections 3.5.3., 8.2.1.2. and 15.3.4.4, McIntyre et al., 2016; Blasiak et al., 2017; Kifani et al., 2018; Bindoff et al., 2019; Atindana et al., 2020; Hasselberg et al., 2020; Farmery et al., 2021). Micronutrient concentrations from marine fisheries vary with species, providing higher concentrations of calcium, iron and zinc in tropical regions and higher concentrations of omega-3 fatty acids in polar regions (Hicks et al., 2019). While consumption of smaller species rich in micronutrients may provide significant benefits against deficiencies in Asia and Africa, local dietary changes in fish consumption may be linked to food preferences, fish availability due to international trade or illegal fishing and competing usage of fish (see Figure MOVING PLATE.3 this chapter, Hicks et al., 2019; Sumaila et al., 2020; Vianna et al., 2020). Industrial fleets are likely to switch target species (Belhabib et al., 2016) and inhibit small-scale fishers via illegal, unreported or unregulated fishing in EEZs (Belhabib et al., 2019; Belhabib et al., 2020). Extreme events can exacerbate issues, as fisheries are frequently increasingly exploited as a coping mechanism under times of crisis, increasing illegal fishing activities and conflict among maritime users (Pomeroy et al., 2016; Mazaris and Germond, 2018). Spatial conflicts between artisanal and commercial foreign fishing fleets are already occurring in Ghana (Penney et al., 2017), and from climate-induced tropical tuna shifts in the Western and Central Pacific Ocean Islands (see Section 15.3.4.4., (Bell et al., 2018a)). Properly managed small-scale fisheries can reduce poverty and improve localised food security and nutrition in low-income countries but will likely require restriction in the number of fishers, boat size or fishing days (Purcell and Pomeroy, 2015; Hicks et al., 2019).

Shifting species have negative implications for the equitable distribution of food provisioning services, increasing the complexity of resolving sovereignty claims and climate justice (*high confidence*) (Allison and Bassett, 2015; Ayers et al., 2018; Baudron et al.; Ojea et al., 2020; Palacios-Abrantes et al., 2020). Higher-latitude countries generally have higher GHG emissions and will benefit from poleward-migrating resources from tropical poorer and lower-emitting GHG countries (Free et al., 2020). In this context, climate justice supporting fishing arrangements could offset socioeconomic impacts from exiting species (Mills, 2018; Lam et al., 2020) and have negative implications particularly for small-scale operators (Farmery et al., 2021), However, considerations of climate justice have not been used by Regional Fisheries Management Organizations (RFMOs) allocation shares to date (Engler, 2020). Species shifting from one historical jurisdiction to another may result in an incentivised depletion of the resource by the country the stock is shifting away from; reforming management to allocate resource sharing of quotas and permits or stock-unrelated side payments in bilateral or multilateral cooperative agreements may compensate or prevent loss (Diekert and Nieminen, 2017; Free et al., 2020; Ojea et al., 2020; Østhagen et al., 2020; Cross-Chapter Paper Polar 6.2.).

Strong governance, ecosystem-based and transboundary management are considered fundamental to ameliorate the impacts of climate change (*high confidence*) but may be limited in effectiveness by the magnitude of change projected under low or no mitigation scenarios

Cross-Chapter Box MOVING PLATE (continued)

(see Sections 2.6.2., 14.4.2.2. and 15.3.4.4., Harrod et al., 2018c; Pinsky et al., 2018; Holsman et al., 2020; Ojea et al., 2020). Flexible and rapid policy reform and management adaptation will help to meet sustainability targets (Nguyen et al., 2016; Pentz and Klenk, 2020), and may only be available for countries with the scientific, technical and institutional capacity to implement these (*high confidence*) (Peck and Pinnegar, 2018; Figures MOVING PLATE.2 and 3 this chapter). Other adaptation options include 'follow the food' thereby migrating further (Belhabib et al., 2016), provision of alternative livelihoods (Thiault et al., 2019; Cross-Chapter Box MIGRATE in Chapter 7, Free et al., 2020), increasing ecosystem resilience by rebuilding coastal mangroves (Tanner et al., 2014; and Box 1.3) and riparian areas of freshwater ecosystems (Mantyka-Pringle et al., 2016) and autonomous adaptations, such as harvesting gear modifications to access new target species (Harrod et al., 2018c; Kifani et al., 2018), practice change, and early-warning systems (see Section 11.3.2.3; Pecl et al., 2019; Melbourne-Thomas et al., 2021). Adaptive capacity will change with country, region, scale (commercial, recreational, Indigenous) of fishery, jurisdiction, and resource dependence (see Figure MOVING PLATE.2 this chapter for adaptation options for marine, freshwater and terrestrial systems). While shifting fishing fleets or herding may be an adaptation option to follow resources, limits to feasibility include institutional, legal, financial and logistical barriers such as costs of sourcing food and operational economic viability (Belhabib et al., 2016); this could potentially lead to maladaptation through increased GHG emissions from fuel usage and cultural displacement from traditional fishing and herding lands. Overall, decreases in GHG emissions under future scenarios would reduce increases in global temperatures and limit species shifts, thereby lowering the likelihood of conflicts and food insecurity (*high confidence*).

Coastal Regions of the Gulf of Guinea: Ghanian Fisheries

Marine fisheries in Ghana are dominated by artisanal fishers with overfished stocks, high nutritional fish dependency, high illegal fishing, low governance capacity (–0.21 2018, (World Bank, 2019)) and low climate awareness in regional fisheries management (Figure MOVING PLATE.3 this chapter; see Chapter 9; Nunoo et al., 2014; Belhabib et al., 2015; Belhabib et al., 2016; Kifani et al., 2018; Belhabib et al., 2019). Artisanal fishing plays a pivotal role in reducing poverty and food insecurity, and the impacts of climate change will risk developing poverty traps (see Section 8.4.5.6., (Kifani et al., 2018)). Climate change induced species redistribution is a large risk to Ghanian fisheries, with projections of over 20 commercial fish species exiting the region with no new species entering under RCP4.5 by 2100 (Oremus et al., 2020), and has already seen increases in warmer-water species with declining stocks. Adaptation options being applied are extending fishing ranges, increasing fishing effort (and cost) to access declining fish (with government fuel incentives) (Kifani et al., 2018; Muringai et al., 2021), developing aquaculture for alternative livelihoods, implementing fleet monitoring to reduce illegal fishing, and developing a robust Fisheries Information and Management System that accounts for environmental and climate drivers (Johnson et al., 2014; FAO, 2016; Kassi et al., 2018). However, fisheries remain insufficiently regulated, there is a lack of a skilled workforce, and there is low access to credit; collectively, these factors limit options for artisanal fishers to find alternative sustainable employment (FAO, 2016).

Shifting Distributions of Freshwater Fishery Resources: Knowledge Gaps

Freshwater fisheries provide the primary source of animal protein and essential micronutrients for an estimated 200 million people globally and are especially important in tropical developing nations (see Section 9.8, Lynch et al., 2017; Funge-Smith and Bennett, 2019.). There is evidence that freshwater fishes have undergone climate-induced distribution shifts (Comte and Grenouillet, 2015; see Section 9.8.5.1.), and further shifts are projected as water temperatures rise and hydrological regimes change, with the largest effects predicted for equatorial, subtropical and semi-arid regions (Barbarossa et al., 2021). Currently, the effects of distribution shifts on local fishery catch potential, food security and/or nutrition have not been quantified for any major inland fishery, representing a key knowledge gap for anticipating future adaptation needs for freshwater fishing societies. However, studies on fishers' perceptions of climate-induced changes in fishery catch rates have revealed that using local knowledge to adjust management practices (see Chapter 12 Central and South America this volume; Oviedo et al., 2016) and shifting gears, fishing grounds and target species (see Section 9.8.5.3.; Musinguzi et al., 2016) can be effective adaptation options.

Terrestrial Species Shifts

There is *robust evidence* of shifts that terrestrial species have shifted poleward in high latitudes, with general declines of sea-ice dependent as well as some extreme-polar-adapted species (*high confidence*) (Arctic and Siberian Tundra, see Section 2.4.2.2., Cross-Chapter Paper 6), with often deleterious effects on the food security and traditional knowledge systems of Indigenous societies (Horstkotte et al., 2017; Pecl et al., 2017; Mallory and Boyce, 2018; Forbes et al., 2020). Recent decades have seen declines in Arctic reindeer and caribou (see Section 2.5.1., Cross-Chapter Paper 6), and adaptation responses include utilisation of Indigenous knowledge with scientific sampling to maintain traditional management practices (Pecl et al., 2017; Barber et al.; Forbes et al., 2020). Preserving herder livelihoods will necessitate novel solutions (supplementary feeding, seasonal movements), where governance, ecological and socioeconomic trade-offs will be balanced at the local level (Horstkotte et al., 2017; Pecl et al., 2017; Mallory and Boyce, 2018; Forbes et al., 2020). Wild meat consumption plays a critical, though not well understood, role in the diets and food security of several hundred million people (*medium evidence*), for example in lower latitudes such as Central Africa and the Amazon basin (Bharucha and Pretty, 2010; Godfray et al., 2010; Nasi et al., 2011; Friant et al., 2020). Although illegal in many countries, wild meat hunting occurs either in places where there is no or

Cross-Chapter Box MOVING PLATE (continued)

limited domesticated livestock production, or in places where shock events such as droughts and floods threaten food supply, forcing increased reliance on wild foods including bush meat (Mosberg and Eriksen, 2015; Bodmer et al., 2018). Appropriate management of wild meat for reliant peoples under projected climate change will necessitate incorporating social justice elements into conservation and public health strategies (see Cross-Chapter Box ILLNESS in Chapter 2, Cross-Chapter Box COVID in Chapter 7, Friant et al., 2020; Ingram, 2020; Pelling et al., 2021).

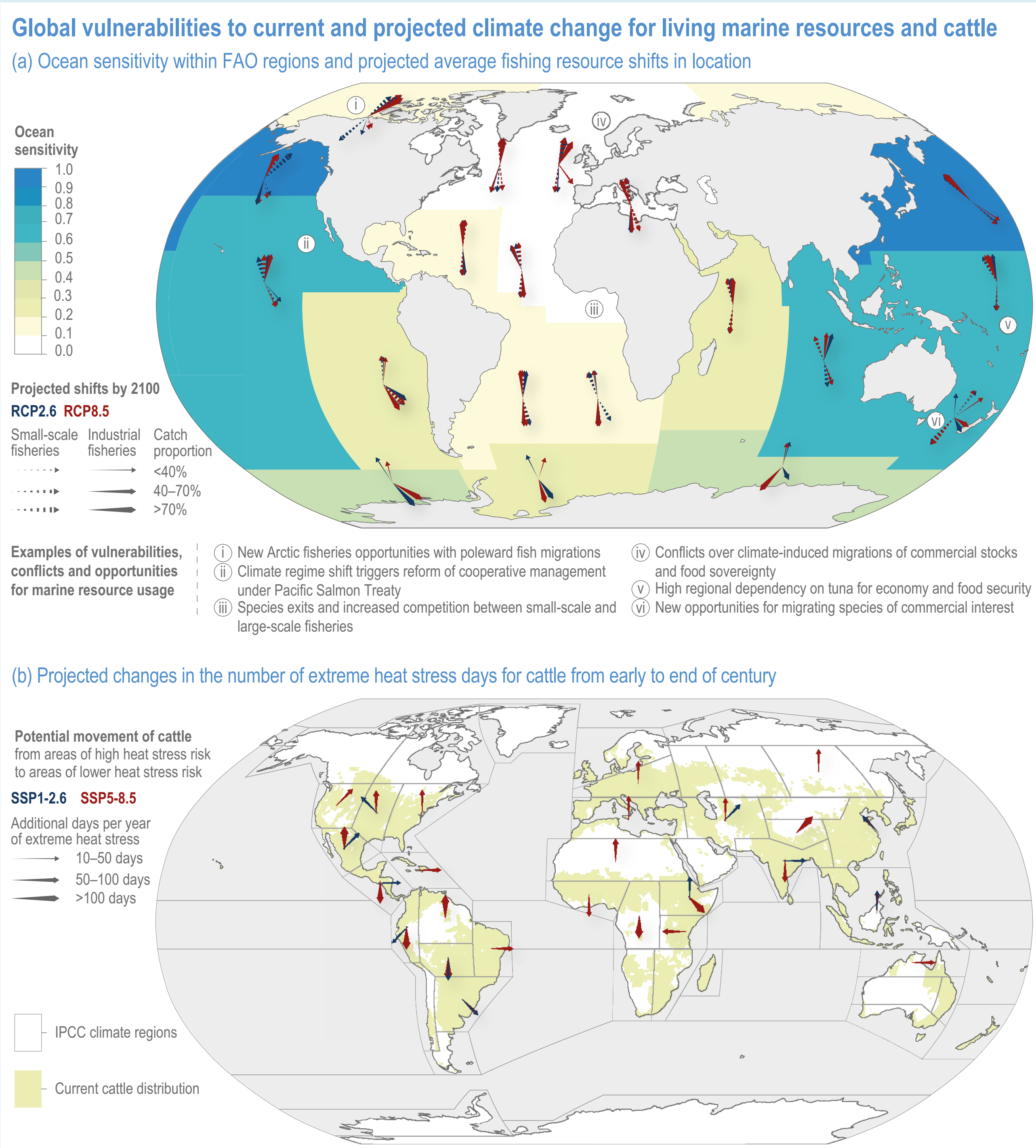


Figure Cross-Chapter Box MOVING PLATE.1 | Global vulnerabilities to current and projected climate change for living marine resources and cattle.

Cross-Chapter Box MOVING PLATE (continued)

(a) Ocean areas are delineated into FAO (Food and Agricultural Organization of the United Nations) regions. Ocean sensitivity is calculated from aggregated sensitivities from Blasiak et al. (2017) S1 country data based on number of fishers, fisheries exports, proportions of economically active population working as fishers, total fisheries landings and nutritional dependence, which was subsequently re-analysed for each FAO region depicted here. Arrows denote projected average commercial and artisanal fishing resource shifts in location under RCP2.6 and under RCP8.5 (dark-blue and red arrows, respectively) scenarios by 2100. Text boxes highlight examples of vulnerabilities (Bell et al., 2018a), conflicts (Miller et al., 2013; Blasiak et al., 2017; Østhagen et al., 2020) or opportunities for marine resource usage (Robinson et al., 2015; Stuart-Smith et al., 2018; Meredith et al., 2019).

(b) Projected changes in the number of extreme heat stress days for cattle from early (1991–2010) to end of century (2081–2100) under SSP1-2.6 and SSP5-8.5, shown as arrows rooted in the most affected area in each IPCC sub-region pointing to the nearest area of reduced or no extreme heat stress. Arrows are shown only for sub-regions where >1 million additional animals are affected. Areas in green are those with >5000 animals per 0.5° grid cell in the eary 21st century (Thornton et al., 2021).

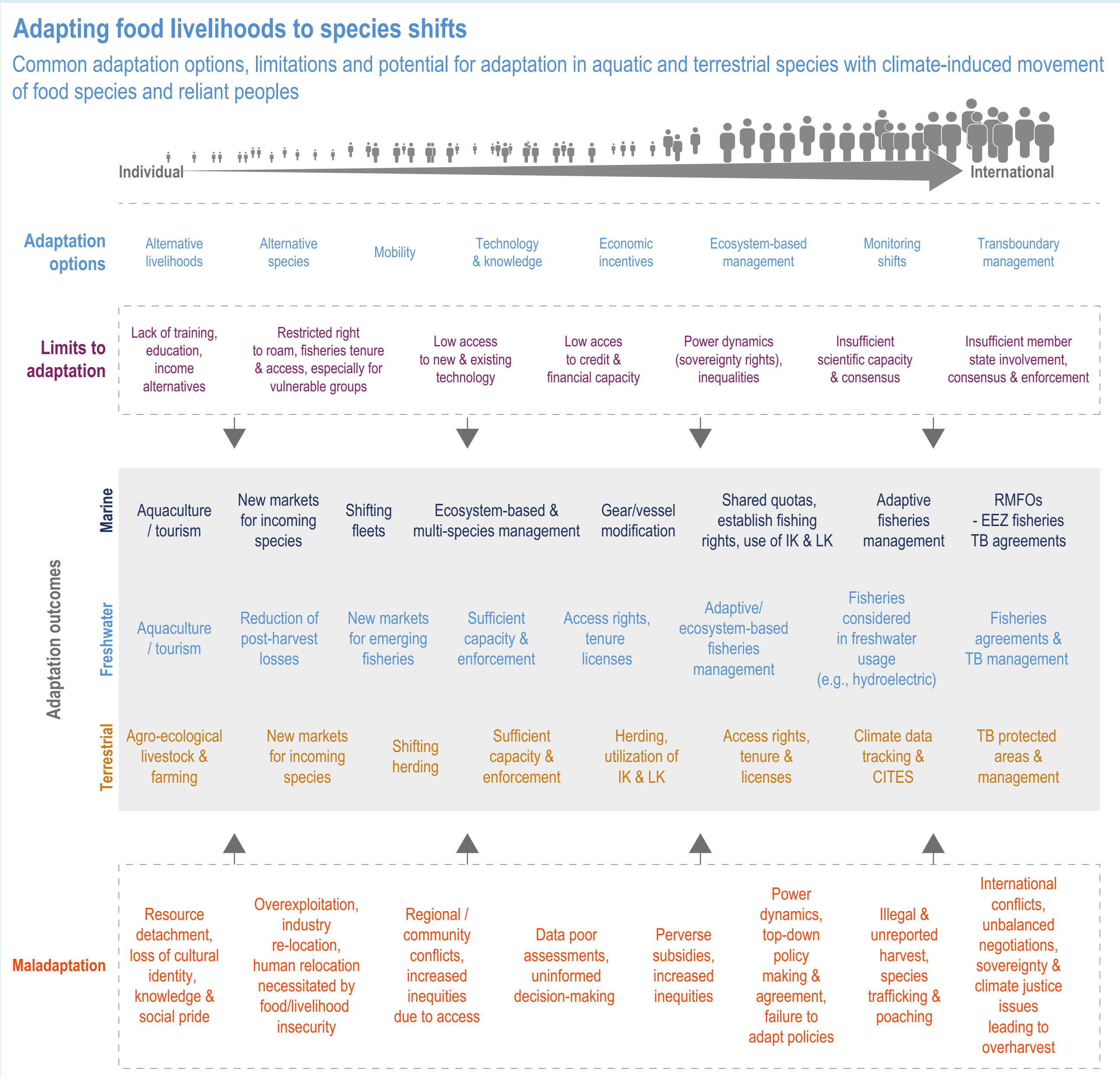
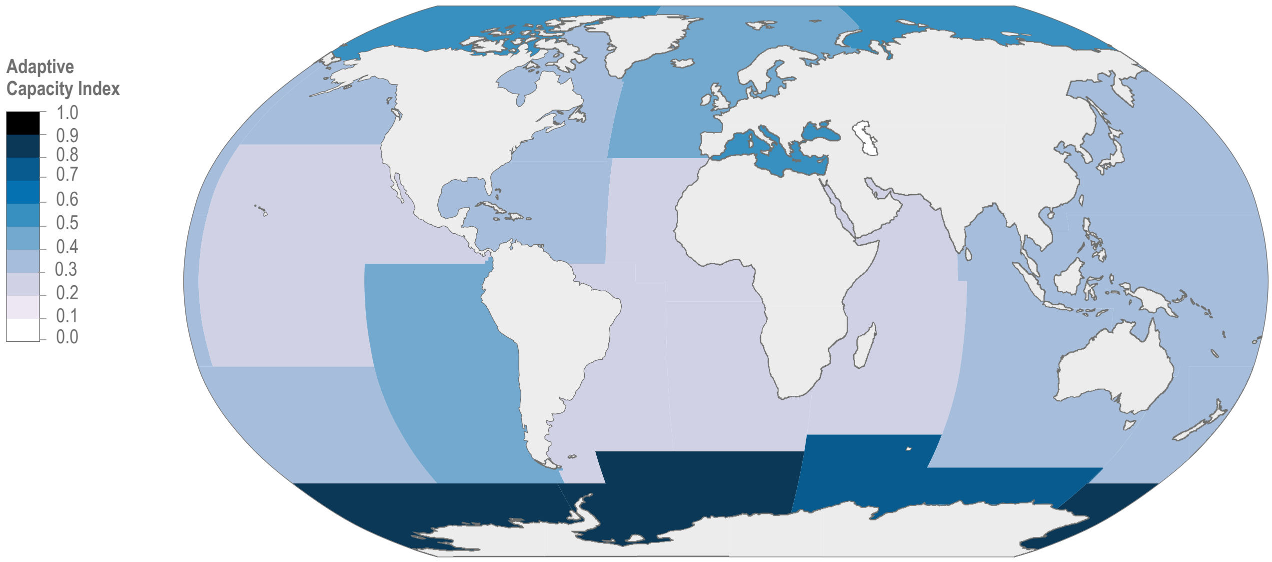


Figure Cross-Chapter Box MOVING PLATE.2 | Common adaptation options, limitations and potential for adaptation and maladaptation in aquatic and terrestrial species with climate-induced movement of food species and reliant peoples.

Cross-Chapter Box MOVING PLATE (continued)

Current fisheries adaptive capacity and regional micronutrient deficiency risks related to seafood-relevant micronutrients in human diets

(a) Documented fisheries adaptive capacity to climate change



(b) Regional seafood-relevant micronutrient deficiency risk (Calcium, Iron, Zinc, Vitamin A)

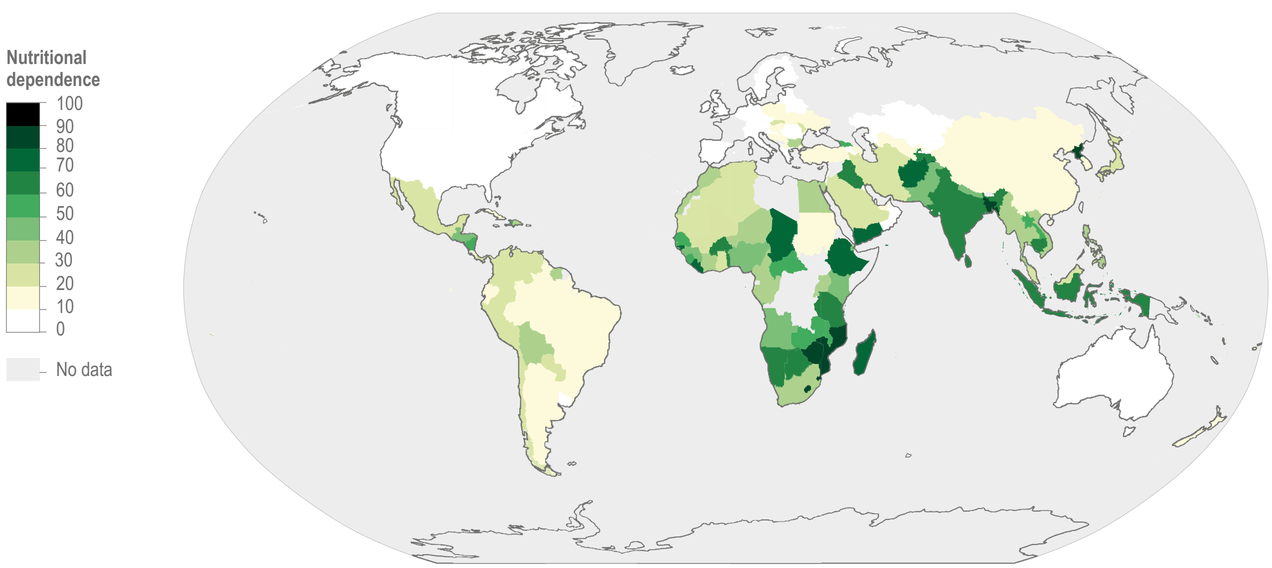


Figure Cross-Chapter Box MOVING PLATE.3 | Global documented fisheries adaptive capacity to climate change and regional seafood micronutrient deficiency risk. Ocean areas are delineated into FAO (Food and Agricultural Organization of the United Nations) regions. Fisheries management adaptive capacity is a function of: averaged GDP World Development Indicators for 2018 (World Bank, 2020); climate awareness assessments of 30 of the FAO recognised most recent RFMOs with direct fisheries linkages (see Supplementary Material SM5.5); governance effectiveness index based on six aggregate indicators (voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law, control of corruption) from 2018 World Governance Indicator (World Bank, 2019) data; and heterogeneity of countries within each FAO zone (highly heterogeneous regions are less likely to establish sustainable and efficient fisheries management for the entire FAO zone). Land area represents the percentage regional averaged seafood micronutrient deficiency risk of calcium, iron, zinc and vitamin A from 2011 data (Beal et al., 2017).

In terrestrial, marine and freshwater systems, human populations already impacted by poverty and hunger experience greater risk under climate change. Future food security will depend on access to other sustainable sources either via transnational agreements or resource/livelihood diversification. Sudden shocks across food production systems (Cottrell et al., 2019) can lead to increases in fisheries harvest

Cross-Chapter Box MOVING PLATE (continued)

and wild meat consumption, and following food species may result in community relocations or disruption and loss of access to historical places of attachment (*high confidence*) (Pecl et al., 2017; Lenoir et al., 2019; Meredith et al., 2019; Melbourne-Thomas et al., 2021; see Cross-Chapter Box MIGRATE in Chapter 7). Ecosystem-based management approaches exist for terrestrial, marine and freshwater systems, but have proved successful only with early engagement of local small-scale, subsistence fishers/harvesters, utilising Indigenous knowledge and local knowledge and needs, in addition to those of larger-scale operators (*high confidence*) (Huntington et al., 2015; McGrath and Costello, 2015; Huq and Stubbings, 2016; Huq et al., 2017; Raymond-Yakoubian et al., 2017; Nalau et al., 2018; Raymond-Yakoubian and Daniel, 2018; Pecl et al., 2019; Planque et al., 2019). Currently, there are large regional differences in climate literacy in RFMOs (Sumby et al., 2021) which, when combined with low governance and GDP per capita, will limit adaptation capacity and increase vulnerabilities, particularly for tropical and subtropical regions already at increased risk due to poleward species migrations (see Figure MOVING PLATE.3 this chapter). Trade will be an alternative to compensate for the moving plate but has specific risks that can amplify inequities and maladaptation (Asche et al., 2015; Vianna et al., 2020).

Cross-Working Group Box BIOECONOMY | Mitigation and Adaptation via the Bioeconomy

Authors: Henry Neufeldt (Denmark/Germany), Göran Berndes (Sweden), Almut Arneth (Germany), Rachel Bezner Kerr (USA/Canada), Luisa F Cabeza (Spain), Donovan Campbell (Jamaica), Jofre Carnicer Cols (Spain), Annette Cowie (Australia), Vassilis Daioglou (Greece), Joanna House (UK), Adrian Leip (Italy/Germany), Francisco Meza (Chile), Michael Morecroft (UK), Gert-Jan Nabuurs (the Netherlands), Camille Parmesan (UK/USA), Julio C Postigo (USA/Peru), Marta G. Rivera-Ferre (Spain), Raphael Slade (UK), Maria Cristina Tirado von der Pahlen (USA/Spain), Pramod K. Singh (India), Peter Smith (UK)

Summary Statement

The growing demand for biomass offers both opportunities and challenges to mitigate and adapt to climate change and natural resource constraints (high confidence). Increased technology innovation, stakeholder integration and transparent governance structures and procedures at local to global scales are key to successful bioeconomy deployment maximising benefits and managing trade-offs (high confidence).

Limited global land and biomass resources accompanied by growing demands for food, feed, fibre and fuels, together with prospects for a paradigm shift towards phasing out fossil fuels, set the frame for potentially fierce competition for land[1] and biomass to meet burgeoning demands even as climate change increasingly limits natural resource potentials (*high confidence*).

Sustainable agriculture and forestry, technology innovation in bio-based production within a circular economy and international cooperation and governance of global trade in products to reflect and disincentivise their environmental and social externalities can provide mitigation and adaptation via bioeconomy development that responds to the needs and perspectives of multiple stakeholders to achieve outcomes that maximise synergies while limiting trade-offs (*high confidence*).

Background

There is *high confidence* that climate change, population growth and changes in per capita consumption will increase pressures on managed as well as natural and semi-natural ecosystems, exacerbating existing risks to livelihoods, biodiversity, human and ecosystem health, infrastructure and food systems (Conijn et al., 2018; IPCC, 2018; IPCC, 2019b; Lade et al., 2020). At the same time, many global mitigation scenarios presented in Intergovernmental Panel on Climate Change (IPCC) assessment reports rely on large greenhouse gas (GHG) emissions reduction in the Agriculture, Forestry, and Other Land Use (AFOLU) sector and concurrent deployment of reforestation/afforestation and biomass use in a multitude of applications (Rogelj et al., 2018; AR6 WGIII Chapter 3 and Chapter 7; Canadell et al., 2021; Lee et al., 2021)

Given the finite availability of natural resources, there are invariably trade-offs that complicate land-based mitigation unless land productivity can be enhanced without undermining ecosystem services (e.g., Obersteiner et al., 2016; Campbell et al., 2017; Caron et al., 2018; Conijn et al., 2018; Heck et al., 2018; WRI, 2018; Smith et al., 2019c). Management intensities can often be adapted to local conditions with consideration of other functions and ecosystem services, but at a global scale the challenge remains to avoid further deforestation and degradation of intact ecosystems, in particular of biodiversity-rich systems (Cross-Chapter Box on NBS-NATURAL in Chapter 2), while meeting the growing demands. Further, increased land use competition can affect food prices and impact food security and livelihoods (To and Grafton, 2015; Chakravorty et al., 2017), with possible knock-on effects related to civil unrest (Abbott et al., 2017; D'Odorico et al., 2018).

Developing New Bio-Based Solutions while Mitigating Overall Biomass Demand Growth

Many existing bio-based products have significant mitigation potential. Increased use of wood in buildings can reduce GHG emissions from cement and steel production while providing carbon storage (Churkina et al., 2020). Substitution of fossil fuels with biomass in manufacture of cement and steel can reduce GHG emissions where these materials are difficult to replace. Dispatchable power based on biomass can provide power stability and quality as the contribution from solar and wind power increases (WGIII Chapter 6), and biofuels can contribute to reducing fossil fuel emissions in the transport and industry sectors (WGIII Chapter 10 and Chapter 11). The use of bio-based plastics, chemicals and packaging could be increased, and biorefineries can achieve high resource-use efficiency in converting biomass into food, feed, fuels and other bio-based products (Aristizábal-Marulanda and Cardona Alzate, 2019; Schmidt et al., 2019). There is also scope for substituting existing bio-based products with more benign products. For example, cellulose-based textiles can replace cotton, which requires large amounts of water, chemical fertilizers and pesticides to ensure high yields.

1 For lack of space, the focus is on land only, although the bioeconomy also includes sea-related bioresources.

Cross-Working Group Box BIOECONOMY (continued)

While increasing and diversified use of biomass can reduce the need for fossil fuels and other GHG-intensive products, unfavourable GHG balances may limit the mitigation value. Growth in biomass use may in the longer term also be constrained by the need to protect biodiversity and ecosystems' capacity to support essential ecosystem services. Biomass use may also be constrained by water scarcity and other resource scarcities and/or challenges related to public perception and acceptance due to impacts caused by biomass production and use. Energy conservation and efficiency measures and deployment of technologies and systems that do not rely on carbon, such as carbon-free electricity supporting, inter alia, electrification of transport as well as industry processes and residential heating (IPCC, 2018; UNEP, 2019), can constrain the growth in biomass demand when countries seek to phase out fossil fuels and other GHG-intensive products while providing an acceptable standard of living. Nevertheless, demand for bio-based products may become high where full decoupling from carbon is difficult to achieve (e.g., aviation, bio-based plastics, and chemicals) or where carbon storage is an associated benefit (e.g., wood buildings, bioenergy with carbon capture and storage (BECCS), biochar for soil amendments), leading to challenging trade-offs (e.g., food security, biodiversity) that need to be managed in environmentally sustainable and socially just ways.

Changes on the demand side as well as improvements in resource-use efficiencies within the global food and other bio-based systems can also reduce pressures on the remaining land resources. For example, dietary changes towards more plant-based food (where appropriate) and reduced food waste can provide climate change mitigation along with health benefits (WGIII Chapter 7.4 and 12.4, Willett et al., 2019) and other co-benefits with regard to food security, adaptation and land use (Mbow et al., 2019; Smith et al., 2019c; WGII Chapter 5). Advancements in the provision of novel food and feed sources (e.g., cultured meat, insects, grass-based protein feed and cellular agriculture) can also limit the pressures on finite natural resources (WGIII Chapter 12.4, Parodi et al., 2018; Zabaniotou, 2018).

Box Cross-Working Group Box BIOECONOMY.1: Circular Bioeconomy

Circular economy approaches (WGIII-12.6) are commonly depicted by two cycles, where the biological cycle focuses on regeneration in the biosphere and the technical cycle focuses on reuse, refurbishment and recycling to maintain value and maximise material recovery (Mayer et al., 2019a). Biogenic carbon flows and resources are part of the biological carbon cycle, but carbon-based products can be included in, and affect, both the biological and the technical carbon cycles (Kirchherr et al., 2017; Winans et al., 2017; Velenturf et al., 2019). The integration of circular economy and bioeconomy principles has been discussed in relation to organic waste management (Teigiserova et al., 2020), societal transition and policy development (Directorate-General for Research Innovation, 2018; Bugge et al., 2019) as well as coronavirus disease 2019 (COVID-19) recovery strategies (Palahi et al., 2020). To maintain the natural resource base, circular bioeconomy emphasises sustainable land use and the return of biomass and nutrients to the biosphere when it leaves the technical cycle.

Biomass scarcity is an argument for adopting circular economy principles for the management of biomass as for non-renewable resources. This includes waste avoidance, product reuse and material recycling, which keep down resource use while maintaining product and material value. However, reuse and recycling is not always feasible, such as when biofuels are used for transport and bio-based biodegradable chemicals are used to reduce ecological impacts where losses to the environment are unavoidable. A balanced approach to management of biomass resources could take departure in the carbon cycle from a value-preservation perspective and the possible routes that can be taken for biomass and carbon, considering a carbon budget defined by the Paris Agreement, principles for sustainable land use and natural ecosystem protection.

Land Use Opportunities and Challenges in the Bioeconomy

Analyses of synergies and trade-offs between adaptation and mitigation in the agriculture and forestry sectors show that outcomes depend on context, design and implementation, so actions have to be tailored to the specific conditions to minimise adverse effects (Kongsager, 2018). This is supported in literature analysing the nexus between land, water, energy and food in the context of climate change, which consistently concludes that addressing these different domains together rather than in isolation would enhance synergies and reduce trade-offs (Obersteiner et al., 2016; D'Odorico et al., 2018; Soto Golcher and Visseren-Hamakers, 2018; Froehse and Schilling, 2019; Momblanch et al., 2019).

Nature-based solutions addressing climate change can provide opportunities for sustainable livelihoods as well as multiple ecosystem services, such as flood risk management through floodplain restoration, saltmarshes, mangroves or peat renaturation (Cross-Chapter Box NATURAL in Chapter 2; UNEP, 2021). Climate-smart agriculture can increase productivity while enhancing resilience and reducing GHG emissions inherent to production (Lipper et al., 2014; Singh and Chudasama, 2021). Similarly, climate-smart forestry considers the whole value chain and integrates climate objectives into forest sector management through multiple measures (from strict reserves

Cross-Working Group Box BIOECONOMY (continued)

to more intensively managed forests) providing mitigation and adaptation benefits (Nabuurs et al., 2018; Verkerk et al., 2020; WGIII Section 7.3)

Agroecological approaches can be integrated into a wide range of land management practices to support a sustainable bioeconomy and address equity considerations (HLPE, 2019). Relevant land use practices, such as agroforestry, intercropping, organic amendments, cover crops and rotational grazing, can provide mitigation and support adaption to climate change via food security, livelihoods, biodiversity and health co-benefits (Ponisio et al., 2015; Garibaldi et al., 2016; D'Annolfo et al., 2017; Bezner Kerr et al., 2019; Clark et al., 2019; Córdova et al., 2019; HLPE, 2019; Mbow et al., 2019; Renard and Tilman, 2019; Sinclair et al., 2019; Bharucha et al., 2020; Bezner Kerr et al., 2021;WGII Cross-Chapter Box NATURAL in Chapter 2). Strategic integration of appropriate biomass production systems into agricultural landscapes can provide biomass for bioenergy and other bio-based products while providing co-benefits such as enhanced landscape diversity, habitat quality, retention of nutrients and sediment, erosion control, climate regulation, flood regulation, pollination and biological pest and disease control (WGIII Chapter12 Box on UNCCD-LDN, Christen and Dalgaard, 2013; Asbjornsen et al., 2014; Holland et al., 2015; Ssegane et al., 2015; Dauber and Miyake, 2016; Milner et al., 2016; Ssegane and Negri, 2016; Styles et al., 2016; Zumpf et al., 2017; Cacho et al., 2018; Alam and Dwivedi, 2019; Cubins et al., 2019; HLPE, 2019; Olsson et al., 2019; Zalesny et al., 2019; Englund et al., 2020). Such approaches can help limit environmental impacts from intensive agriculture while maintaining or increasing land productivity and biomass output.

Figure Cross-Working Group Box BIOECONOMY.1 | Left: High-input intensive agriculture, aiming for high yields of a few crop species, with large fields and no semi-natural habitats. Right: Agroecological agriculture, supplying a range of ecosystem services, relying on biodiversity and crop and animal diversity instead of external inputs, and integrating plant and animal production, with smaller fields and presence of semi-natural habitats. Credit: Jacques Baudry (left); Valérie Viaud (right), published in van der Werf et al. (2020).

Transitions from conventional to new biomass production and conversion systems include challenges related to cross-sector integration and limited experience with new crops and land use practices, including needs for specialised equipment (WGII Chapter 5.10, Thornton and Herrero, 2015; HLPE, 2019). Introduction of agroecological approaches and integrated biomass/food crop production can result in lower food crop yields per hectare, particularly during transition phases, potentially causing indirect land use change, but can also support higher and more stable yields, reduce costs, and increase profitability under climate change (Muller et al., 2017; Seufert and Ramakutty, 2017; Barbieri et al., 2019; HLPE, 2019; Sinclair et al., 2019; Smith et al., 2019c; Smith et al., 2020a). Crop diversification, organic amendments and biological pest control (HLPE, 2019) can reduce input costs and risks of occupational pesticide exposure and food and water contamination (Gonzalez-Alzaga et al., 2014; European Food Safety Authority Panel on Plant Protection Products and their Residues et al., 2017; Mie et al., 2017), reduce farmers' vulnerability to climate change (e.g., droughts and spread of pests and diseases affecting plant and animal health; Delcour et al., 2015; FAO, 2020a) and enhance provisioning and sustaining ecosystem services, such as pollination (D'Annolfo et al., 2017; Sinclair et al., 2019).

Barriers towards wider implementation include absence of policies that compensate landowners for providing enhanced ecosystem services and other environmental benefits, which can help overcome short-term losses during the transition from conventional practices before longer-term benefits can accrue. Other barriers include limited access to markets, knowledge gaps, financial, technological or

Cross-Working Group Box BIOECONOMY (continued)

labour constraints, lack of extension support and insecure land tenure (Jacobi et al., 2017; Kongsager, 2017; Hernández-Morcillo et al., 2018; Iiyama et al., 2018; HLPE, 2019). Regional-level agroecology transitions may be facilitated by co-learning platforms, farmer networks, private sector, civil society groups, regional and local administration, and other incentive structures (e.g., price premiums, access to credit, regulation) (Coe et al., 2014; Pérez-Marin et al., 2017; Mier y Terán Giménez Cacho et al., 2018; HLPE, 2019; Valencia et al., 2019; SAPEA, 2020). With the right incentives, improvements can be made with regard to profitability, making alternatives more attractive to landowners.

Governing the Solution Space

Literature analysing the synergies and trade-offs between competing demands for land suggest that solutions are highly contextualised in terms of their environmental, socioeconomic and governance-related characteristics, making it difficult to devise generic solutions (Haasnoot et al., 2020). Aspects of spatial and temporal scale can further enhance the complexity, for instance where transboundary effects across jurisdictions or upstream–downstream characteristics need to be considered, or where climate change trajectories might alter relevant biogeophysical dynamics (Postigo and Young, 2021). Nonetheless, there is broad agreement that taking the needs and perspectives of multiple stakeholders into account in a transparent process during negotiations improves the chances of achieving outcomes that maximise synergies while limiting trade-offs (Ariti et al., 2018; Metternicht, 2018; Favretto et al., 2020; Kopáček, 2021; Muscat et al., 2021). Yet differences in agency and power between stakeholders or anticipated changes in access to or control of resources can undermine negotiation results even if there is a common understanding of the overarching benefits of more integrated environmental agreements and the need for greater coordination and cooperation to avoid longer-term losses to all (Aarts and Leeuwis, 2010; Weitz et al., 2017). There is also the risk that strong local participatory processes can become disconnected from broader national plans, and thus fail to support the achievement of national targets. Thus, connection between levels is needed to ensure that ambition for transformative change is not derailed at the local level (Aarts and Leeuwis, 2010; Postigo and Young, 2021).

Decisions on land uses between biomass production for food, feed, fibre or fuel, as well as nature conservation or restoration and other uses (e.g., mining, urban infrastructure), depend on differences in perspectives and values. Because the availability of land for diverse biomass uses is invariably limited, setting priorities for land use allocations therefore first depends on making the perspectives underlying what is considered as 'high-value' explicit (Fischer et al., 2007; Garnett et al., 2015; de Boer and van Ittersum, 2018; Muscat et al., 2020). Decisions can then be made transparently based on societal norms, needs and the available resource base. Prioritisation of land use for the common good therefore requires societal consensus-building embedded in the socioeconomic and cultural fabric of regions, societies and communities. Integration of local decision making with national planning ensures local actions complement national development objectives.

International trade in the global economy today provides important opportunities to connect producers and consumers, effectively buffering price volatilities and potentially offering producers in low-income countries access to global markets, which can be seen as an effective adaptation measure (Baldos and Hertel, 2015; Costinot et al., 2016; Hertel and Baldos, 2016; Gouel and Laborde, 2021; WGII Chapter 5.11).. But there is also clear evidence that international trade and the global economy can enhance price volatility, lead to food price spikes and affect food security due to climate and other shocks, as seen recently due to the COVID-19 pandemic (WGII Chapter 5.12, Cottrell et al., 2019; WFP-FSIN, 2020; Verschuur et al., 2021). The continued strong demand for food and other bio-based products, mainly from high- and middle-income countries, therefore, requires better cooperation between nations and global governance of trade to more accurately reflect and disincentivise their environmental and social externalities. Trade in agricultural and extractive products driving land use change in tropical forest and savanna biomes is of major concern because of the biodiversity impacts and GHG emissions incurred in their provision (WGII Cross-Chapter Paper 7, Hosonuma et al., 2012; Forest Trends, 2014; Henders et al., 2015; Curtis et al., 2018; Pendrill et al., 2019; Seymour and Harris, 2019; Kissinger et al., 2021).

In summary, there is significant scope for optimising use of land resources to produce more biomass while reducing adverse effects (*high confidence*). Context-specific prioritisation, technology innovation in bio-based production, integrative policies, coordinated institutions and improved governance mechanisms to enhance synergies and minimise trade-offs can mitigate the pressure on managed as well as natural and semi-natural ecosystems (*medium confidence*). Yet, energy conservation and efficiency measures, and deployment of technologies and systems that do not rely on carbon-based energy and materials, are essential for mitigating biomass demand growth as countries pursue ambitious climate goals (*high confidence*).

Cross-Working-Group Box URBAN | Cities and Climate Change

Authors: Xuemei Bai (Australia), Vanesa Castán Broto (UK/Spain), Winston Chow (Singapore), Felix Creutzig (Germany), David Dodman (Jamaica/UK), Rafiq Hamdi (Belgium), Bronwyn Hayward (New Zealand), Şiir Kılkış (Turkey), Shuaib Lwasa (Uganda), Timon McPhearson (USA), Minal Pathak (India), Mark Pelling (UK), Diana Reckien (Germany), Karen Seto (USA), Ayyoob Sharifi (Japan/Iran), Diána Ürge-Vorsatz (Hungary)

Introduction

This Cross-Working Group Box on Cities and Climate Change responds to the critical role of urbanisation as a megatrend impacting climate adaptation and mitigation. Issues associated with cities and urbanisation are covered in substantial depth within all three Working Groups (including WGI Box TS.14, WGII Chapter 6 'Cities, settlements and key infrastructure'; WGII regional chapters; WGII Cross-Chapter Paper 'Cities and settlements by the sea'; WGIII Chapter 8 'Urban systems and other settlements'). This Box highlights key findings from Working Groups II and III and substantial gaps in literature where more research is urgently needed relating to policy action in cities. It describes methods of addressing mitigation and adaptation in an integrated way across sectors and cities to advance sustainable development and equity outcomes; and assesses the governance and finance solutions required to support climate resilient responses.

Urbanisation: A Megatrend Driving Global Climate Risk and Potential for Low-Carbon and Resilient Futures

Severe weather events, exacerbated by anthropogenic emissions, are already having devastating impacts on people who live in urban areas, and on the infrastructure that supports these communities and those of many other distant places (*high confidence*) (Cai et al., 2019; Folke et al., 2021). Between 2000 and 2015, the global population in locations that were affected by floods grew by 58–86 million (Tellman et al., 2021). The direct economic costs of all extreme events reached USD 210–268 billion in 2020 (Aon, 2021) or about USD 0.7 billion d^{-1}; this figure does not include knock-on costs in supply chains or days off work lost so that the actual economic costs could be far higher. Depending on RCP, between half (RCP2.6) and three-quarters (RCP8.5) of the global population could be exposed to periods of life-threatening climatic conditions arising from coupled impacts of extreme heat and humidity by 2100 (see Section 6.2.2.1; WGII Figure 6.3; Mora et al., 2017; Zhao et al., 2021; Huang et al., 2019).

The interdependencies between infrastructure, services and networks driven by urban production and consumption mean that urban systems are now global; remittance flows and investments reach into rural places shaping natural resource use far from the city and bring risk to the city when these places are impacted by climate change. This urbanisation megatrend (Kourtit, Nijkamp and Scholten, 2015) amplifies and shapes the potential impacts of climate events. It provides the economic and institutional framework for integrating the aims and approaches that can deliver mitigation, adaptation and sustainable development (*medium evidence*, *high agreement*) (Zscheischler et al., 2018; Dawson et al., 2018; Tsavdaroglou et al., 2018). For cities facing flood damage, wide-ranging impacts have been recorded on other urban areas (Simpson et al., 2021; Carter et al., 2021) as production and trade is disrupted (Shughrue et al., 2020). In the absence of integrated mitigation and adaptation across and between infrastructure systems and local places, impacts that bring urban economies to a standstill can extend into supply chains or across energy networks causing power outages.

Urban settlements are drivers of climate change, generating about 70% of global CO_2-eq emissions (*high confidence*) (WGI Box TS.14; WGIII 8 ES; WGII 6.1, WGII 6.2). This global impact feeds back to cities through the exposure of infrastructure, people and business to the impacts of climate-related hazards. Especially in the larger cities, this climate feedback is exacerbated by local choices in urban design, land use, building design and human behaviour (Viguié et al., 2020) that shape local environmental conditions. Local and global conditions influence the nature of hazards in urban centres: urban form can add up to 2°C to warming, concretisation of open space can increase runoff and building height and orientation influences wind direction and strength (WGII 6.3).

Building today for resilience and lower emissions is far easier than retrofitting tomorrow. As urbanisation unfolds, its legacy continues to be the locking in of emissions and vulnerabilities (*high confidence*) (Ürge-Vorsatz et al., 2018; Seto et al., 2016). Retrofitting, disaster reconstruction and urban regeneration programmes offer scope for strategic direction changes to low-carbon and high-resilience urban form and function if they are inclusive in design and implementation. Rapid urban growth means new investment, new buildings and infrastructure, new demands for energy and transport and new questions about what a healthy and fulfilling urban life can be. The USD 90 trillion expected to be invested in new urban development by 2030 (NCE, 2018), is a global opportunity to place adaptation and mitigation directly into urban infrastructure and planning, and social policy including education and health care and environmental management (Ürge-Vorsatz et al., 2018). If this opportunity is missed, if business as usual urbanisation persists, then social and physical vulnerability will be not be so easily confronted.

Cross-Working Group Box URBAN (continued)

The benefits of actions taken to reduce greenhouse gas (GHG) emissions and climate stressors diminish with delayed action, indicating the necessity for rapid responses. Delaying the same actions for increasing the resilience of infrastructure from 2020 to 2030 is estimated to have a median cost of at least USD 1 trillion (Hallegatte et al., 2019), while also missing the carbon emissions reductions required in the narrowing window of opportunity to limit global warming to 1.5°C (WGI). In contrast, taking integrated actions toward mitigation, adaptation and sustainable development will provide multiple benefits for the health and well-being of urban inhabitants and avoid stranded assets (WGII 6.3, WGII 17; WGIII 5; WGIII 8.2; Cross-Chapter Box FEASIB in Chapter 18).

The Policy-Action Gap: Urban Low-Carbon and Climate Resilient Development

Cities are critical places to realise actions on both adaptation and mitigation simultaneously, with potential co-benefits that extend far beyond cities (*medium evidence*, *high agreement*) (Grafakos et al., 2020; Göpfert, Wamsler and Lang, 2019). Given rapid changes in the built environment, transforming the use of materials and the land intensiveness of urban development including in many parts of the Global South in the next decades will be critical, as well as mainstreaming low-carbon development principles in new urban development in all regions. Much of this development will be self-built and 'informal', and new modes of governance and planning will be required to engage with this. Integrating mitigation and adaptation now rather than later, through reshaping patterns of urban development and associated decision making processes, is a prerequisite for attaining resilient and zero carbon cities.

While more cities have developed plans for climate adaptation and mitigation since AR5, many remain to be implemented (*limited evidence*, *high agreement*) (Araos et al., 2017; Olazabal and De Gopegui, 2021; Aguiar et al., 2018). A review of local climate mitigation and adaptation plans across 885 urban areas of the European Union suggests mitigation plans are more common than adaptation plans, and that city size, national legislation and international networks can influence the development of local climate plans with an estimated 80% of cities with above 500,000 inhabitants having a mitigation and/or an adaptation plan (Reckien et al., 2018b).

Integrated approaches to tackle common drivers of emissions and cascading risks provide the basis for strengthening synergies across mitigation and adaptation, and managing possible trade-offs with sustainable development (*limited evidence, medium agreement*) (Grafakos et al., 2019; Landauer, Juhola and Klein, 2019). Analysis of 315 local authority emission reduction plans across the European Union reveals that the most common policies cover municipal assets and structures (Palermo et al. 2020). Estimates of emission reductions by non-state and sub-state actors in 10 high-emitting economies projected GHG emissions in 2030 would be 1.2–2.0 $GtCO_2$-eq per year or 3.8–5.5% lower compared to scenario projections for current national policies (31.6–36.8 $GtCO_2$-eq per year) if the policies are fully implemented and do not change the pace of action elsewhere (Kuramochi et al. 2020). The value of integrating mitigation and adaptation is underscored in the opportunities for decarbonising existing urban areas, and investing in social, ecological and technological infrastructure resilience (WGII 6.4). Integrating mitigation and adaption is challenging (Landauer, Juhola and Klein, 2019) but can provide multiple benefits for the health and well-being of urban inhabitants (Sharifi, 2020).

Effective climate strategies combine mitigation and adaptation responses, including through linking adaptive urban land use with GHG emission reductions (*medium evidence*, *high agreement*) (Xu et al., 2019; Patterson et al., 2021). For example, urban green and blue infrastructure can provide co-benefits for mitigation and adaptation (Ürge-Vorsatz et al., 2018) and is an important entry point for integrating adaptation and mitigation at the urban level (Frantzeskaki et al., 2019). Grey and physical infrastructure such as sea defences can immediately reduce risk, but can also transfer risk and limit future options. Social policy interventions including social safety nets provide financial security for the most at risk and can manage vulnerability determined both by specific hazards and independently. Hazard-independent mechanisms for vulnerability reduction, such as population-wide social security, provide resilience in the face of unanticipated cascading impacts or surprise and novel climate-related hazard exposure. Social interventions can also support, or be led by, ambitions to reach the Sustainable Development Goals (Archer, 2016). Climate resilient development invites planners to plan interventions and monitor the effectiveness of outcomes beyond individual projects and across wider remits that reach into sustainable development. Curbing the emission impacts of urban activities to reach net zero in the next decades while improving the resilience of urban areas necessitates an integrated response now.

Key gaps in knowledge include urban enabling environment; how smaller settlements, low-income communities living in slums and informal settlements, but also those in rental housing spread across the city, and actions to reduce supply chain risk can be supported to accelerate equitable and sustainable adaptation in the face of financial and governance constraints (Birkmann et al., 2016; Shi et al., 2016; Dulal, 2019; Rosenzweig et al., 2018b).

Cross-Working Group Box URBAN (continued)

Enabling Action

Innovative governance and finance solutions are required to manage complex and interconnected risks across essential key infrastructures, networks and services and meet basic human needs in urban areas (*medium confidence*) (Moser et al., 2019; Colenbrander, Dodman and Mitlin, 2018). There are many examples of 'ready-to-use' policy tools, technologies and practical interventions for policymakers seeking to act on adaptation and mitigation (Keenan, Chu and Peterson, 2019; Bisaro and Hinkel, 2018; Chirambo, 2021). Tax and fiscal incentives for business and individuals can help support city-wide change behaviour toward low carbon and risk reducing choices. Change can start where governments have most control; in public sector institutions and investment, but the challenge ahead requires partnership with private sector and community actors acting at scale and with accountability. Urban climate governance and finance needs to address urban inequalities at the forefront if the urban opportunity is to realise the ambition of the Sustainable Development Goals.

Increasing investment at pace will put pressure on governance capability and transparency and accountability of decision making (*medium confidence*) (WG II 6.6.4.5). Urban climate action that actively includes local actors and is built on an evidence base open to independent scrutiny is more likely to avoid unintended, negative maladaptive impacts and mobilise a wide range of local capacities. In the long run, this is also more likely to carry public support, even if some experiments and investments do not deliver the intended social benefits. Legislation, technical capacity and governance capability is required to be able to absorb additional finance. About USD 384 billion yr^{-1} of climate finance has been invested in urban areas in recent years. This remains at about 10% of the annual climate finance that would be necessary for low-carbon and resilient urban development (Negreiros et al., 2021). Rapid deployment of funds to stimulate economies in recovery from COVID-19 have highlighted the pitfalls of funding expansion ahead of policy innovation and capacity building. The result can be an intensification of existing urban forms, exactly the kinds of choices and preferences that contribute to risk creation and its concentration among those with little public voice or economic power.

Iterative and experimental approaches to climate adaptation and mitigation decision making co-generated in partnership with communities, can advance climate-resilient decarbonisation (*medium evidence*, *high agreement*) (Caldarice, Tollin and Pizzorni, 2021; Culwick et al., 2019; van der Heijden and Hong, 2021). Conditions of complexity, uncertainty and constrained resources require innovative solutions which are both adaptive and anticipatory. Complex interactions among multiple agents in times of uncertainty makes decision making about social, economic, governance, and infrastructure choices challenges, and can lead decision makers to postpone action. This is the case for those balancing household budgets, residential investment portfolios and city-wide policy responsibilities. Living with climate change requires changes to business-as-usual design making. Co-design and collaboration with communities through iterative policy experimentation can point the way toward CRD pathways (Ataöv and Peker, 2021). Key to successful learning is transparency in policymaking, inclusive policy processes and robust local modelling, monitoring and evaluation, which are not yet widely undertaken (Ford et al., 2019; Sanchez Rodriguez, Ürge-Vorsatz and Barau, 2018).

The diversity of cities' experiences of climate mitigation and adaptation strategies brings an advantage for those city government and other actors willing to 'learn together' (*limited evidence*, *high agreement*) (Bellinson and Chu, 2019; Haupt and Coppola, 2019). While contexts are varied, policy options are often similar enough for the sharing of experiments and policy champions. Sharing expertise can build on existing regional and global networks, many of which have already placed knowledge, learning and capacity building at the centre of their agendas. Learning from innovative forms of governance and financial investment, and strengthening co-production of policy through inclusive access to knowledge and resources, can help address mismatches in local capacities, strengthen wider Sustainable Development Goals and COVID-19 Recovery agendas (*limited evidence*, *medium agreement*). Perceptions of risk can greatly influence the reallocation of capital and shift financial resources (Battiston et al., 2021). Coupling mitigation and adaptation in an integrated approach offers opportunities to enhance efficiency, increases the coherence of urban climate action, generates cost savings and provides opportunities to reinvest the savings into new climate action projects to make all urban areas and regions more resilient.

Local governments play an important role in driving climate action across mitigation and adaptation as managers of assets, regulators, mobilisers and catalysts of action, but few cities are undertaking transformative climate adaptation or mitigation actions (*limited evidence*, *medium agreement)* (Heikkinen, Ylä-Anttila and Juhola, 2019). Local actors are providers of infrastructure and services, regulators of zoning, and can be conveners and champions of an integrated approach for mitigation and adaptation at multiple levels (*limited evidence*, *high confidence*). New opportunities in governance and finance can enable cities to pool resources together and aggregate interventions to innovate ways of mobilising urban climate finance at scale (White and Wahbah, 2019; Simpson et al., 2019; Colenbrander, Dodman and Mitlin, 2018). However, research increasingly points toward the difficulties faced during the implementation of climate financing *in situ*, such as the fragmentation of structures of governance capable of managing large investments effectively (Mohammed et al., 2019).

Cross-Working Group Box URBAN (continued)

Scaling up transformative place-based action for both adaptation and mitigation requires enabling conditions including land-based financing, intermediaries and local partnerships (*medium evidence*, *high agreement*) (Tirumala and Tiwari, 2021;). Governance structures that combine actors working at different levels with different mixes of tools are effective in addressing challenges related to implementation of integrated action, while cross-sectoral coordination is necessary (Singh et al., 2020). Joint institutionalisation of mitigation and adaptation in local governance structures can also enable integrated action (Göpfert et al., 2020; Hurlimann et al., 2021). However, the proportion of international finance that reaches local recipients remains low, despite the repeated focus of climate policy on place-based adaptation and mitigation (Manuamorn, 2019). Green financing instruments that enable local climate action without exacerbating current forms of inequality can jointly address mitigation, adaptation and sustainable development. Climate finance that also reaches beyond non-state enterprises, including SMEs, communities and NGOs, and is responsive to the needs of urban inhabitants, including disabled individuals and different races or ethnicities, is essential for inclusive and resilient urban development (Colenbrander, Dodman and Mitlin, 2018Frenova, 2020). Developing networks that can exert climate action at scale is another priority for climate finance.

The urbanisation megatrend is an opportunity to transition global society. Enabling urban governance to avert cascading risk and achieve low-carbon, resilient development will involve co-production of policy and planning, rapid implementation and greater cross-sector coordination, monitoring and evaluation (*limited evidence*, *medium agreement)* (Grafakos et al., 2019; Di Giulio et al., 2018). New constellations of responsible actors are required to manage hybrid local-city or cross-city risk management and decarbonisation initiatives (*limited evidence*, *medium agreement*). These may increasingly benefit from linkages across more urban and more rural space as recognition of cascading and systemic risk brings recognition of supply chains, remittance flows and migration trends as vectors of risk and resilience. Urban governance will be better prepared in planning, prioritising and financing the kind of measures that can reduce GHG emissions and improve resilience at scale and pace when considering a view of cascading risks and carbon lock-ins globally, while acting locally to address local limitations and capacities, including the needs and priorities of urban citizens (Colenbrander, Dodman and Mitlin, 2018).

Cross-Chapter Box COVID | COVID-19

Authors: Maarten van Aalst (Netherlands, Chapter 16), Guéladio Cissé (Mauritania/Switzerland/France, Chapter 7), Ayansina Ayanlade (Nigeria, Chapter 9), Lea Berrang-Ford (United Kingdom/Canada, Chapter 16), Rachel Bezner Kerr (Canada/USA, Chapter 5), Robbert Biesbroek (Netherlands, Chapter 13), Kathryn Bowen (Australia, Chapter 7), Martina Angela Caretta (Sweden, Chapter 4), So-Min Cheong (Republic of Korea, Chapter 17), Winston Chow (Singapore, Chapter 6), Mark John Costello (New Zealand/Norway/Ireland, Chapter 11, CCP1), Kristie Ebi (USA, Chapter 7), Elisabeth Gilmore (USA/Canada, Chapter 14), Bruce Glavovic (South Africa/New Zealand, Chapter 18, CCP2), Walter Leal (Germany, Chapter 8), Stefanie Langsdorf (Germany, TSU), Elena Lopez-Gunn (Spain/United Kingdom, Chapter 4), Ruth Morgan (Australia, Chapter 4), Aditi Mukherji (India, Chapter 4), Camille Parmesan (France/ United Kingdom /USA, 2), Mark Pelling (United Kingdom, Chapter 6), Elvira Poloczanska (United Kingdom, TSU), Marie-Fanny Racault (United Kingdom/France, Chapter 3), Diana Reckien (Germany/Netherlands, Chapter 17), Jan C. Semenza (Sweden, Chapter 7), Pramod Kumar Singh (India, Chapter 18), Stavana E. Strutz (USA), Maria Cristina Tirado von der Pahlen (Spain/USA, Chapter 7), Corinne Schuster-Wallace (Canada), Alistair Woodward (New Zealand, Chapter 11), Zinta Zommers (Latvia, Chapter 17)

Introduction

The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which causes COVID-19, emerged in late 2019, halfway through the preparation of the IPCC WGII Sixth Assessment Report. This Cross-Chapter Box assesses how the massive shock of the pandemic and response measures interact with climate-related impacts and risks as well as its significant implications for risk management and climate resilient development.

COVID-19 and environmental connections

Infectious diseases may emerge and spread through multiple climate-related avenues, including direct effects of climatic conditions on disease reproduction and transmission and various indirect effects, often interlinked with ecosystem degradation (high confidence). Climate change is affecting the risk of emerging infectious diseases by contributing to factors that drive the movements of species, including vectors and reservoirs of diseases, into novel human populations and vice versa (*high confidence*) (Sections 2.4.2.7, 5.2.2.3; Cross-Chapter Box Illness in Chapter 2; IPCC, 2019b; IPBES 2020). The spillover of some emerging infectious diseases from wildlife into humans is associated with live animal–human markets, intensified livestock production and climate-related movements of humans and wild animals into new areas that alter human–animal interactions (Section 2.4.2.7; Chapter 3; Sections 5.2.2.3, 7.2; Cross-Chapter Box ILLNESS in Chapter 2; Cross-Chapter Box MOVING PLATE in Chapter 5).

Human-to-human transmission is the prominent driver in the spread of the COVID-19 pandemic, rather than climatic drivers (high confidence). There is emerging literature on the environmental determinants of COVID-19 transmission, incidence and mortality rates, with initial evidence suggesting that temperature, humidity and air pollution contribute to these patterns (Brunekreef et al., 2021; Xiong et al., 2020; Zhang et al., 2020b; AR6 WGI CCB 6.1: Implications of COVID-19 restrictions for emissions, air quality and climate). Climate change is altering environmental factors like temperature and seasonality that affect COVID-19 transmission (Choi et al., 2021).

The impact of COVID-19 containment measures resulted in a temporary reduction in greenhouse gas (GHG) emissions and reduced air pollution *(high confidence)* (IPCC WGI TS; Arias et al., 2021; AR6 WGI CCB 6.1: Implications of COVID-19 restrictions for emissions, air quality and climate). However, global and regional climate responses to the radiative effect were undetectable above internal climate variability due to the temporary nature of emission reductions. They therefore do not result in detectable changes in impacts or risks due to changes in climate hazards (Arias et al 2021; AR6 WGI CCB 6.1: Implications of COVID-19 restrictions for emissions, air quality and climate; Naik et al., 2021).

Cascading and compounding risks and impacts

The COVID-19 pandemic posed a severe shock to many socioeconomic systems, resulting in substantial changes in vulnerability and exposure of people to climate risks (*high confidence*). The disease and response measures significantly affected human health, economic activity, food production and availability, health services, poverty, social and gender inequality, education, supply chains, infrastructure maintenance and the environment. These COVID-19 impacts interact with many risks associated with climate change (IMF, 2020), often through a cascade of impacts across numerous sectors (van den Hurk et al., 2020). Beyond COVID-19-related mortality and long-term COVID, mortality from other diseases (some of which may also have a climate-related component), as well as maternal and neonatal mortality, increased because of disruption in health services (Barach et al., 2020; Maringe et al., 2020; Zadnik et al., 2020; Goyal et al., 2021). In addition, a rapid rise in poverty has disproportionately affected poorer countries and people (Ferreira et al., 2021), and thus increased their vulnerability. After many years of steady declines, extreme poverty increased by about 100 million people in 2020 (World Bank, 2021). The effects of the pandemic increased food insecurity and malnourishment, which increased by 1.5 percentage points to around 9.9% in 2020 after being virtually unchanged for the previous five years (FAO et al., 2021).

Cross-Chapter Box COVID (continued)

During the pandemic, extreme weather and climate events such as droughts, storms, floods, wildfires and heatwaves continued, resulting in disastrous compounding impacts (*high confidence*). Between March and September 2020, 92 extreme weather events coincided with the COVID-19 pandemic, affecting an estimated 51.6 million people; additionally, 431.7 million people were exposed to extreme heat, and 2.3 million people were affected by wildfires (Walton and van Aalst, 2020). The COVID-19 pandemic, in combination with extreme events, affected disaster preparedness, disaster response and safe evacuations, while physical distancing regulations reduced the capacity of temporary shelters (UN DRR Asia-Pacific, 2020; Tozier de la Poterie et al., 2020; Shumake-Guillemot, J, et al, 2020; Bose-O'Reilly et al., 2021). Complex humanitarian emergencies were aggravated, with vulnerable populations facing the combined risks of conflict, displacement, COVID-19 and climate impacts (FSIN, 2020). Compounding events are not only found in low-income countries but also in medium- and high-income countries, for instance in the case of COVID-19 and heatwaves (Shumake-Guillemot et al., 2020; Bose-O'Reilly et al., 2021).

Responses and implications for adaptation and climate resilient development

The pandemic emphasises the inter-connected and compound nature of risks, vulnerabilities and responses to emergencies that are simultaneously local and global (high confidence). COVID-19 is often considered a more 'explosive' risk than the more gradual anthropogenic climate change. However, many climate-related risks do already appear as severe shocks at smaller scales, and infrequent or unprecedented extreme weather-related events often warrant similar rapid responses (Dodds et al., 2020; Gebreslassie, 2020; Hynes et al., 2020; Phillips et al., 2020; Schipper, 2020; Semenza et al., 2021; illustrated in Figure COVID.1). Individuals, households, sub-national and national entities, and international organisations had generally delayed responses or denied the pandemic's severity before responding at the scale and urgency required, a pattern that resembles the international action required on climate change (Polyakova et al., 2020; Shrestha et al., 2020).

Improved contingency and recovery planning, including disease mitigation measures, were crucial in responding to the pandemic in similar ways to those seen in the aftermath of climate-related disasters (Guo et al., 2020; Ebrahim et al., 2020; Baidya et al., 2020; Shultz et al., 2020; Mukherjee et al., 2020). The pandemic highlighted the lack of global and country-specific capacity to respond to an unexpected and unplanned event and the need to implement more flexible detection and response systems (Ebi et al., 2021b).

It also exposed underlying vulnerabilities, such as the lack of water access and healthcare in select low- and middle-income countries and among indigenous and marginalised groups in high-income countries (Section 4.4.3; Box 4.3; 5.12.1). Increased risks of COVID-19 transmission emerged in crowded areas such as urban settings, refugee camps, detention centres and some workplaces, including in rural settings (Brauer et al., 2020; Ramos et al., 2020; Staddon et al., 2020; Haddout et al., 2020). Public health responses to the COVID-19 pandemic, such as mandates for social distancing and advice for frequent handwashing, underlined the need for access to water and sanitation facilities and wastewater management. However, they also sometimes interfered with access, for example, in evacuation and shelter infrastructure during climate-related disasters (Armitage and Nellums, 2020; Adelodun et al., 2020; Poch et al., 2020; Hallema et al., 2020; Patel et al., 2020; Espejo et al., 2020).

The experience of COVID-19 demonstrates that many warnings about the risks of the emergence of zoonotic transmission ('delay is costly', 'adapt early' and 'prevention pays') did not result in sufficient political attention, funding and pandemic prevention. In some countries, there has been an increased awareness of the risks and the real or perceived trade-offs associated with risk management (e.g., economy compared with health and impacts compared with adaptation). Building trust and participatory processes and establishing stronger relationships with communities and other civic institutions may enable a recalibration of how the government responds to crises and society–government relationships more generally (Amat et al., 2020; Deslatte, 2020).

The management of the COVID-19 pandemic has highlighted the value of scientific (including medical and epidemiological) expertise and the importance of fast, accurate and comprehensive data to inform policy decisions and to anticipate and manage risk (high confidence). It emphasises the importance of effective communication of scientific knowledge (Semenza et al., 2021), decision-making under uncertainty and decision frameworks that navigate different values and priorities. Successful policy responses were based on the emerging data, medical advice and collaboration with a wider set of societal stakeholders beyond public health experts. For instance, experience in Aotearoa, New Zealand, highlights the importance of pandemic responses attuned to the needs of different sociocultural groups and Indigenous Peoples in particular. Their strengths-based COVID-19 response goes beyond identifying vulnerabilities to unlocking the resources, capabilities and potential that might otherwise be latent in communities (McMeeking and Savage, 2020). As far as the value of information for risk management is concerned, compared to the initial uncertainties regarding COVID-19, data about near- and longer-term climate-related hazards is generally very good; however, high-quality and dense meteorological data are often still lacking in lower income countries (Otto et al., 2020). Health data are particularly difficult to obtain in real time, as is the case for biodiversity data, which

Cross-Chapter Box COVID (continued)

has a time lag of years before being made available and for which there is no coordinated monitoring, hampering effective risk management (Navarro et al., 2017). Therefore, both epidemiological and meteorological forecasts would benefit from more focus on (a) decision support, (b) conveying uncertainty and (c) capturing vulnerability (Coughlan de Perez et al., 2021).

Compound risk and compound resilience to pandemic and climate change

Figure COVID.1 | Compound risk and compound resilience to pandemic and climate change. Source: Pelling et al. (2021).

Cross-Chapter Box COVID (continued)

There is a considerable evidence base of specific actions that have co-benefits for reducing pandemic and climate change risks while enhancing social justice and biodiversity conservation (high confidence). The pandemic highlighted aspects of risk management that have long been recognised but are often not reflected in national and international climate policy: the value of addressing structural vulnerability rather than taking specific measures to control single hazards and drivers of risk and the importance of decision-making capacities and transparency, the rule of law, accountability and addressing inequities (or social exclusion) (reviewed by Pelling et al. (2021); see also Figure COVID.1).

Comprehensive and integrated risk management strategies can enable countries to address both the current pandemic and increase resilience against climate change and other risks (Reckien, 2021; Semenza et al., 2021; Ebi et al., 2021b). In particular, given their immense scale, COVID-19 recovery investments may offer an opportunity to contribute to climate resilient development pathways (CRDPs) through a green, resilient, healthy and inclusive recovery (*high confidence*) (Sovacool et al., 2020; Rosenbloom and Markard, 2020; Lambert et al., 2020; Boyle et al., 2020; Bouman et al., 2020; UN DRR Asia-Pacific, 2020; Brosemer et al., 2020; Dodds et al., 2020; Hynes et al., 2020; Markard and Rosenbloom, 2020; Phillips et al., 2020; Schipper, 2020; Willi et al., 2020; Semenza et al., 2021; Pasini and Mazzocchi, 2020; Meige et al., 2020; Pelling et al., 2021). However, windows of opportunity to enable such transitions are only open for a limited period and need to be swiftly acted upon to effect change (*high confidence*) (Chapter 18; Weible et al., 2020; Reckien, 2021). Initial indications suggest that only USD 1.8 trillion of the greater than USD 17 trillion COVID-19-related stimulus financing by G20 countries and other major economies that was committed up until mid-2021 contributed to climate action and biodiversity objectives, with significant differences between countries and sectors (Vivideconomics, 2021). Moreover, responses to previous crises (e.g., the 2008–2011 global financial crisis) demonstrate that despite high ambitions during the response phase, opportunities for reform do not necessarily materialise (Bol et al., 2020; Boin et al., 2005). In addition, heightened societal and political attention to one crisis often comes at the cost of other policy priorities (*high confidence*) (Maor, 2018; Tosun et al., 2017), which could affect investments for climate resilient development (Hepburn et al., 2020; WHO, 2020a; Bateman et al., 2020; Meige et al., 2020; Semenza et al., 2021).

In summary, the emerging literature suggests that the COVID-19 pandemic has aggravated climate-related health risks, demonstrated the global and local vulnerability to cascading shocks and illustrated the importance of integrated solutions that tackle ecosystem degradation and structural vulnerabilities in human societies. This highlights the potential and urgency of interventions that reduce pandemic and climate change risks while enhancing compound resilience, social justice and biodiversity conservation (see Figure COVID.1).

Cross-Chapter Box MIGRATE | Climate-Related Migration

Authors: David Wrathall (USA, Chapter 8), Robert McLeman (Canada, Chapter 7), Helen Adams (United Kingdom, Chapter 7), Ibidun Adelekan (Nigeria, Chapter 9), Elisabeth Gilmore (USA/Canada, Chapter 14), François Gemenne (Belgium, Chapter 8), Nathalie Hilmi (Monaco, Chapter 18), Ben Orlove (USA, Chapter 17), Ritwika Basu (India/United Kingdom, Chapter 18), Halvard Buhaug (Norway, Chapter 16), Edwin Castellanos (Guatemala, Chapter 12), David Dodman (United Kingdom, Chapter 6), Felix Kanungwe Kalaba (Zambia, Chapter 9), Rupa Mukerji (Switzerland/India, Chapter 18), Karishma Patel (USA, Chapter 1), Chandni Singh (India, Chapter 10), Philip Thornton (United Kingdom, Chapter 5), Christopher Trisos (South Africa, Chapter 9), Olivia Warrick (New Zealand, Chapter 15), Vishnu Pandey (Nepal, Chapter 4)

Key messages on migration in this report

Migration is a universal strategy that individuals and households undertake to improve well-being and livelihoods in response to economic uncertainty, political instability and environmental change (*high confidence*). Migration, displacement and immobility that occur in response to climate hazards are assessed in general in Chapter 7, with specific sectoral and regional dimensions of climate-related migration assessed in sectoral and regional Chapters 5 to 15 (Table MIGRATE.1 in Chapter 7) and involuntary immobility and displacement being identified as representative key risks in Chapter 16 (Sections 16.2.3.8, 16.5.2.3.8). Since AR5 there has been a considerable expansion in research on climate–migration linkages, with five key messages from the present assessment report warranting emphasis.

Climatic conditions, events and variability are important drivers of migration and displacement (*high confidence*) *(Table MIGRATE.1 in Chapter 7), with migration responses to specific climate hazards being strongly influenced by economic, social, political and demographic processes* (*high confidence*) *(Sections 7.2.6, 8.2.1.3).* Migration is among a wider set of possible adaptation alternatives and often emerges when other forms of adaptation are insufficient (Sections 5.5.1.1, 5.5.3.5, 7.2.6, 8.2.1.3, 9.7.2). Involuntary displacement occurs when adaptation alternatives are exhausted or not viable and reflects non-climatic factors that constrain adaptive capacity and create high levels of exposure and vulnerability (*high confidence*) (Cross-Chapter Box SLR in Chapter 3; Sections 4.3.7, 7.2.6; Box 8.1; Section 10.3; Box 14.7). There is strong evidence that climatic disruptions to agricultural and other rural livelihoods can generate migration (*high confidence*) (Sections 5.5.4, 8.2.1.3, 9.8.3; Box 9.8).

Specific climate events and conditions may cause migration to increase, decrease or flow in new directions (high confidence), and the more agency migrants have (i.e., the degree of voluntarity and freedom of movement), the greater the potential benefits for sending and receiving areas (*high agreement, medium evidence*) *(Sections 5.5.3.5, 7.2.6, 8.2.1.3; Box 12.2)*. Conversely, displacement or low-agency migration is associated with poor outcomes in terms of health, well-being and socioeconomic security for migrants and returns fewer benefits to sending or receiving communities (*high agreement, medium evidence*) (Sections 4.3.7, 4.5.7; Box 8.1; Sections 9.7.2, 10.3; Box 14.7).

Most climate-related migration and displacement observed currently takes place within countries (*high confidence*) *(Sections 4.3.7, 4.5.7, 5.12.2, 7.2.6).* The climate hazards most commonly associated with displacement are tropical cyclones and flooding in most regions, with droughts being an important driver in sub-Saharan Africa, parts of south Asia and South America (*high confidence*) (Sections 7.2.6.1, 9.7.2, 10.4.6.3, 11.4.1, 12.5.8.4, 13.8.1.3, 14.4.7.3). Currently, observed international migration associated with climatic hazards is considerably smaller relative to internal migration and is most often observed as flowing between states that are contiguous and have labour-migration agreements and/or longstanding cultural ties (*high agreement, robust evidence*) (Sections 4.3.7, 4.5.7, 5.12.2, 7.2.6).

In many regions, the frequency and/or severity of floods, extreme storms and droughts is projected to increase in coming decades, especially under high-emissions scenarios (WGI AR6 Chapter 12 (Ranasinghe et al. 2021)), raising future risk of displacement in the most exposed areas (*high confidence*) *(Section 7.3.2.1).* The additional impacts of climate change anticipated to generate future migration and displacement include mean sea level rise that increases flooding and saltwater contamination of soil and/or groundwater in low-lying coastal areas and small islands (*high confidence*) (Section 7.3.2.1; Cross-Chapter Box SLR in Chapter 3) and more frequent extreme heat events that threaten the habitability of urban centres in the tropics and arid/semiarid regions (*medium confidence*), although the causal links between heat and migration are less clear (Section 7.3.2.1).

There is growing evidence about the future prospects of immobile populations: groups and individuals that are unable or unwilling to move away from areas highly exposed to climatic hazards (*high confidence*) *(Sections 4.6.9, 7.2.6.2; Box 8.1; Box 10.2).* Involuntarily immobile populations may be anticipated to require government interventions to continue living in exposed locations or to relocate elsewhere (*high agreement, medium evidence)* (Box 8.1). Managed retreat and organised relocations of people from hazardous areas in recent years have proven to be politically and emotionally charged, socially disruptive and costly (*high confidence*) (Section 7.4.5.4).

Cross-Chapter Box MIGRATE (continued)

Climate-migration interactions and outcomes

Figure MIGRATE.1 in Chapter 7 presents a simplified framework for understanding how migration and displacement may emerge from the interactions of climatic and non-climatic factors, based on the characteristic risk framework introduced in Chapter 1 (Section 1.3). Voluntary migration can be used by households when adapting to climate hazards, while less voluntary forms of migration and displacement emerge when other forms of adaptation (referred to in Figure MIGRATE.1 in Chapter 7 as *in situ* adaptation) are inadequate. Migration outcomes—expressed in Figure MIGRATE.1 in Chapter 7 as changes in future risks to the well-being of migrants, sending communities and destination communities—are heavily influenced by the political, legal, cultural and socioeconomic conditions under which migration occurs. Groups and individuals that are involuntarily immobile may find that their exposure, vulnerability and risk increase over time. Table MIGRATE.1 in Chapter 7 summarises the range of potential migration outcomes that may emerge from this dynamic and indicates specific sections in sectoral and regional chapters of the report that describe examples of each.

Climate-migration processes and outcomes

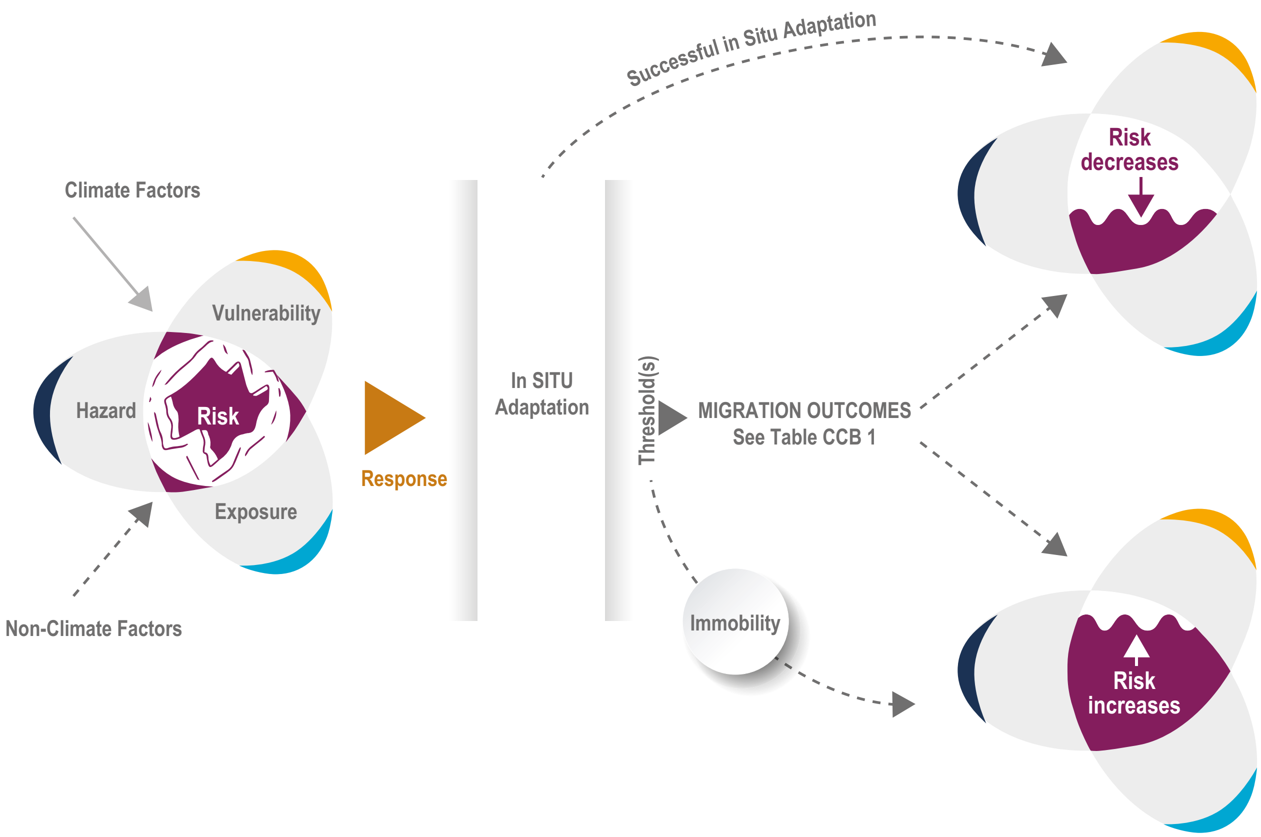


Figure MIGRATE.1 | General interactions between climatic and non-climatic processes, adaptation, potential migration outcomes and implications for future risk. Adapted from McLeman et al. (2021).

Cross-Chapter Box MIGRATE (continued)

Table MIGRATE.1 | Typology of climate-related migration and examples in sectoral and regional chapters of AR6.

Type of climate-related migration	Characteristics	Recent or current examples	Examples in the literature	References in AR6 WGII
Temporary and/or seasonal migration	Frequently used as a risk-reduction strategy by rural households in less-developed regions with highly seasonal precipitation; includes transhumance	Pastoralists in sub-Saharan Africa; seasonal farm workers in south Asia; rural–urban labour migration in Central America	Afifi et al. (2016); Call et al. (2017); Piguet et al. (2018); Borderon et al. (2019); Cattaneo et al. (2019); Hoffmann et al. (2020); Lopez-i-Gelats et al. (2015); Lu et al. (2016) Kaczan and Orgill-Meyer (2020)	Sections 5.5.1.1, 5.5.3.5; Section 7.2.6; Section 8.2.1.3; Section 9.8.3; Box 13.2
Indefinite or permanent migration	Less common than temporary or seasonal migration, particularly when the whole household permanently relocates	Numerous examples in all regions	See reviews listed in cell above	Section 7.2.6; Section 8.2.1.3; Box 10.2
Internal migration	Movements within state borders; most common form of climate-related migration	Numerous examples in all regions	See reviews listed in cell above	Section 4.3.7; Sections 5.5.4, 5.10.1.1; Section 7.2.6; Sections 9.7.2, 9.11; Box 9.8; Sections 10.3.3, 10.4.6.3, Box 10.2; Section 11.4.1; Section 12.5.8.4; Section 13.8.1.3; Section 14.4.7.3; Section 15.3.4.6
International migration	Less common than internal migration; most often occurs between contiguous countries within the same region; often undertaken for purpose of earning wages to remit home	Cross-border migration within south and Southeast Asia, sub-Saharan Africa	See reviews listed in cell above; also Veronis et al. (2018); McLeman (2019); Cattaneo and G. (2016); Missirian and Schlenker (2017); Schutte et al. (2021)	Sections 4.3.7, 4.5.7; Section 5.12.2; Section 7.2.6
Rural–urban or rural–rural	Typically internal but may also flow between contiguous states; may be for temporary or indefinite periods; migration may be undertaken by an individual household member or the entire household; may be followed by remittances	Drought migration in Mexico, east Africa and south Asia	See reviews in the cell above; also Adger et al. (2015); Gautier et al. (2016); Nawrotzki et al. (2017); Wiederkehr et al. (2018); Robalino et al. (2015); Borderon et al. (2019); Murray-Tortarolo and Martnez (2021)	Section 5.13.4; Section 7.2.6; Section 6.2.4.3; Section 8.2.1.3; Section 9.8.1.2; Section 12.5.8.4; Section 14.4.7.1
Displacement	Households are forced to leave homes for temporary or indefinite period; typically occurs as a result of extreme events and starts with seemingly temporary evacuation; risk is expected to rise in most regions due to sea level rise and changes in associated coastal hazards	Tropical cyclones in the Caribbean, Southeast Asia and Bay of Bengal region	Islam and Shamsuddoha (2017); Desai et al. (2021); see Internal Displacement Monitoring Centre annual reports for global statistics	Cross-Chapter Box SLR in Chapter 3; Section 4.3.7; 4.5.7; Cross-Chapter Box MOVING PLATE in Chapter 5; Section 7.2.6.1; Box 8.1; Section 9.7.2; Section 9.9.2; Section 10.3; Box 14.7; Sections 15.3.4.6; CCP2.2.2
Planned and/or organised resettlement	Initiated in areas where settlements become permanently uninhabitable; requires assistance from governments and/or institutions; government-sponsored sedentarisation of pastoral populations	Fiji, Carteret Islands, Papua New Guinea, Gulf of Mexico coast and coastal Alaska, USA	Marino and Lazrus (2015); Hino et al. (2017); McNamara et al. (2018); McMichael and Katonivualiku (2020); Tadgell et al. (2017); Arnall (2014); Wilmsen and Webber (2015)	Section 4.6.9; Sections 5.14.1, 5.14.2; Section 7.4.4.4; Section 10.4.6; Section 15.5.3; CCP2.2.2; CCP6.3.2
Immobility	Adverse weather or climatic conditions warrant moving, but households are unable to relocate because of lack of resources or choose to remain because of strong social, economic or cultural attachments to place	Examples in most regions	Adams (2016); Zickgraf (2018); Nawrotzki and DeWaard (2018); Farbotko et al. (2020)	Section 4.6.9; Section 7.2.6.2; Box 8.1; Box 10.2

Policy implications

Future migration and displacement patterns in a changing climate will depend not only on the physical impacts of climate change, but also on future policies and planning at all scales of governance (*high confidence*) *(4.6.9, 5.14.1, 5.14.1.2, 7.3.2, 7.4.4, 8.2.1.3; Box 8.1; CCP6.3.2).* Policy interventions can remove barriers to and expand the alternatives for safe, orderly and regular migration that allows

Cross-Chapter Box MIGRATE (continued)

vulnerable people to adapt to climate change (*high confidence*) (Section 7.2.6). With adequate policy support, migration in the context of climate change can result in synergies for both adaptation and development (Sections 5.12.2, 7.4.4, 8.2.1.3). Migration governance at local, national and international levels will influence the outcomes of climate-related migration for the migrants themselves as well as for receiving and origin communities (Sections 5.13.4, 7.4.4, 8.2.1.3). At the international level, a number of relevant policy initiatives and agreements, including Global Compacts for Safe, Orderly and Regular Migration and for the protection of Refugees; the Warsaw International Mechanism of the UNFCCC; the Sustainable Development Goals; the Sendai Framework for Disaster Risk Reduction; and the Platform on Disaster Displacement, have already been established, merit continued pursuit and provide potential migration governance pathways (Section 7.4.4). Policy and planning decisions at regional, national and local scales that relate to housing, infrastructure, water provisioning, schools and healthcare are relevant for successful integration of migrants into receiving communities (Sections 5.5.4, 5.10.1.1, 5.12.2, 9.8.3). Policies and practices on movements of people across international borders are also relevant to climate-related migration, with restrictions on movement having implications for the adaptive capacity of communities exposed to climate hazards (Section 7.4.4.2; Box 8.1). Perceptions of migrants and the framing of policy discussions in receiving communities and nations are important determinants of the future success of migration as an adaptive response to climate change (Section 7.4.4.3) (*high agreement, medium evidence*).

Reducing the future risk of large-scale population displacements, including those requiring active humanitarian interventions and organised relocations of people, requires the international community to meet the requirements of the Paris Agreement and take further action to control future warming (*high confidence*) *(Cross-Chapter Box SLR in Chapter 3; Section 7.3.1; Box 8.1).* Current emissions pathways lead to scenarios for the period between 2050 and 2100 in which hundreds of millions of people will be at risk of displacement due to rising sea levels, floods, tropical cyclones, droughts, extreme heat, wildfires and other hazards, with land degradation exacerbating these risks in many regions (Section 7.3.2; IPCC 2019b; Cross-Chapter Box SLR in Chapter 3). At high levels of warming, tipping points may exist, particularly related to sea level rise, that, if crossed, would further increase the global population potentially at risk of displacement (Ranasinghe et al. 2021). Populations in low-income countries and small-island states that have historically had low greenhouse gas (GHG) emissions are at particular risk of involuntary migration and displacement due to climate change, reinforcing the urgency for industrialised countries to continue lowering GHG emissions, to support adaptive capacity-building initiatives under the UNFCCC and to meet objectives expressed in the Global Compacts regarding safe, orderly and regular migration and the support and accommodation of displaced people (Sections 4.3.7, 4.5.7, 5.12.2, 7.4.5.5, 8.4.2; Box 8.1; Cross-Chapter Box SLR in Chapter 3).

Cross-Chapter Box HEALTH | Co-benefits of Climate Actions for Human Health, Well-Being and Equity

Authors: Cristina Tirado (USA/Spain, Chapter 7); Robbert Biesbroek (Netherlands, Chapter 13); Mark Pelling (United Kingdom, Chapter 6); Jeremy Hess (USA, Chapter 7); Felix Creutzig (Germany, WGIII); Rachel Bezner Kerr (Canada/USA, Chapter 5); Siri Eriksen (Norway, Chapter 18); Diarmid Campbell-Lendrum (United Kingdom, Chapter 7); Elisabeth Gilmore (USA/Canada, Chapter 14); Maria Figueroa (Denmark/Venezuela, WGIII); Nathalie Hilmi (Monaco, Chapter 18); Peter Newman (Australia, WGIII); Sebastian Mirasgedis (Greece, WGIII); Sharma Rohit (India); Yamina Saheb (France/Algeria, WGIII); Gerardo Sanchez Martinez (Spain); Peter Smith (United Kingdom, WGIII); Adrian Leip (Italy, WGIII); Dhar Subash (Denmark/India, WGIII); Chris Trisos (South Africa, Chapter 9); Mercedes Bustamante (Brazil, WGIII); Luisa Cabeza (Spain, WGIII); Diana Urge-Vorsatz (Hungary, WGIII)

Achieving the Paris Agreement and SDGs can result in low-carbon, healthy, resilient and equitable societies with high well-being for all (very high confidence) (Alfredsson et al., 2018; O'Neill et al., 2018). Given the overlap in sources of greenhouse gases (GHGs) and co-pollutants in energy systems, strategies that pursue GHG emission reductions and improvements in energy efficiency hold significant potential health co-benefits through air pollution emission reductions (*high confidence*) (Gao et al., 2018). Air quality improvements alone can substantially offset, or most likely exceed, mitigation costs at the societal level (Schucht et al., 2015; Chang et al., 2017; Markandya et al., 2018; Vandyck et al., 2018; Peng et al., 2017; Woodward et al., 2019; Sampedro et al., 2020; Xie et al., 2018). Pursuit of a mitigation pathway compatible with warming of +1.5°C with associated cleaner air, avoided extreme events and improved food security and nutrition could result in 152 ± 43 million fewer premature deaths worldwide between 2020 and 2100 compared with a business-as-usual scenario (Shindell et al., 2018). Reaching the Paris Agreement could result in an annual reduction of 1.18 million air pollution-related deaths, 5.86 million diet-related deaths and 1.15 million deaths due to physical inactivity across nine major economies by 2040 (Hamilton et al., 2021). In Europe, a mitigation scenario compatible with RCP2.6 could reduce total pollution costs, mostly from PM2.5, by 84%, with human health benefits equal to more than Euro 1 trillion over five years (Scasny et al., 2015). In the EU, ambitious climate mitigation policies could reduce years of lost life due to fine particulate matter (PM) from over 4.6 million in 2005 to 1 million in 2050, reduce ozone-related premature deaths from 48,000 to 7,000 and generate health benefits of Euro 62 billion yr^{-1} in 2050 (Schucht et al., 2015).

However, there may be significant trade-offs between mitigation and other societal goals (Dong et al., 2019; Gao et al., 2018). In some scenarios, mitigation policies consistent with the NDCs may slow poverty reduction efforts (Campagnolo and Davide, 2019) with implications for health. A framework of 'co-impacts' that assumes neither a general beneficial nature of all implications from mitigation policy nor a hierarchy between climate and other types of benefits, may be more appropriate (Ürge-Vorsatz et al., 2014; Cohen et al., 2017).

Transitioning to affordable clean energy sources for all presents opportunities for substantial well-being, health, and equity co-benefits (high confidence) (Gibon et al., 2017; Lacey et al., 2017; Peng et al., 2018; Vandyck et al., 2018; Williams et al., 2018). Residential solid fuel use affects health and degrades indoor air quality for up to 3.1 billion people in low- and middle-income countries (WHO, 2016b; Wang et al., 2017a). Adherence to planned emission reductions from the Paris Agreement related to renewables could subsequently improve air quality and prevent 71,000–99,000 premature deaths annually by 2030 (Vandyck et al., 2018). This effect increases with a 2°C pathway, with 0.7–1.5 million premature deaths avoided annually by 2050 (Vandyck et al., 2018). Co-benefits are also observed at national and regional levels. For instance, China could expect 55,000–69,000 averted deaths in 2030 if it transitioned to a half-decarbonised power supply for its residential and vehicle sectors (Peng et al., 2018).

Investing in universal basic infrastructure, including sanitation, clean drinking water, drainage, electricity, and land-rights, can transform development opportunities, increase adaptive capacity, and reduce vulnerability to climate-related risks (high agreement, high evidence). Transformative approaches that reduce climate-related risks and deliver enhanced social inclusion and development opportunities for the urban poor are most likely where local governments act in partnership with local communities and other civil society actors (*high confidence*) (Chapter 6, sections 6.1, 6.3, 6.4).

Rapid urbanisation offers a time-limited opportunity to work at scale towards transformational adaptation and climate resilient development (medium evidence, high agreement). Multi-level leadership, institutional capacity and financial resources to support inclusive adaptation in the context of multiple pressures and inter-connected risks can help ensure that the additional 2.5 billion people projected to live in urban areas by 2050 are less exposed to climate-related hazards and contribute less to global warming (*high confidence*) (Chapter 6, sections 6.1, 6.3, 6.4). Integrating low-carbon, inclusive adaptation into infrastructure investment driven by rapid urban population growth and COVID-19 recovery can accelerate co-benefits (Chapter 6).

Urban planning that combines clean, affordable public transportation, shared clean vehicles and accessible active transportation modes can improve air quality and contribute to healthy, equitable societies and higher well-being for all. Stimulating active mobility (walking

Cross-Chapter Box HEALTH (continued)

and bicycling) can bring physical and mental health benefits (*high confidence*) (Chapter 6; Rojas-Rueda et al., 2016; Avila-Palencia et al., 2018; Gascon et al., 2019; Hamilton et al., 2021). The health gains from active mobility outweigh traffic-related injuries due to a decreased incidence of chronic diseases (Ahmad et al., 2017; Maizlish et al., 2017; Tainio et al., 2017; Woodcock et al., 2018).

Urban green and blue spaces contribute to climate change adaptation and mitigation and improve physical and mental health and well-being (high confidence) (Hansen 2017; EC, 2018; WHO, 2018a; Rojas-Rueda et al. 2019; 13.7.3, WGII; 6. WGII; 8.4 WGIII). Urban green infrastructure including urban gardens, can bring benefits to social cohesion, mental health and well-being and reduce the health impacts of heatwaves by decreasing temperatures, thus reducing inequities in exposure to heat stress for low income, marginalised groups (Hoffman et al., 2020; Hoffmann et al., 2020; Chapter 5 section 5.12.5; Chapter 6; Chapter 7 section 7.4; Chapter 13 section 13.7). The trade-offs of increasing urban green and blue spaces include potential public health risks related to increased vectors or hosts for infectious diseases, toxic algal blooms, drowning and aeroallergens (Choi et al., 2021; Stewart-Sinclair et al., 2020; Chapter 6).

Climate adaptation and mitigation policies in the building sector offer multiple well-being and health co-benefits (high confidence) (Diaz-Mendez et al., 2018; Macnaughton et al., 2018; Chpater 3 section 3.6.2). Leadership in Energy and Environmental Design (LEED) certified buildings in the USA, Brazil, China, India, Germany and Turkey saved an estimated USD 7.5 billion in energy costs and averted 33 Mt of CO_2 from 2000–2016 (Macnaughton et al., 2018). These measures can increase health benefits through better indoor air quality, reduction of the heat island effect, improved social well-being through energy poverty alleviation, creation of new jobs, increased productive time and income, increased thermal comfort and lighting indoors and reduced noise impact (Smith et al., 2016; McCollum et al., 2018; Thema et al., 2017; Mirasgedis et al., 2014; Alawneh et al., 2019; Diaz-Mendez et al., 2018). The value of these multiple co-benefits associated with climate actions in buildings is equal to or greater than the costs of energy savings (Ürge-Vorsatz et al., 2016; Payne et al., 2015; Chapter 14 section 14.4.5).

Shifting to sustainable food systems that provide affordable, diverse and plant-rich diets with moderate quantities of GHG-intensive animal protein can bring health co-benefits and substantially reduce GHG emissions, especially in high income countries and where ill health related to overconsumption of animal-based products is prevalent (very high confidence) (Chapter 5 section 5.12.6; Chapter 7 section 7.4, Chapter 13 section 13.5; Springmann et al., 2018c; IPCC, 2019b; Clark and Tilman, 2017; Poore and Nemecek, 2018; Hayek et al., 2021). Transforming the food system by limiting the demand for GHG-intensive animal foods, reducing food over-consumption and transitioning to nutritious, plant-rich diets can have significant co-benefits to health (*high confidence*) (Hedenus et al., 2014; Ripple et al., 2014; Tirado, 2017; Springmann et al., 2018c; IPCC, 2018; IPCC, 2019a; IPCC, 2019b; Nelson et al., 2016; Willett et al., 2019; Tilman and Clark, 2014; Green et al., 2015; Springmann et al., 2016b; Springmann et al., 2018b; Springmann et al., 2018a; Springmann et al., 2018c; Milner et al., 2015; Milner et al., 2017; Farchi et al., 2017; Song et al., 2017; Willett et al., 2019). Reduction of red meat consumption reduces the risk of cardiovascular disease (CVD) and colorectal cancer; the consumption of more fruits and vegetables can reduce the risk of CVD, type II diabetes, cancer and all causes of mortality (Tilman and Clark, 2014; Sabate and Soret, 2014; Willett et al., 2019; Chapter 7 section 7.4; Chapter 5 section 5.12.5). Globally, it is estimated that transitioning to more plant-based diets—in line with World Health Organization (WHO) recommendations on healthy eating—could reduce global mortality by 6–10% and food-related GHG emissions by 29–70% by 2050 (Springmann et al., 2016b). There are limitations in accessibility of affordable of healthy and diverse diets for all (Springmann et al., 2020) and trade-offs such as the potential increase of GHG emissions from producing healthy and diverse diets in low- and medium-income countries (Semba et al., 2020). Agroecological approaches have mitigation and adaptation potential and deliver ecosystem services, biodiversity, livelihoods and benefits to nutrition, health and equity (Rosenstock et al., 2019; Bezner Kerr et al., 2021; Chapter 5 sections 5.4.4, 5.14.1; Chapter 13 section 13.5; Chapter 14 section 14.4.4).

Cross-Chapter Box INTEREG | Inter-regional Flows of Risks and Responses to Risk

Authors: Birgit Bednar-Friedl (Austria, Chapter 13), Christopher Trisos (South Africa, Chapter 9), Laura Astigarraga (Uruguay, Chapter 12), Magnus Benzie (Sweden/UK), Aditi Mukherji (India, Chapter 4), Maarten Van Aalst (the Netherlands, Chapter 16)

Introduction

Our world today is characterised by a high degree of interconnectedness and globalisation which establish pathways for the transmission of climate-related risks across sectors and borders (*high confidence*) (Challinor et al., 2018; Hedlund et al., 2018). While the IPCC 5th Assessment Report (AR5) has pointed to this connection of risks across regions as 'cross-regional phenomena' (Hewitson et al., 2014), only a few countries so far have integrated inter-regional aspects into their climate change risks assessments (Liverman, 2016; Surminski et al., 2016; Adams et al., 2020), and adaptation is still framed as a predominantly national or local issue (Dzebo and Stripple, 2015; Benzie and Persson, 2019).

Inter-regional risks from climate change—also called cross-border, transboundary, transnational or indirect risks—are risks that are transmitted across borders (e.g., transboundary water use) and/or via teleconnections (e.g., supply chains, global food markets) (Moser and Hart, 2015). The risks can result from impacts, including compound or concurrent impacts, that cascade across several tiers, in ways that either diminish or escalate risk within international systems (Carter et al., 2021). Risk transmission may occur through trade and finance networks, flows of people (Cross-Chapter Box MIGRATE in Chapter 7), biophysical flows (natural resources such as water) and ecosystem connections. However, not only risks are transmitted across borders and systems; the adaptation response may also reduce risks at the origin of the risk, along the transmission channel or at the recipient of the risk (Carter et al., 2021). This cross-chapter box discusses four inter-regional risk channels (trade, finance, food and ecosystems) and how adaptation can govern these risks.

Trade

Most commodities are traded on global markets, and supply chains have become increasingly globalised. For instance, specialised industrial commodities such as semiconductors are geographically concentrated in a few countries (Challinor et al., 2017; Liverman, 2016). When climatic events like flooding or heat affect the location of these extraction and production activities, economies are not only disrupted locally but also across borders and in distant countries (*high confidence*), as exemplified by the Thailand flood 2011 that led to a shortage of key inputs to the automotive and electronics industry not only in Thailand but also in Japan, Europe and the USA (Figure Cross-Chapter Box INTEREG.1). For many industrialised countries like the UK, Japan, the USA and the European Union, there is increasing evidence that the trade impacts of climate change are significant and can have substantial domestic impacts (*medium confidence*) (Nakano, 2017; Willner et al., 2018, Section 13.9.1; Benzie and Persson, 2019; Knittel et al., 2020). Enhanced trade can transmit risks across borders and thereby amplify damages (Wenz and Levermann, 2016), but it can also increase resilience (Lim-Camacho et al., 2017; Willner et al., 2018).

Finance

Climate risks can also spread through global financial markets (Mandel et al., 2021). For the case of coastal and riverine flooding with low adaptation 2080 (RCP 8.5-SSP5), the financial system is projected to amplify direct losses by a factor of 2 (global average), but reach up to a factor of 10 for countries that are central financial hubs (Mandel et al., 2021, Figure 13.28). Indirect impacts may also arise through indirect effects on foreign direct investment, remittance flows and official development assistance (Hedlund et al., 2018).

Food

The global supply of agricultural products is concentrated to a few main breadbaskets (Bren d'Amour et al., 2016; Gaupp et al., 2020, Chapter 5). For instance, Central and South America is one of the regions with the highest potential to increase food supplies to more densely populated regions in Asia, the Middle East and Europe (Chapter 12). The exports of agricultural commodities (coffee, bananas, sugar, soybean, corn, sugarcane, beef livestock) have gained importance in the past two decades as international trade and globalisation of markets have shaped the global agri-food system (Chapter 5).

The export of major food crops like wheat, maize and soybeans from many of the world's water-scarce area—the Middle East, North Africa, parts of South Asia, North China Plains, southwest USA, Australia—to relatively water-abundant parts of the world carries a high virtual water content (the net volume of water embedded in trade) (*high confidence*) (Hoekstra and Mekonnen, 2012; Dalin et al., 2017; Zhao et al., 2019, Chapter 4). Both importing and exporting countries are exposed to transboundary risk transmission through climate change impacts on distant water resources (Sartori et al., 2017; Zhao et al., 2019; Ercin et al., 2021). Climate change is projected to exacerbate risk and add new vulnerabilities for risk transmission (*medium confidence*). Rising atmospheric CO_2 concentration is projected to decrease water efficiency of growing maize and temperate cereal crops in parts of the USA, East and Mediterranean Europe, South Africa, Argentina, Australia and Southeast Asia, with important implications for future trade in food grains (Fader et al., 2010). By 2050 (SRES B2 scenario), virtual water importing countries in Africa and the Middle East may be exposed to imported water stress as they rely on imports of food grains from countries which have unsustainable water use (Sartori et al., 2017). Until 2100, virtual trade in irrigation water is projected

Cross-Chapter Box INTEREG (continued)

to almost triple (for SSP2-RCP6.5 scenarios) and the direction of virtual water flows is projected to reverse, with the currently exporting regions like South Asia becoming importers of virtual water (Graham et al., 2020). An additional 10–120% trade flow from water-abundant regions to water-scarce regions will be needed to sustain environmental flow requirements on a global scale by the end of the century (Pastor et al., 2019). Exports of agricultural commodities contribute to deforestation, over-exploitation of natural resources and pollution, affecting the natural capital base and ecosystem services (Agarwala and Coyle, 2020; Rabin et al., 2020, Section 12.5.4).

Figure Cross-Chapter Box INTEREG.1 | Inter-regional climate risks: the example of the trade transmission channel, illustrated for the Thailand flood 2011 (Abe and Ye, 2013; Haraguchi and Lall, 2015; Carter et al., 2021).

Cross-Chapter Box INTEREG (continued)

Species and ecosystems

The spatial distributions of species on land and in the oceans are shifting due to climate change, with these changes projected to accelerate at higher levels of global warming (Pecl et al., 2017). These 'species on the move' have large effects on ecosystems and human well-being, and present challenges for governance (Pecl et al., 2017). For example, the number of transboundary fish stocks is projected to increase as key fisheries species are displaced by ocean warming (Pinsky et al., 2018). Conflict over shifting mackerel fisheries has already occurred between European countries (Spijkers and Boonstra, 2017), because few regulatory bodies have clear policies on shifting stocks; this leaves species open to unsustainable exploitation in new waters in the absence of regularly updated catch allocations to reflect changing stock distributions (Caddell, 2018).

Human health will also be affected as vector-borne diseases such as malaria and dengue shift geographic distributions (Caminade et al., 2014). There is also evidence that many warm-adapted invasive species, such as invasive freshwater cyanobacterium, have spread to higher latitudes because of climate change (Chapter 2).

Adaptation to inter-regional climate risks

Adaptation responses to reduce inter-regional risks can be implemented at a range of scales: at the point of the initial climate change impact (e.g., assistance for recovery after an extreme event, development of resilient infrastructure, climate-smart technologies for agriculture); at or along the pathway via which impacts are transmitted to the eventual recipient (e.g., trade diversification, re-routing of transport); in the recipient country (e.g., increasing storage to buffer supply disruptions), or by third parties (e.g., adaptation finance, technology transfer) (Bren d'Amour et al., 2016; Carter et al., 2021; Talebian et al., 2021). A knowledge gap exits on the need for, effectiveness of, and limits to adaptation under different socioeconomic and land use futures.

Due to regional and global interdependencies, climate resilience has a global, multi-level public good character (Banda, 2018). The benefits of adaptation are therefore shared beyond the places where adaptation is initially implemented. Conversely, adaptation may be successful at a local level while redistributing vulnerability elsewhere or even driving or exacerbating risks in other places (Atteridge and Remling, 2018). International cooperation is therefore needed to ensure that inter-regional effects are considered in adaptation and that adaptation efforts are coordinated to avoid maladaptation. However, regional- and global-scale governance of adaptation is only just beginning to emerge (Persson, 2019).

The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement frames adaptation as a 'global challenge' (Article 7.2) and establishes the global goal on adaptation (Article 7.1), which provides space for dialogue between parties on the global-scale challenge of adaptation and the need for renewed political and financial investment in adaptation, including to address inter-regional effects (Benzie et al., 2018).

National Adaptation Plans (NAPs) can evolve to consider inter-regional effects as well as domestic ones (Liverman, 2016; Surminski et al., 2016; European Environment, 2020). Regional and international coordination of NAPs, coupled with building capacities and addressing existing knowledge gaps at the country level, can help to ensure that resources are oriented towards reducing inter-regional risks and building systemic resilience to climate change globally (Booth et al., 2020; Wijenayake et al., 2020).

Given the important role of private actors in managing inter-regional climate risks (Goldstein et al., 2019; Tenggren et al., 2019), efforts will be needed to align public and private strategies for managing inter-regional climate risks to avoid maladaptation and ensure just and equitable adaptation at different scales (Talebian et al., 2021).

Cross-Working Group Box SRM | Solar Radiation Modification

Authors: Christopher H. Trisos (South Africa), Oliver Geden (Germany), Sonia I. Seneviratne (Switzerland), Masahiro Sugiyama (Japan), Maarten van Aalst (the Netherlands), Govindasamy Bala (India), Katharine J. Mach (USA), Veronika Ginzburg (Russia), Heleen de Coninck (the Netherlands), Anthony Patt (Switzerland)

Proposed solar radiation modification schemes

This cross-working group box assesses solar radiation modification (SRM) proposals, their potential contribution to reducing or increasing climate risk, as well as other risks they may pose (categorised as risks from responses to climate change in the IPCC AR6 risk definition in 1.2.1.1), and related perception, ethics and governance questions.

SRM refers to proposals to increase the reflection of shortwave radiation (sunlight) back to space to counteract anthropogenic warming and some of its harmful impacts (de Coninck et al., 2018) (Cross-Chapter Box 10; WGI Chapters 4, 5). A number of SRM options have been proposed, including: stratospheric aerosol interventions (SAI), marine cloud brightening (MCB), ground-based albedo modifications (GBAM) and ocean albedo change (OAC). Although not strictly a form of SRM, cirrus cloud thinning (CCT) has been proposed to cool the planet by increasing the escape of longwave thermal radiation to space and is included here for consistency with previous assessments (de Coninck et al., 2018). SAI is the most-researched proposal. Modelling studies show SRM could reduce surface temperatures and potentially ameliorate some climate change risks (with more confidence for SAI than other options), but SRM could also introduce a range of new risks.

There is *high agreement* in the literature that for addressing climate change risks SRM cannot be the main policy response to climate change and is, at best, a supplement to achieving sustained net zero or net negative CO_2 emission levels globally (de Coninck et al., 2018; MacMartin et al., 2018; Buck et al., 2020; National Academies of Sciences and Medicine, 2021b). SRM contrasts with climate change mitigation activities, such as emission reductions and carbon dioxide removal (CDR), as it introduces a 'mask' to the climate change problem by altering the Earth's radiation budget, rather than attempting to address the root cause of the problem, which is the increase in greenhouse gases (GHGs) in the atmosphere. In addition, the effects of proposed SRM options would only last as long as a deployment is maintained—for example, requiring ca. yearly injection of aerosols in the case of SAI as the lifetime of aerosols in the stratosphere is 1–3 years (Niemeier et al., 2011) or continuous spraying of sea salt in the case of MCB as the lifetime of sea salt aerosols in the atmosphere is only about 10 d—which contrasts with the long lifetime of CO_2 and its climate effects, with global warming resulting from CO_2 emissions *likely* remaining at a similar level for a hundred years or more (MacDougall et al., 2020) and long-term climate effects of emitted CO_2 remaining for several hundreds to thousands of years (Solomon et al., 2009).

Which scenarios?

The choice of SRM deployment scenarios and reference scenarios is crucial in assessment of SRM risks and its effectiveness in attenuating climate change risks (Keith and MacMartin, 2015; Honegger et al., 2021). Most climate model simulations have used scenarios with highly stylised large SRM forcing to fully counteract large amounts of warming in order to enhance the signal-to-noise ratio of climate responses to SRM (Kravitz et al., 2015; Sugiyama et al., 2018a; Tilmes et al., 2018; Krishna-Pillai et al., 2019).

The effects of SRM fundamentally depend on a variety of choices about deployment (Sugiyama et al., 2018b), including: its position in the portfolio of human responses to climate change (e.g., the magnitude of SRM used against the background radiative forcing), governance of research and potential deployment strategies, and technical details (latitude, materials, and season, among others, see WGI Section 4.6.3.3). The plausibility of many SRM scenarios is highly contested, and not all scenarios are equally plausible because of socio-political considerations (Talberg et al., 2018b), as with, for example, CDR (Fuss et al., 2014; Fuss et al., 2018). Development of scenarios and their selection in assessments should reflect a diverse set of societal values with public and stakeholder inputs (Sugiyama et al., 2018a; Low and Honegger, 2020), as depending on the focus of a limited climate model simulation, SRM could look grossly risky or highly beneficial (Pereira and al., 2021).

In the context of reaching the long-term global temperature goal of the Paris Agreement, there are different hypothetical scenarios of SRM deployment: early, substantial mitigation with no SRM, more limited or delayed mitigation with moderate SRM, unchecked emissions with total reliance on SRM, and regionally heterogeneous SRM. Each scenario presents different levels and distributions of SRM benefits, side effects and risks. The more intense the SRM deployment, the larger is the likelihood for the risks of side effects and environmental risks (e.g., Heutel et al., 2018). Regional disparities in climate hazards may result from both regionally deployed SRM options such as GBAM, and more globally uniform SRM such as SAI (Jones et al., 2018a; Seneviratne et al., 2018b). There is an emerging literature on smaller forcings of SAI to reduce global average warming, for instance, to hold global warming to 1.5°C or 2°C alongside ambitious conventional mitigation (Jones et al., 2018a; MacMartin et al., 2018), or bring down temperature after an overshoot (Tilmes

Cross-Working Group Box SRM (continued)

et al., 2020). If emissions reductions and CDR are deemed insufficient, SRM may be seen by some as the only option left to ensure the achievement of the Paris Agreement's temperature goal by 2100.

Table Cross-Working Group Box SRM.1 | SRM options and their potential climate and non-climate impacts. Description, potential climate impacts, potential impacts on human and natural systems, and termination effects of a number of SRM options: stratospheric aerosol interventions (SAI), marine cloud brightening (MCB), ocean albedo change (OAC), ground-based albedo modifications (GBAM) and cirrus cloud thinning (CCT).

SRM option	SAI	MCB	OAC	GBAM	CCT
Description	Injection of reflective aerosol particles directly into the stratosphere or a gas which then converts to aerosols that reflect sunlight	Spraying sea salt or other particles in marine clouds, making them more reflective	Increase surface albedo of the ocean (e.g., by creating microbubbles or placing reflective foam on the surface)	Whitening roofs, changes in land use management (e.g., no-till farming, bioengineering to make crop leaves more reflective), desert albedo enhancement, covering glaciers with reflective sheeting	Seeding to promote nucleation of cirrus clouds, reducing optical thickness and cloud lifetime to allow more outgoing longwave radiation to escape to space
Potential climate impacts *other than reduced warming*	Change precipitation and runoff pattern; reduced temperature and precipitation extremes; precipitation reduction in some monsoon regions; decrease in direct and increase in diffuse sunlight at surface; changes to stratospheric dynamics and chemistry; potential delay in ozone hole recovery; changes in surface ozone and UV radiation	Change in land-sea contrast in temperature and precipitation, regional precipitation and runoff changes	Change in land–sea contrast in temperature and precipitation, regional, precipitation and runoff changes	Changes in regional precipitation pattern, regional extremes and regional circulation	Changes in temperature and precipitation pattern, altered regional water cycle, increase in sunlight reaching the surface
Potential impacts on human and natural systems	Changes in crop yields, changes in land and ocean ecosystem productivity, acid rain (if using sulphate), reduced risk of heat stress to corals	Changes in regional ocean productivity, changes in crop yields, reduced heat stress for corals, changes in ecosystem productivity on land, sea salt deposition over land	Unresearched	Altered photosynthesis, carbon uptake and side effects on biodiversity	Altered photosynthesis and carbon uptake
Termination effects	Sudden and sustained termination would result in rapid warming, and abrupt changes to water cycle. Magnitude of termination depends on the degree of warming offset	Sudden and sustained termination would result in rapid warming, and abrupt changes to water cycle. Magnitude of termination depends on the degree of warming offset	Sudden and sustained termination would result in rapid warming. Magnitude of termination depends on the degree of warming offset	GBAM can be maintained over several years without major termination effects because of its regional scale of application. Magnitude of termination depends on the degree of warming offset	Sudden and sustained termination would result in rapid warming. Magnitude of termination depends on the degree of warming offset
References (also see main text of this box)	Tilmes et al. (2018); Simpson et al. (2019); Visioni et al. (2017)	Latham et al. (2012); Ahlm et al. (2017); Stjern et al. (2018)	Evans et al. (2010); Crook et al. (2015a)	Zhang et al. (2016); Field et al. (2018); Seneviratne et al. (2018a); Davin et al. (2014); Crook et al. (2015a)	Storelvmo and Herger (2014); Crook et al. (2015a); Jackson et al. (2016); Gasparini et al. (2020); Duan et al. (2020)

SRM risks to human and natural systems and potential for risk reduction

Since AR5, hundreds of climate modelling studies have simulated effects of SRM on climate hazards (Kravitz et al., 2015; Tilmes et al., 2018). Modelling studies have shown SRM has the potential to offset some effects of increasing GHGs on global and regional climate, including the increase in frequency and intensity of extremes of temperature and precipitation, melting of Arctic sea ice and mountain glaciers, weakening of Atlantic meridional overturning circulation, changes in frequency and intensity of tropical cyclones, and decrease in soil moisture (WGI, Chapter 4). However, while SRM may be effective in alleviating anthropogenic climate warming either locally or

Cross-Working Group Box SRM (continued)

globally, it would neither maintain the climate in its present-day state nor return the climate to a pre-industrial state (climate averaged over 1850–1900, see WGI Chapter 1, Box 1.2) in all regions and in all seasons even when used to fully offset the global mean warming (*high confidence*) (WGI Chapter 4). This is because the climate forcing and response to SRM options are different from the forcing and response to GHG increase. Because of these differences in climate forcing and response patterns, the regional and seasonal climates of a world with a global mean warming of 1.5°C or 2°C achieved via SRM would be different from a world with similar global mean warming but achieved through mitigation (MacMartin et al.., 2019). At the regional scale and seasonal time scale, there could be considerable residual climate change and/or overcompensating change (e.g., more cooling, wetting or drying than just what is needed to offset warming, drying or wetting due to anthropogenic greenhouse gas emissions), and there is *low confidence* in understanding of the climate response to SRM at the regional scale (WGI, Chapter 4).

SAI implemented to partially offset warming (e.g., offsetting half of global warming) may have potential to ameliorate hazards in multiple regions and reduce negative residual change, such as drying compared with present-day climate, that is associated with fully offsetting global mean warming (Irvine and Keith, 2020), but may also increase flood and drought risk in Europe compared with unmitigated warming (Jones et al., 2021). Recent modelling studies suggest it is conceptually possible to meet multiple climate objectives through optimally designed SRM strategies (WGI, Chapter 4). Nevertheless, large uncertainties still exist for climate processes associated with SRM options (e.g., aerosol–cloud–radiation interaction) (WGI, Chapter 4) (Kravitz and MacMartin, 2020).

Compared with climate hazards, many fewer studies have examined SRM risks—the potential adverse consequences to people and ecosystems from the combination of climate hazards, exposure and vulnerability—or the potential for SRM to reduce risk (Curry et al., 2014; Irvine et al., 2017). Risk analyses have often used inputs from climate models forced with stylised representations of SRM, such as dimming the sun. Fewer have used inputs from climate models that explicitly simulated injection of gases or aerosols into the atmosphere, which include more complex cloud radiative feedbacks. Most studies have used scenarios where SAI is deployed to hold average global temperature constant despite high emissions.

There is *low confidence* and large uncertainty in projected impacts of SRM on crop yields due in part to a limited number of studies. Because SRM would result in only a slight reduction in CO_2 concentrations relative to the emission scenario without SRM (Chapter 5, WGI), the CO_2 fertilisation effect on plant productivity is nearly the same in emissions scenarios with and without SRM. Nevertheless, changes in climate due to SRM are likely to have some impacts on crop yields. A single study indicates MCB may reduce crop failure rates compared with climate change from a doubling of CO_2 pre-industrial concentrations (Parkes et al., 2015). Models suggest SAI cooling would reduce crop productivity at higher latitudes compared with a scenario without SRM by reducing the growing season length, but benefit crop productivity in lower latitudes by reducing heat stress (Pongratz et al., 2012; Xia et al., 2014; Zhan et al., 2019). Crop productivity is also projected to be reduced where SAI reduces rainfall relative to the scenario without SRM, including a case where reduced Asian summer monsoon rainfall causes a reduction in groundnut yields (Xia et al., 2014; Yang et al., 2016). SAI will increase the fraction of diffuse sunlight, which is projected to increase photosynthesis in forested canopy, but will reduce the direct and total available sunlight, which tends to reduce photosynthesis. As total sunlight is reduced, there is a net reduction in crop photosynthesis with the result that any benefits to crops from avoided heat stress may be offset by reduced photosynthesis, as indicated by a single statistical modelling study (Proctor et al., 2018). SAI would reduce average surface ozone concentration (Xia et al., 2017) mainly as a result of aerosol-induced reduction in stratospheric ozone in polar regions, resulting in reduced downward transport of ozone to the troposphere (Pitari et al., 2014; Tilmes et al., 2018). The reduction in stratospheric ozone also allows more UV radiation to reach the surface. The reduction in surface ozone, together with an increase in surface UV radiation, would have important implications for crop yields but there is *low confidence* in our understanding of the net impact.

Few studies have assessed potential SRM impacts on human health and well-being. SAI using sulphate aerosols is projected to deplete the ozone layer, increasing mortality from skin cancer, and SAI could increase particulate matter due to offsetting warming, reduced precipitation and deposition of SAI aerosols, which would increase mortality, but SAI also reduces surface-level ozone exposure, which would reduce mortality from air pollution, with net changes in mortality uncertain and depending on aerosol type and deployment scenario (Effiong and Neitzel, 2016; Eastham et al., 2018; Dai et al., 2020). However, these effects may be small compared with changes in risk from infectious disease (e.g., mosquito-borne illnesses) or food security due to SRM influences on climate (Carlson et al., 2020). Using volcanic eruptions as a natural analogue, a sudden implementation of SAI that forced the El Niño-Southern Oscillation (ENSO) system may increase risk of severe cholera outbreaks in Bengal (Trisos et al., 2018; Pinke et al., 2019). Considering only mean annual temperature and precipitation, SAI that stabilises global temperature at its present-day level is projected to reduce income inequality between countries compared with the highest warming pathway (RCP8.5) (Harding et al., 2020). Some integrated assessment model scenarios have included SAI (Arino et al., 2016; Emmerling and Tavoni, 2018; Heutel et al., 2018; Helwegen et al., 2019; Rickels et al.,

Cross-Working Group Box SRM (continued)

2020) showing the indirect costs and benefits to welfare dominate, since the direct economic cost of SAI itself is expected to be relatively low (Moriyama et al., 2017; Smith and Wagner, 2018). There is a general lack of research on the wide scope of potential risk or risk reduction to human health, well-being and sustainable development from SRM and on their distribution across countries and vulnerable groups (Carlson et al., 2020; Honegger et al., 2021).

SRM may also introduce novel risks for international collaboration and peace. Conflicting temperature preferences between countries may lead to counter-geoengineering measures such as deliberate release of warming agents or destruction of deployment equipment (Parker et al., 2018). Game-theoretic models and laboratory experiments indicate that a powerful actor or group with a higher preference for SRM may use SAI to cool the planet beyond what is socially optimal, imposing welfare losses on others, although this cooling does not necessarily imply that excluded countries would be worse off relative to a world of unmitigated warming (Ricke et al., 2013; Weitzman, 2015; Abatayo et al., 2020). In this context, counter-geoengineering may promote international cooperation or lead to large welfare losses (Heyen et al., 2019; Abatayo et al., 2020).

Cooling caused by SRM would increase the global land and ocean CO_2 sinks (*medium confidence*), but this would not stop CO_2 from increasing in the atmosphere or affect the resulting ocean acidification under continued anthropogenic emissions (*high confidence*) (WGI Chapter 5).

Few studies have assessed potential SRM impacts on ecosystems. SAI and MCB may reduce risk of coral reef bleaching compared with global warming with no SAI (Latham et al., 2013; Kwiatkowski et al., 2015), but risks to marine life from ocean acidification would remain, because SRM proposals do not reduce elevated levels of anthropogenic atmospheric CO_2 concentrations. MCB could cause changes in marine net primary productivity by reducing light availability in deployment regions, with important fishing regions off the west coast of South America showing both large increases and decreases in productivity (Partanen et al., 2016; Keller, 2018).

There is large uncertainty in terrestrial ecosystem responses to SRM. By decoupling increases in atmospheric greenhouse gas concentrations and temperature, SAI could generate substantial impacts on large-scale biogeochemical cycles, with feedbacks to regional and global climate variability and change (Zarnetske et al., 2021). Compared with a high-CO_2 world without SRM, global-scale SRM simulations indicate reducing heat stress in low latitudes would increase plant productivity, but cooling would also slow down the process of nitrogen mineralisation, which could decrease plant productivity (Glienke et al., 2015; Duan et al., 2020). In high-latitude and polar regions, SRM may limit vegetation growth compared with a high-CO_2 world without SRM, but net primary productivity may still be higher than pre-industrial climate (Glienke et al., 2015). Tropical forests cycle more carbon and water than other terrestrial biomes, but large areas of the tropics may tip between savanna and tropical forest depending on rainfall and fire (Beer et al., 2010; Staver et al., 2011). Thus, SAI-induced reductions in precipitation in Amazonia and central Africa are expected to change the biogeography of tropical ecosystems in ways different from both present-day climate and global warming without SAI (Simpson et al., 2019; Zarnetske et al., 2021). This would have potentially large consequences for ecosystem services (Chapter 2 and Chapter 9). When designing and evaluating SAI scenarios, biome-specific responses need to be considered if SAI approaches are to benefit rather than harm ecosystems. Regional precipitation change and sea salt deposition over land from MCB may increase or decrease primary productivity in tropical rainforests (Muri et al., 2015). SRM that fully offsets warming could reduce the dispersal velocity required for species to track shifting temperature niches, whereas partially offsetting warming with SAI would not reduce this risk unless rates of warming were also reduced (Trisos et al., 2018; Dagon and Schrag, 2019). SAI may reduce high-fire-risk weather in Australia, Europe and parts of the Americas, compared with global warming without SAI (Burton et al., 2018). Yet SAI using sulphur injection could shift the spatial distribution of acid-induced aluminium soil toxicity into relatively undisturbed ecosystems in Europe and North America (Visioni et al., 2020). For the same amount of global mean cooling, SAI, MCB and CCT would have different effects on gross and net primary productivity because of different spatial patterns of temperature, available sunlight, and hydrological cycle changes (Duan et al., 2020). Large-scale modification of land surfaces for GBAM may have strong trade-offs with biodiversity and other ecosystem services, including food security (Seneviratne et al., 2018a). Although existing studies indicate SRM will have widespread impacts on ecosystems, risks and potential for risk reduction for marine and terrestrial ecosystems and biodiversity remain largely unknown.

A sudden and sustained termination of SRM in a high CO_2 emissions scenario would cause rapid climate change (*high confidence*; WGI Chapter 4). More scenario analysis is needed on the potential likelihood of sudden termination (Kosugi, 2013; Irvine and Keith, 2020). A gradual phase-out of SRM combined with emission reduction and CDR could avoid these termination effects (*medium confidence*) (MacMartin et al., 2014; Keith and MacMartin, 2015; Tilmes et al., 2016). Several studies find that large and extremely rapid warming and abrupt changes to the water cycle would occur within a decade if a sudden termination of SAI occurred (McCusker et al., 2014; Crook et al., 2015b). The size of this 'termination shock' is proportional to the amount of radiative forcing being masked by SAI. A sudden

Cross-Working Group Box SRM (continued)

termination of SAI could place many thousands of species at risk of extinction, because the resulting rapid warming would be too fast for species to track the changing climate (Trisos et al., 2018).

Public perceptions of SRM

Studies on the public perception of SRM have used multiple methods: questionnaire surveys, workshops, and focus group interviews (Burns et al., 2016; Cummings et al., 2017). Most studies have been limited to Western societies, with some exceptions. Studies have repeatedly found that respondents are largely unaware of SRM (Merk et al., 2015). In the context of this general lack of familiarity, the public prefers CDR to SRM (Pidgeon et al., 2012), is very cautious about SRM deployment because of potential environmental side effects and governance concerns, and mostly rejects deployment for the foreseeable future. Studies also suggest conditional and reluctant support for research, including proposed field experiments, with conditions of proper governance (Sugiyama et al., 2020). Recent studies show that the perception varies with the intensity of deliberation (Merk et al., 2019), and that the public distinguishes different funding sources (Nelson et al., 2021). Limited studies for developing countries show a tendency for respondents to be more open to SRM (Visschers et al., 2017; Sugiyama et al., 2020), perhaps because they experience climate change more directly (Carr and Yung, 2018). In some Anglophone countries, a small portion of the public believes in chemtrail conspiracy theories, which are easily found in social media (Tingley and Wagner, 2017; Allgaier, 2019). Since researchers rarely distinguish different SRM options in engagement studies, there remains uncertainty in public perception.

Ethics

There is broad literature on ethical considerations around SRM, mainly stemming from philosophy or political theory, and mainly focused on SAI (Flegal et al., 2019). There is concern that publicly debating, researching and potentially deploying SAI could involve a 'moral hazard', with potential to obstruct ongoing and future mitigation efforts (Morrow, 2014; Baatz, 2016; McLaren, 2016), while empirical evidence is limited and mostly at the individual, not societal, level (Burns et al., 2016; Merk et al., 2016; Merk et al., 2019). There is *low agreement* whether research and outdoors experimentation will create a 'slippery slope' towards eventual deployment, leading to a lock-in to long-term SRM, or can be effectively regulated at a later stage to avoid undesirable outcomes (Hulme, 2014; Parker, 2014; Callies, 2019; McKinnon, 2019). Regarding potential deployment of SRM, procedural, distributive and recognitional conceptions of justice are being explored (Svoboda and Irvine, 2014; Svoboda, 2017; Preston and Carr, 2018; Hourdequin, 2019). With the SRM research community's increasing focus on distributional impacts of SAI, researchers have started more explicitly considering inequality in participation and inclusion of vulnerable countries and marginalised social groups (Flegal and Gupta, 2018; Whyte, 2018; Táíwò and Talati, 2021), including considering stopping research (Stephens and Surprise, 2020; National Academies of Sciences and Medicine, 2021a). There is recognition that SRM research has been conducted predominantly by a relatively small number of experts in the Global North, and that more can be done to enable participation from diverse peoples and geographies in setting research agendas and research governance priorities, and undertaking research, with initial efforts to this effect (e.g., Rahman et al., 2018), noting unequal power relations in participation could influence SRM research governance and potential implications for policy (Whyte, 2018; Táíwò and Talati, 2021; Winickoff et al., 2015; Frumhoff and Stephens, 2018; Biermann and Möller, 2019; McLaren and Corry, 2021; National Academies of Sciences and Medicine, 2021b)

Governance of research and of deployment

Currently, there is no dedicated, formal international SRM governance for research, development, demonstration or deployment (see WGIII Chapter 14). Some multilateral agreements—such as the UN Convention on Biological Diversity or the Vienna Convention on the Protection of the Ozone Layer—indirectly and partially cover SRM, but none is comprehensive, and the lack of robust and formal SRM governance poses risks (Ricke et al., 2013; Talberg et al., 2018a; Reynolds, 2019a). While governance objectives range broadly, from prohibition to enabling research and potentially deployment (Sugiyama et al., 2018b; Gupta et al., 2020), there is agreement that SRM governance should cover all interacting stages of research through to any potential, eventual deployment with rules, institutions and norms (Reynolds, 2019b). Accordingly, governance arrangements are co-evolving with respective SRM technologies across the interacting stages of research, development, demonstration and—potentially—deployment (Rayner et al., 2013; Parker, 2014; Parson, 2014). Stakeholders are developing governance already in outdoors research, for example for MCB and OAC experiments on the Great Barrier Reef (McDonald et al., 2019). Co-evolution of governance and SRM research provides a chance for responsibly developing SRM technologies with broader public participation and political legitimacy, guarding against potential risks and harms relevant across a full range of scenarios, and ensuring that SRM is considered only as a part of a broader portfolio of responses to climate change (Stilgoe, 2015; Nicholson et al., 2018). For SAI, large-scale outdoor experiments even with low radiative forcing could be transboundary, and those with deployment-scale radiative forcing may not be distinguished from deployment, such that MacMartin and Kravitz (2019) argue for continued reliance on modelling until a decision on whether and how to deploy is made, with modelling helping governance development. For further discussion of SRM governance, see Chapter 14, WGIII.

Cross-Working Group Box ECONOMIC | Estimating Global Economic Impacts from Climate Change

Authors: Steven Rose (USA), Delavane Diaz (USA), Tamma Carleton (USA), Laurent Drouet (Italy), Celine Guivarch (France), Aurélie Méjean (France), Franziska Piontek (Germany)

This Cross-Working Group Box assesses literature estimating the potential global aggregate economic costs of climate change and the social cost of carbon (SCC), where the former are sometimes referred to as estimates of global 'climate damages' and the latter are estimates of the potential monetised impacts to society of an additional metric ton of carbon dioxide emitted to the atmosphere. These measures include the economic costs of climate change that could be felt in market sectors such as agriculture, energy services, labour productivity and coastal resources, as well as non-market impacts such as other types of human health risks (including mortality effects) and ecosystems. Global economic impacts estimates can inform decisions about global climate management strategy, while SCC estimates can inform globally incremental emissions decisions. In practice, economic damage estimates have been used to explore economically efficient ('economically optimal') global emissions pathways (e.g., Nordhaus and Moffat, 2017), while SCCs have been used to inform federal and state-level policy assessment in some countries (Greenstone et al., 2013; Rose and Bistline, 2016), but the type of SCC and application matters (Rose, 2017). This literature has been assessed in previous WGII reports (e.g., Arent et al., 2014), and this box serves this need for this report. The assessment in this box was performed jointly across WGII and WGIII, building on the foundation of WGII AR6 Chapter 16's 'Risk to living standards' assessment (Section 16.5.2.3.4), which includes consideration of severe risks to global aggregate economic output, and WGIII AR6 Chapter 3's assessment of the benefits of mitigation. It also informs Chapter 16's global aggregate impacts Reasons for Concern and supports Chapter 18's assessment of global emissions transitions, risk management and climate resilient development. In keeping with the broad risk framing presented in Chapter 1 of this report, other lines of evidence regarding climate risks, beyond monetary estimates, should be considered in decision making, including key risks and Reasons for Concern.

Methods for estimating global economic costs of climate impacts

There are several broad approaches to estimating climate damages, including biophysical process models, structural economic models, statistical methods (also called empirical or econometric) and hybrid approaches, with each methodology having strengths and weaknesses. Process models simulate physical, natural science and/or engineering processes and their response to climate variables, which are then monetised (e.g., Anthoff and Tol, 2014; Sieg et al., 2019; Narita et al., 2020). Process approaches have the advantage of being explicit and interpretable, though they can be computationally intensive; may omit relevant impact channels, interactions and market dynamics affecting valuation; and often lack a rigorous empirical basis for calibration (Fisher-Vanden et al.). Structural economic modelling represents climate impacts on inputs, production, household consumption, aggregate investment, and markets for economic sectors and regional economies (e.g., Reilly et al., 2007; Roson and Van der Mensbrugghe, 2012; Anthoff and Tol, 2014; Dellink et al., 2019; Takakura et al., 2019), often using computable general equilibrium (CGE) frameworks. Structural models can evaluate how market and non-market impacts might enter and transmit through economies, and adaptation responses within input and output markets, consumer and investment choices, and inter-regional trade (e.g., Darwin and Tol, 2001; Dellink et al., 2019; Takakura et al., 2019). Statistical methods estimate economic impacts in a given sector (e.g., Auffhammer, 2018) or in aggregate (e.g., Dell et al., 2014; Burke et al., 2015; Hsiang et al., 2017; Pretis et al., 2018; Kahn et al., 2019), inferred from observed changes in economic factors, weather and climate, with responses and net results constrained by available data. Since AR5, hybrid approaches have taken different forms to integrate process, statistical and/or structural methods, and represent a potentially promising means of leveraging the strengths of different approaches (e.g., Moore and Diaz, 2015; and Hsiang et al., 2017; Moore et al., 2017a; Ricke et al., 2018; Yumashev et al., 2019; Chen et al., 2020b). There is also a small literature that uses expert elicitation to gather subjective assessments of climate risks and potential economic impacts (Nordhaus, 1994; IPCC, 2019a; Pindyck, 2019).

In addition to differences in methods, there are also differences in scope—geographic, sectoral and temporal. Global estimates are frequently based on an aggregation of independent sector and/or regional modelling and estimates; however, there are examples of estimates from global modelling that simulate multiple types of climate impacts and their potential interactions within a single, coherent framework (e.g., Roson and Van der Mensbrugghe, 2012; Dellink et al., 2019; Takakura et al., 2019). Differences in scope also represent strengths and weaknesses between the methodologies, with narrower scope allowing for more detailed assessment, but missing potential interactions with the scope not covered (e.g., other geographic areas, sectors, markets or periods of time).

Comprehensive economic estimates are challenging to produce for many reasons, including complex interactions among physical, natural and social systems; pervasive climate, socioeconomic and system response uncertainties; and the heterogeneous nature of climate impacts that vary across space and time. Critiques and commentaries of global estimation methods (Pindyck, 2013; Stern, 2013; van den Bergh and Botzen, 2015; Cropper et al., 2017; Diaz and Moore, 2017; Pindyck, 2017; Rose et al., 2017; Stoerk et al., 2018; DeFries et al., 2019; Pezzey, 2019; Calel et al., 2020; Warner et al., 2020; EPRI, 2021; Grubb et al., 2021; Newell et al., 2021) include, among other things, concerns about statistical methods estimating weather but not climate relationships, making out-of-sample extrapolations,

Cross-Working Group Box ECONOMIC (continued)

and model specification uncertainty, concerns about the observational grounding of structural modelling, and overall concerns about the lack of adaptation consideration, as well as representation and evaluation of potential large-scale singular events such as ice sheet destabilisation or biodiversity destruction, some questioning the ability to generate robust estimates (i.e., estimates insensitive to reasonable alternative inputs and specifications), and general concerns about methodological details, transparency and justification.

Additional methodological challenges to address (see, for instance, EPRI, 2021; Piontek et al., 2021) include how to capture and represent uncertainty and variability in potential damage responses for a given climate and societal condition, combine estimates from different methods and sources (including aggregating independent sectoral and regional results), assess sensitivity and evaluate robustness of estimates (including sensitivity to model specification), capture interactions and spillovers between regions and sectors, estimate societal welfare implications (versus gross domestic product [GDP] changes) of market and non-market impacts, consider distributional effects, represent micro- and macro-adaptation processes (and adaptation costs), specify non-gradual damages and nonlinearities, and improve understanding of potential long-run economic growth effects. Note that the treatment of time preference, risk aversion and equity considerations have important welfare implications for the aggregation of both potential economic impacts and climate change mitigation costs.

In addition to updated and new methods and estimates, newer literature has explored non-gradual damages, such as climatic and socioeconomic tipping points (Lontzek et al., 2015; Méjean et al., 2020), potential damage to economic growth (e.g., Burke et al., 2015; Moore and Diaz, 2015), valuing uncertainty in potential damages (Jensen and Traeger, 2014; Lemoine and Traeger, 2016; Cai and Lontzek) and representing adaptation (Takakura et al., 2019; Carleton et al., 2020; Rode et al., 2021). Going forward, to help advance science and decisions, a key research priority is to understand and evaluate methodological strengths and weaknesses in damage estimation, and reconcile the differences affecting comparability in such a way that it informs use of the different lines of evidence. This will require greater transparency and assessment of details and assumptions in individual methods, communication and evaluation of alternatives for specifying or calibrating climate damage functional representations with respect to climate and non-climate drivers and potential nonlinearities, including evaluating data sufficiency for levels within and beyond observations and for characterising physical system dynamics, and evaluating the sensitivity of results to model specification and input parameter choices (Cropper et al., 2017). Improving the robustness of economic impact estimates is an active area of research. Below we describe the latest estimates.

Global estimates of the economic costs of climate impacts

Since AR5, many new estimates of the global economic costs of climate change have been produced. Figure Cross-Working Group Box ECONOMIC.1 shows a wide spread of estimates, with growing variance at higher levels of warming, both within and across methodology types (i.e., statistical, structural or meta-analysis). Meta-analysis is used here to refer to studies that treat other studies' estimates as data points in an attempt to derive a synthesised functional form.

Global aggregate economic impact estimates (Figure Cross-Working Group Box ECONOMIC.1) are generally found to increase with global average temperature change, as well as vary by other drivers, such as income and population and the composition of the economy. Most estimates are nonlinear with higher marginal economic impacts at higher temperature, although some recover declining marginal economic impacts, and functional forms cannot be determined for all studies. The drivers of nonlinearity found in economic impact estimates, and the differences in nonlinearity across estimates (e.g., convex versus concave, degree of curvature), are not well understood, with methodology construction, assumptions and data all being potential factors. Relative to AR5, there have been more estimates and greater variation in estimates, including some recent estimates significantly higher than the range reported in AR5. For most of the studies shown in Figure Cross-Working Group Box ECONOMIC.1, the visible variation within a study represents alternative socioeconomic projections and climate modelling, not economic impacts response uncertainty for a given socioeconomic and climate condition. Response uncertainty could be significant, as indicated by some of the results shown in the figure (e.g., Burke et al., 2015; Rose et al., 2017), but methodological differences in how uncertainty is characterised (model specification, errors and confidence intervals versus distributions of results) limit comparability and assessment. Note that modelling factors between global temperature change and the economic impact calculation, such as regional temperature pattern assumptions or assumed SLR dynamics, can also impact calculated estimates (e.g., Warren et al.., 2021 PAGE09 estimates versus those in Rose et al.., 2017, Chen et al.., 2020 PAGE-ICE estimates versus Burke et al.., 2015).

From Figure Cross-Working Group Box ECONOMIC.1, we find a large span of damage estimates, even without considering uncertainty/confidence in damage responses, including for today's level of warming (about 1°C). There is also evidence that some regions benefit from low levels of warming, leading to net benefits globally at these temperatures. The size of the span of estimates grows with global warming level, with variation across statistical estimates larger than variation in structural estimates. The structural and meta-analyses estimates appear to be in closer agreement, but that outcome is contingent on the meta-analyses' data considerations and approach. Meta analyses to date have not assessed the alternative methods and dealt with the lack of comparability between methods.

Cross-Working Group Box ECONOMIC (continued)

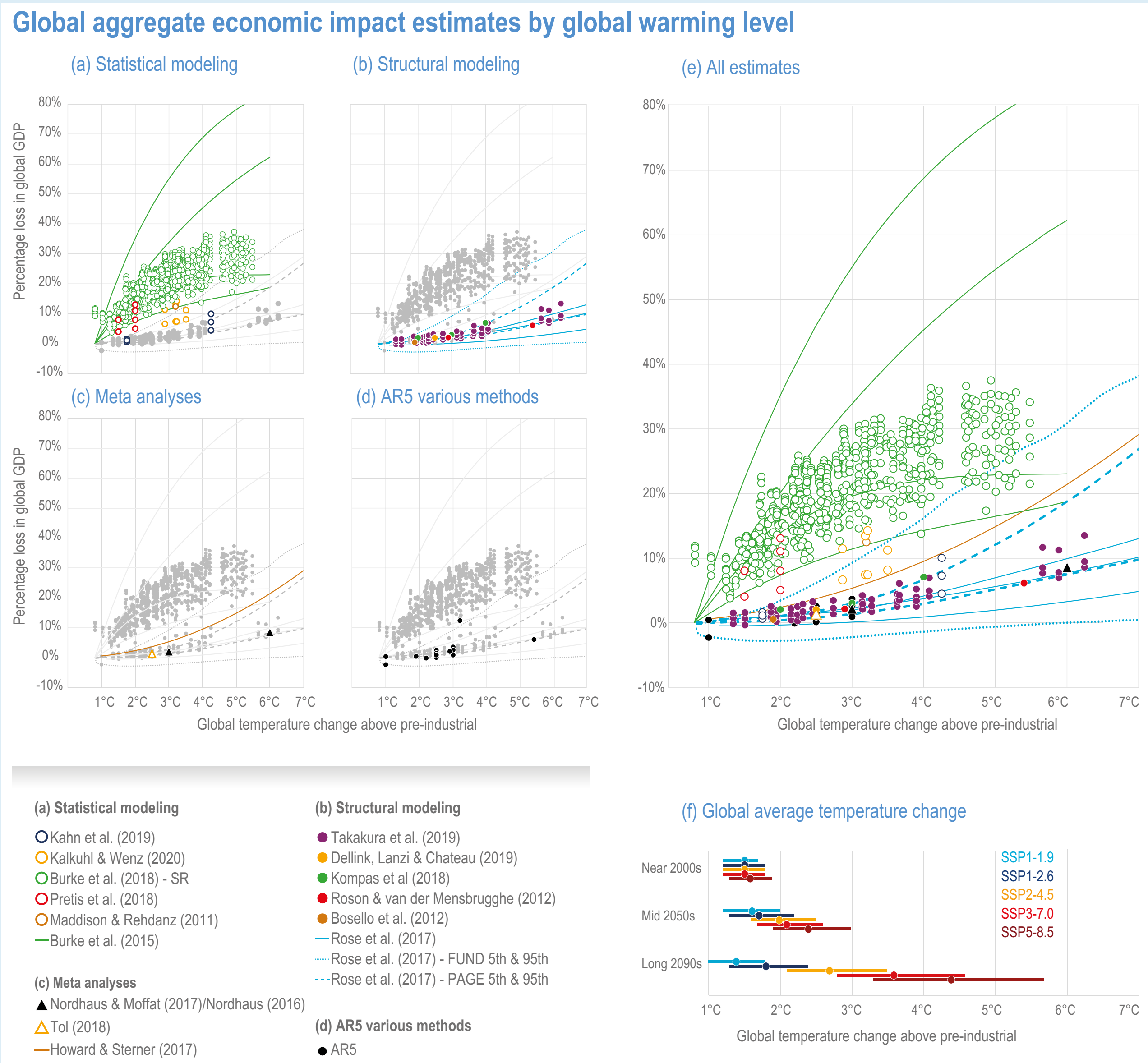


Figure Cross-Working Group Box ECONOMIC.1 | Global aggregate economic impact estimates by global warming level (annual % global GDP loss relative to GDP without additional climate change). Top row panels present estimates by methodology type: (a) statistical modelling, (b) structural modelling and (c) meta-analyses, with all estimates from a paper in the same colour and estimates from methodologies other than that highlighted by the panel in grey for reference. Second row left panel (d) presents AR5 estimates. Second row right panel (e) presents all estimates in one figure, with the same colours as panels (a–d) using outlined dots for the statistical modelling estimates, solid dots for structural modelling estimates, and triangles for meta-analysis estimates. In all panels, lines represent functions, with dashed and dotted lines 5th and 95th percentile functions from structural modelling. To avoid duplication, estimates from papers using the economic impacts estimates or model formulations already represented in the figure are not included (e.g., Diaz and Moore, 2017; Chen et al., 2020b; Glanemann et al., 2020; Warren et al., 2021). The exception is Burke et al. (2018), with the different estimates shown representing variation across climate scenarios for a given aggregate economic impacts specification from Burke et al. (2015)—the 'pooled, short run' statistical specification. Results shown for the latter are estimates with the author's different statistical model specifications (and a fixed climate scenario, SSP5). From top to bottom, the Burke et al. (2015) estimates are for the 'pooled, long run', 'differentiated, long run', 'pooled, short run' (authors' base case) and 'differentiated, short run' statistical specifications. For Howard and Sterner (2017), the authors' preferred function is shown. Overall, estimates shown in the figure can correspond to different future years, reflecting different socioeconomic conditions and climate pathways to a global warming level. Global average temperature change bars relative to the period 1850–1900 are shown below the economic cost estimates to provide context to potential future warming. Shown are the WGI AR6 assessed best estimates and 90% intervals for the illustrative emissions scenarios considered for the near term 2021–2040, mid-term 2041–2060 and long term 2081–2100.

Cross-Working Group Box ECONOMIC (continued)

Differences in methodology type and scope complicate comparison, assessment and synthesis (Cropper et al., 2017; Diaz and Moore, 2017; EPRI, 2021; Piontek et al., 2021). In particular, structural economic modelling and empirical aggregate output modelling are fundamentally different, which has been identified as an issue affecting the comparability of results (Cropper et al., 2017). The different methodologies affect outcomes, with global aggregate estimates based on statistical methodologies typically higher than those from structural modelling (Figure Cross-Working Group Box ECONOMIC.1). This is, in part, due to the relationships in observational data captured by statistical modelling, assumed persistence of impacts in statistical modelling, broader adaptation responses in structural modelling, and differences in the representation of future societies and how they might evolve, respond and interact. Within statistical modelling, results are also found to be very sensitive to the statistical model specification (e.g., Burke et al., 2015; Newell et al., 2021). Within structural modelling, differences in representations of biophysical changes and economic structural dynamics contribute to differences across structural estimates (e.g., Rose et al., 2017).

The wide range of estimates, and the lack of comparability between methodologies, does not allow for identification of a robust range of estimates with confidence (*high confidence*). Evaluating and reconciling differences in methodologies is a research priority for facilitating use of the different lines of evidence (*high confidence*). However, the existence of higher estimates than AR5 indicate that global aggregate economic impacts could be higher than previously estimated (*low confidence* due to the lack of comparability across methodologies and robustness of estimates).

While Figure Cross-Working Group Box ECONOMIC.1 summarises global aggregate estimates, the literature exhibits significant heterogeneity in regional economic impacts that are also sensitive to methodology, model specification and societal assumptions (with, for instance, larger estimates due to the assumed size of society, but offsetting adaptive capacity improvements and adaptation responses). Regional results illustrate the potential for overall net benefits in more temperate regions at lower levels of warming with potential lower energy demand and comparative advantages in agricultural markets; however, at higher levels of warming, net losses are estimated. In addition, economic impacts for poorer households and poorer countries represent a smaller share in aggregate quantifications expressed in GDP terms than their influence on well-being or welfare (Byers et al., 2018; Hallegatte et al., 2020).

Social cost of carbon methods and estimates

The global economic impact estimates discussed in the previous section serve as a key input into the calculation of the value of potential net damages caused by a marginal ton of carbon dioxide emissions, or the SCC. To compute an SCC, damage estimates are commonly combined in a multi-century modelling framework with socioeconomic and emissions projections, a physical model of the climate, including a SLR component, and assumptions about the discount rate, with current frameworks having highly stylised representations of these components. Though we do not present quantitative estimates here, due to the challenge of comparability, for economic impacts methodologies (as discussed above) as well as other SCC estimation elements, large variations in SCC estimates are found in the literature assessed due to, among other things, differences in modelling component representations, input and parameter assumptions, considerations of uncertainty, and discounting, inflation, and emissions year (e.g., Tol, 2009; Tol, 2018; Pezzey, 2019; Iese et al., 2021). There are also different 'variants' of SCC estimates that differ conceptually, and in magnitude, depending on the reference condition for evaluating the impact of a marginal metric ton—is it being evaluated relative to a no-climate-policy baseline, an economically efficient pathway that weighs the benefits and costs of emissions mitigation, or a pathway based on a particular climate policy or goal such as 2°C or a concentration target (Rose et al., 2017)? The variant of SCC has implications for its applicability to different policy contexts (Rose and Bistline, 2016).

In addition to the economic impacts methodological challenges discussed above with respect to aggregate economic impact estimates, the additional components needed for SCC calculations give rise to a new set of technical issues and critiques, including incorporation of uncertainties in the components beyond climate damages, links between components, and discounting (van den Bergh and Botzen, 2015; Cropper et al., 2017; Diaz and Moore, 2017; Pindyck, 2017; Rose et al., 2017; EPRI, 2021). For component-specific discussions and assessment, see Cropper et al. (2017), Rose et al. (2017) and EPRI (2021).

Substantial progress has been made in recent years to better reflect complexities in the global economy, the climate system, and their interaction. For example, recent studies have explored damages to natural capital (Bastien-Olvera and Moore, 2021), the influence of imperfect substitutability between environmental services and market goods (Sterner and Persson, 2008; Weitzman, 2012; Drupp and Hänsel, 2021), the implications of heterogeneous climate change impacts across income groups (Dennig et al., 2015; EPRI, 2021; Errickson et al., 2021), the potential for persistent climate impacts to economic growth instead of effects on levels of economic output (Dietz and Stern, 2015; Moore and Diaz, 2015; Ricke et al., 2018; Kikstra et al., 2021; Newell et al., 2021), valuing the risks of climate tipping points (Cai and Lontzek, 2019; Rising et al., 2020), valuing uncertainty under risk aversion (Jensen and Traeger, 2014; Lemoine and Traeger,

Cross-Working Group Box ECONOMIC (continued)

2016), and modelling a distinction between intertemporal inequality aversion and risk aversion in the social welfare utility function (Crost and Traeger, 2013; Jensen and Traeger, 2014; Daniel et al., 2015). These new studies have, in general, raised estimates of the SCC (Crost and Traeger, 2013; Jensen and Traeger, 2014; Gerlagh and Michielsen, 2015; Moore and Diaz, 2015; Faulwasser et al., 2018; Guivarch and Pottier, 2018; Budolfson et al., 2019; Cai and Lontzek, 2019; Dietz and Venmans, 2019; Kalkuhl and Wenz, 2020), in some cases by an order of magnitude (Ricke et al., 2018). However, challenges persist in terms of moving from conceptual to practical application, such as pinning down parameter specifications, modelling specific mechanisms for impacts, and more fully representing adaptation.

Despite these scientific advances, SCC estimates vary widely in the literature. Technical issues with past and current modelling (e.g., Pezzey, 2019; Pindyck, 2019; EPRI, 2021) and the challenge of comparability across methodologies imply that many estimates are not robust (*high confidence*). Also, as a result, the issue of directional bias of past estimates remains unsettled. Better representation of uncertainty in methods can improve robustness, while detailed methodology assessment and comparison will help define the relative biases of methods (*high confidence*).

Application to decision making

The literature has also assessed the application of aggregate economic impact cost and SCC estimates (Rose and Bistline, 2016; Rose et al., 2017; Kaufman et al., 2020) and identified conceptual and technical issues that need to be considered when using results to inform policy decisions. These issues include: accounting for endogenous marginal benefits and socioeconomic conditions in evaluating policies with non-incremental global emissions implications; consistency in assumptions and treatment of uncertainty across benefit and cost calculations; fully accounting for the streams of both mitigation costs and benefits over time; avoiding inefficiently valuing or pricing emissions more than once across policies and jurisdictions; and accounting for emissions leakage to capture net climate implications. Furthermore, concerns about the robustness of estimates have led some to recommend considering alternatives, such as using marginal mitigation cost estimates based on modelling of policy goals instead of the SCC (e.g., Rose, 2012; Pezzey, 2019; Kaufman et al., 2020), although this comes with its own set of assumptions and technical challenges.

Cross-Chapter Box LOSS | Loss and Damage

Authors: Reinhard Mechler (Austria/Germany), Adelle Thomas (Bahamas), Christian Huggel (Switzerland), Emily Boyd (Sweden), Veruska Muccione (Italy), Ivo Wallimann-Helmer (Switzerland), Laurens Bouwer (the Netherlands), Sirkku Juhola (Finland), Chandni Singh (India), Carolina Adler (Switzerland/Chile/Australia), Kris Ebi (USA), Patricia Pinho (Brazil), Rawshan Ara Begum (Malaysia/Australia/Bangladesh), Adugna Gemeda (Ethiopia), Johanna Nalau (Australia/Finland), Katja Frieler (Germany), Richard Jones (UK), Riyanti Djalante (Japan), Rosa Perez (Philippines), Tabea Lissner (Germany), Anita Wreford (New Zealand), Mark Pelling (UK), Francois Gemenne (Belgium), Nick Simpson (Zimbabwe/South Africa), Doreen Stabinsky (USA)

An intensifying dialogue

This Cross-Chapter Box offers an assessment of the growing literature on Loss and Damage. Capitalised letter 'Loss and Damage' (L&D) has been used to refer to negotiations under the UNFCCC. Research has used lowercase 'losses and damages' for residual effects from (observed) impacts and (projected) risks (see Glossary, Annex II).

Dialogue around L&D issues started with a proposal for insurance and compensation by the Alliance of Small Island States (AOSIS) (INC, 1991) and has intensified over recent years with suggestions made to consider complements to adaptation in order to manage residual impacts and risks 'beyond adaptation' in vulnerable developing countries (Section 1.4.5). L&D was formally recognised in 2013 at the 19th meeting of the Conference of the Parties (COP19) through the *Warsaw International Mechanism on Loss and Damage* (UNFCCC, 2013), governed by an Executive Committee (ExCom), to advance knowledge, foster dialogue and enhance action and support. Article 8 of the Paris Agreement provided a permanent legal basis for the Warsaw International Mechanism (WIM) (UN, 2015).

IPCC's first assessment of L&D in 2018 found residual risks to rise with further global warming leading to soft and hard adaptation limits in some natural and human systems (e.g., coral reefs, human health, coastal livelihoods) (Roy et al., 2018). Sections 8.4.5.6, 16.4 and 17.2 corroborate these findings concluding that, depending on mitigation and adaptation pathways, residual risks in key systems in many regions will create potential for negative impacts beyond adaptation limits (*medium confidence*). The assessment in 2018 also noted that there is 'not one definition of L&D'. This ambiguity has persisted, and a policy space for L&D has not clearly been delimited (*high confidence*). There is, however, coalescence in dialogue among academia, civil society and policy around a distinct set of themes as identified by stakeholder surveys as well as literature, methods and evidence reviews (Vanhala and Hestbaek, 2016; Boyd et al., 2017; Mechler et al., 2018; Calliari, 2019; McNamara and Jackson, 2019): risk management, limits to adaptation, existential risk, finance and support, including liability, compensation and litigation (Sections 8.3, 16.4; *medium confidence*; Figure Cross-Chapter Box LOSS.1). Various advisory groups have been set up with participation of policy and experts from research, civil society and practice to help inform the implementation of WIM workplans (UN, 2015; UN, 2019).

Risk management

An increasing body of research has focused on the role of climate risk management (Sections 8.3, 16.4 and 17.2; *high confidence*) (Birkmann and Welle, 2015; Gall, 2015; van der Geest and Warner, 2015; Mechler and Schinko, 2016; Boyd et al., 2017; IPCC, 2018b; IPCC, 2019b; Boda et al., 2020; Broberg and Romera, 2020). A technical expert group on comprehensive risk management (TEG CRM) advises the WIM ExCom, while other expert groups focus on slow-onset events and non-economic L&D (UNFCCC, 2019a).

There is evidence that, without strong risk management and adaptation, losses and damages will continue to affect the poorest vulnerable populations, potentially creating poverty traps (*high confidence*) (Sections 8.3, 8.4.5.6 and Tables 8.7, 17.2; Serdeczny, 2019; Tschakert et al., 2019; Thomas et al., 2020). Research has started to develop global inventories on losses and damages, including on intangible effects (Tschakert et al., 2019; Otto et al., 2020), and engaged with the practice community for data collection. Practice has provided guidance to report on losses and damages in countries (I)NDCs (WWF & Practical Action, 2020). Yet, systematic risk assessments of climate-related losses and damages including adaptation limits (see, e.g., Leal Filho and Nalau, 2018; Robinson, 2018) have remained scarce (Section 16.4; *high confidence*). Thus, many vulnerable countries lack comprehensive data at scale of risk management including on economic (e.g., loss of livelihood assets and infrastructure) and non-economic losses and damages (e.g., culture, health, biodiversity), thus hampering effective risk management (Thomas and Benjamin, 2018; Martyr-Koller et al., 2021; Singh et al. 2021). Van den Homberg and McQuistan (2019) propose a losses and damages inventory also to be used to monitor how technologies may shape risks as well as adaptation limits. While early warning and other risk reduction options as well as risk retention considerations are being discussed, L&D dialogue has strongly focused on risk finance for residual risks, particularly through the donor-supported provision of public insurance systems (Linnerooth-Bayer et al., 2019; Schäfer et al., 2019; Broberg and Romera, 2020; Nordlander et al., 2020).

Cross-Chapter Box LOSS (continued)

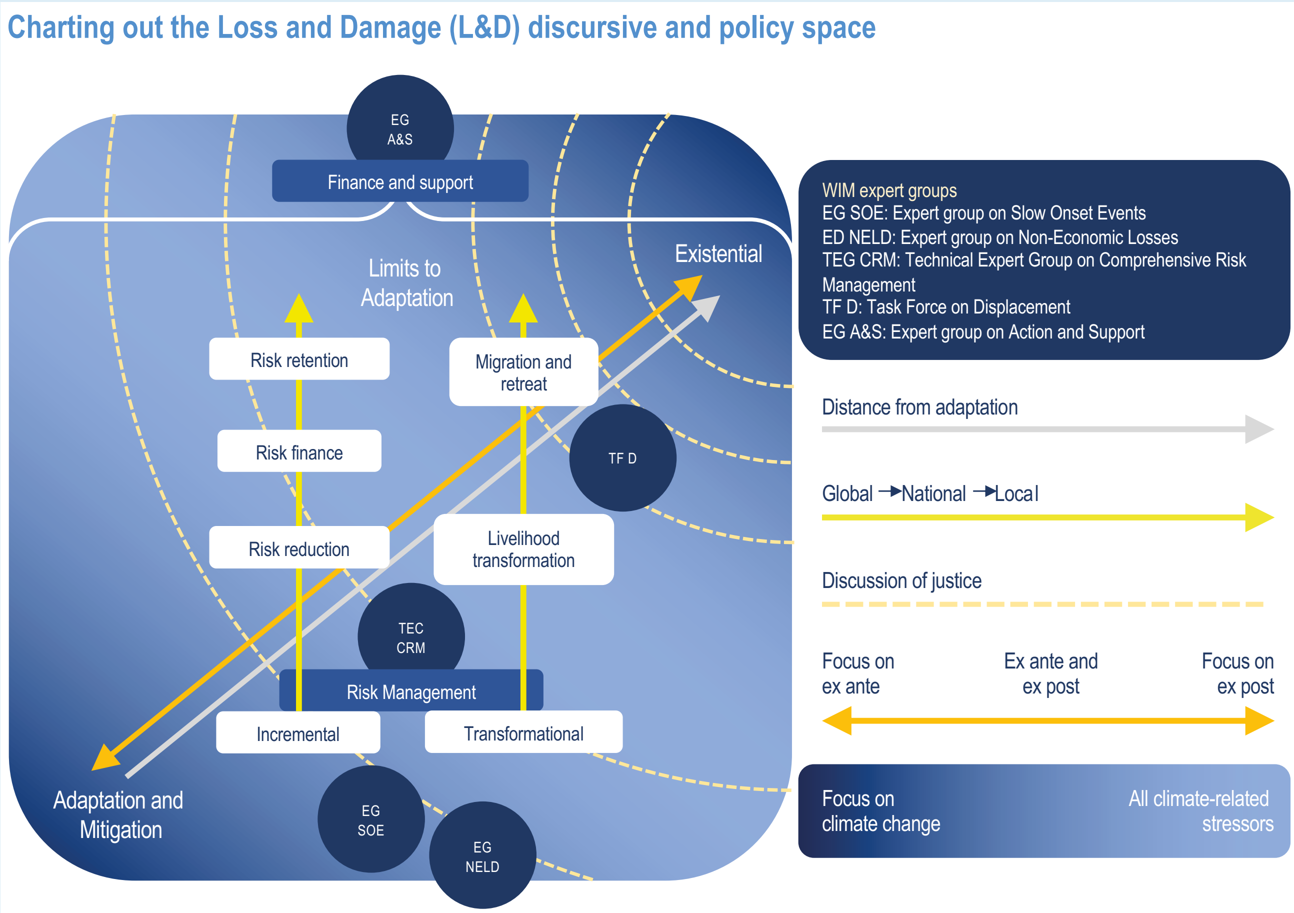


Figure Box Cross-Chapter Box LOSS.1 | Charting out the L&D discursive and policy space. The figure shows key discursive strands relevant for L&D, including their inter-relationships with and distinction from adaptation. The figure also identifies expert groups set up under the WIM and showcases the scale of responses discussed, a focus on *ex ante* risk management and *ex post* attention to losses and damages as well as contributions by climate change and other stresses for the themes. Adapted from Boyd et al. (2017) and building on Vanhala and Hestbaek (2016), Mechler et al. (2018), McNamara and Jackson (2019) and Calliari (2019).

Transformation

The role of transformation in risk management for overcoming any soft limits to adaptation is seeing emerging attention (*medium confidence*, *limited evidence*), and the TEG CRM has also been tasked to consider transformation. Relocation and retreat of assets and communities, where *in situ* adaptation is considered impossible, is increasingly being debated in research and practice, including in terms of finance and L&D implications (Section 8.4.4; Boston et al., 2021; Desai et al., 2021; Mach and Siders, 2021; van der Geest and van den Berg, 2021; Zickgraf, 2021). Livelihood transformation occurs where current livelihoods become unfeasible in the face of multiple climatic and non-climatic stressors (Section 8.3.4.1) requiring change within sectors (such as switching from cropping to livestock rearing (Escarcha et al., 2020) or across sectors, when farming households relocate to offer labour elsewhere (Section 9.1; Rasel et al., 2013). Biermann and Boas (2017) suggest revamping global governance systems to effectively address the protection and voluntary resettlement of those displaced by climate variability and change. A WIM taskforce on displacement is tasked to further advise on human mobility, including migration, displacement and planned relocation (UNFCCC, 2019a).

The existential dimension

There has been less and often implicit discussion on the existential dimension of climate-related risk as pertaining to L&D (*medium confidence*). McNamara and Jackson (2019) infer an existential dimension from notions of inevitability and irreversibility associated with migration and relocation of communities (Eckersley, 2015; Mayer, 2017; McNamara et al., 2018), socio-cultural impacts linked to glacial retreat (Jurt et al., 2015) and adverse psychological and inter-subjective effects (Herington, 2017; Adams et al., 2021). Many SIDS in their NDCs refer to sea level rise in particular posing existential threats, and call for enhanced international support for L&D (Thomas and Benjamin, 2017).

Cross-Chapter Box LOSS (continued)

Finance and support

International support and finance, including compensation for losses and damages, have been in the spotlight from the beginning of the dialogue (*high confidence*), starting with AOSIS' proposal (INC, 1991). Recent work has focused on *finance sources*, such as solidarity-based donor and other support for experienced losses and damages and climate-induced displacement as well as questions of compensation and litigation (Roberts et al., 2017; Gewirtzman et al., 2018; Mechler and Deubelli, 2021; Robinson et al., 2021). A selection of finance *options* has also been explored such as donor-supported insurance systems with built-in risk reduction provisions (Gewirtzman et al., 2018) as well as roles for social protection (Aleksandrova and Costella, 2021). International policy and donors have provided technical assistance for insurance-related options (Insuresilience Global Partnership, 2018).

As national and donor-related funding for impacts and risk management remains limited (Schäfer and Künzel, 2019; 17.2; Serdeczny, 2019) even at current global warming, many highly exposed developing countries remain financially constrained in their capacity to attend to residual impacts and risk management needs (Linnerooth-Bayer and Hochrainer-Stigler, 2015; Roberts et al., 2017; UNEP, 2021a) (*high confidence*). Discussion on options for the risk retention layer 'beyond adaptation' are likely to see further attention as the dialogue proceeds.

Although there is no explicit mandate regarding L&D, about a quarter of the Green Climate Fund's approved projects explicitly refer to L&D, while 16% of projects have thematic links to L&D across their main project activities (Kempa et al., 2021). Any estimate of L&D finance needs and spending, however, remains highly speculative, as long as its exact remit including in relation to adaptation has not been clarified politically (*medium evidence*, *high agreement*) (Markandya and González-Eguino, 2019).

Liability and compensation, implying legally defined reimbursement of losses and damages attributable to climate change, remain contentious in L&D dialogue (*high confidence*). Yet, in half of the academic and grey literature surveyed by McNamara and Jackson (2019), compensation is mentioned. Studies have laid out responsibility principles, such as historical responsibility based on the polluter pays principle, beneficiary pays and ability to pay. Discussions on compensation are closely linked to justice and equity scholarship which has studied compensatory, distributive and procedural equity considerations for burden sharing (Roser et al., 2015; Wallimann-Helmer, 2015; Huggel et al., 2016; Boran, 2017; Page and Heyward, 2017; Roberts et al., 2017; Shockley and Hourdequin, 2017; Wallimann-Helmer et al., 2019; Garcia-Portela, 2020).

Litigation and liability are linked, and a growing research body has examined the role of litigation and international law for the L&D context finding that litigation risks for governments and business may increase as the science, particularly on attribution, matures further (Mayer, 2016; Banda and Fulton, 2017; WGI CWGB Attribution, 8.2.1.2); Marjanac and Patton, 2018; James et al., 2019; Simlinger and Mayer, 2019; Wewerinke-Singh and Salili, 2019; Toussaint and Martinez Blanco, 2020) (*high agreement*, *medium evidence*).

Outlook

The WIM has been reviewed twice as to its delivery on its key functions. As an outcome of the second review in 2019, an expert group on Action and Support has been set up to further discuss issues pertaining to finance, technology and capacity building and a Santiago Network for Technical Assistance will be established to consider providing technical support directly to developing countries (UNFCCC, 2019b). Overall, the L&D dialogue under the WIM supported by an increasing body of research has made important advances with regard to the two functions of knowledge generation and coordination, yet less so on action and support (*medium confidence*) (Calliari et al., 2020). Resolution on the last item will need additional attention as, despite the coalescence of themes, the L&D dialogue continues to proceed across interlinked yet contested discussion strands.

Cross Chapter Box DEEP | Effective Adaptation and Decision-Making Under Deep Uncertainties

Authors: Carolina Adler (Switzerland/Chile/Australia), Robert Lempert (USA), Andrew Constable (Australia), Marjolijn Haasnoot (the Netherlands), Judy Lawrence (New Zealand), Katharine J. Mach (USA), Simon French (UK), Robert Kopp (USA), Camille Parmesan (USA), Mauricio Dominguez Aguilar (Mexico), Elisabeth A. Gilmore (USA), Rachel Bezner Kerr (Canada), Adugna Gemeda (Ethiopia), Cristina Tirado-von der Pahlen (USA/Spain), Debora Ley (Mexico), Rupa Mukerji (India).

Decision-relevant uncertainties for managing climate risk

Adaptation decision-making can benefit from assessments that support planning for both 'what is most likely' as well as for stress-testing adaptation options over a range of scenarios (Sections 11.7 and 17.3; Cross-Chapter Box.5 in SROCC Chapter 1). This Cross-Chapter Box summarises how deep uncertainties (Section 1.2; IPCC, 2019a) can be assessed in decision-making and addressed practically for adaptation.

The concept of deep uncertainty has evolved in IPCC assessments, expanding beyond a focus on reducing uncertainty, to also considering a range of tools and approaches that guide robust and timely decisions to address climate risks. Deep uncertainty is defined as circumstances where experts or stakeholders do not know or cannot agree on one or more of the following: (1) appropriate conceptual models that describe relationships among drivers in a system; (2) the probability distributions used to represent uncertainty about variables and parameters; and/or (3) how to weigh and value desirable alternative outcomes (Cross-Chapter Box 5 in Chapter 1; Lempert et al., 2003; IPCC, 2019a; IPCC, 2019c).

Decisions by individuals, households, the private sector, governments and public–private partnerships are generally made with partial or uncertain information. This is also the case for adaptation and development decisions where there is often deep uncertainty about the impacts and the societal conditions, preferences and priorities, and responses over time. Under such conditions, decision makers employ decision processes and scientific information differently from situations where most decision-relevant information is available, uncontested and confidently characterised with single joint probability distribution. Assuming scientific information is certain, when it is not, is a barrier to effective communication of risks and to successful decisions under uncertainty, increasing the potential for failure and regret of investments, lost opportunities and transfers of costs to future generations (Sarewitz and Byerly, 2000; Marchau et al., 2019; Sections 11.7 and 17.6).

Addressing deep uncertainty is contextual as it depends on the decision options available, outcomes at stake and the available scientific information (Box 1.1. in Marchau et al., 2019). The IPCC uncertainty guidance note (Mastrandrea et al., 2010) addresses only the latter (see also Mastrandrea and Mach, 2011; Section 1.3.4). Deep uncertainty is generally more salient when policy-relevant statements have *low confidence* or lack relevant data or information, or in cases where significant uncertainty contributes to disagreements and disputes (Sriver et al., 2018). Recent work has also included moral uncertainty (MacAskill et al., 2020) by evaluating the outcomes of alternative strategies with analyses organised around different perspectives on the appropriate principles of justice (Ciullo et al., 2020; Section 17.3; Jafino et al., 2021; Lempert and Turner, 2021).

To better communicate deep uncertainty, WGI AR6 complements projections of likely global mean sea level change, driven by processes in which there is at least *medium confidence*, with projections that incorporate ice-sheet processes in which there is *low confidence* (Section 9.6.3 in Fox-Kemper et al., 2021). The latter are accompanied by storylines to highlight the physical processes that would generate extreme outcomes (Box 9.4 in Fox-Kemper et al., 2021). These *low confidence* projections and storylines are useful because the likelihood of high-end (>1.5 m) global mean sea level (GMSL) rise in the 21st century is difficult to determine but important to consider in coastal settings (e.g., Cross-Chapter Paper 2; Cross-Chapter Box SLR in Chapter 3). High-end GMSL rise by 2100 could be caused by earlier-than-projected disintegration of marine ice shelves, the abrupt, widespread onset of marine ice sheet instability and marine ice cliff instability around Antarctica, or faster-than-projected changes in the surface mass balance and dynamical ice loss from Greenland (Box TS.4 in Arias et al., 2021; Box 9.4 in Fox-Kemper et al., 2021). In a low-likelihood, high-impact storyline and a high CO_2 emissions scenario, such processes could in combination contribute more than one additional metre of sea level rise by 2100 (Box TS.4 in Arias et al., 2021; Section 9.6.3 and Box 9.4 in Fox-Kemper et al., 2021). Other hazards assessed in WGI AR6 that address similar aspects relevant for decision-making under deep uncertainty include drought (Section 8.4.1.6 in Douville et al., 2021; Section 11.6.5 in Seneviratne et al., 2021), flood (Section 8.4.1.5 in Douville et al., 2021; Section 11.5.5 in Seneviratne et al., 2021) and wildfire weather (days) (Section 11.8.3 and Box 11.2 in Seneviratne et al., 2021), among others.

Approaches and information requirements for managing deep uncertainty

Many approaches are available for evaluating robust decisions under conditions of deep uncertainty (Sections 17.3 and 11.7; Box 11.5 in Chapter 11). The majority use multiple scenarios to stress-test adaptation options and explore how alternative adaptation pathways might evolve under a range of different conditions (Swanson and Bhadwal, 2009). Approaches differ in terms of their focus, types of strategies best addressed, and data and other resources required (Marchau et al., 2019).

Cross Chapter Box DEEP (continued)

'Low regret' options are one relatively simple and common approach to deep uncertainty (Sections 17.3 and 17.6) expected to perform well over a wide range of scenarios and represent one example of robust strategies. However, such options will generally be insufficient for adaptive responses to adapt over long time frames and to avoid lock-in of investments (Section 11.7; Box 11.5 in Chapter 11).

'Adaptation pathways' provide another approach for addressing deep uncertainty and staging decisions over time (Haasnoot et al., 2013), by linking the choice of near-term adaptation actions with pre-determined future thresholds. Observation of such thresholds trigger subsequent actions in the planning or implementation stages of adaptation strategies. Adaptation pathways can begin with low-regret, near-term actions that aim to create and preserve future options to adjust if and when necessary. Alternative pathways can be explored and evaluated to design an adaptive plan with short-term actions and long-term options.

Climate resilient development (CRD), and the pathways (CRDPs) to it, can also involve decision-making under deep uncertainty. Literature assessed in sectoral and regional chapters of this report present several examples of potential risks to achieving development goals under climate change, at global as well as national and local levels (*high confidence*) (Chapter 18). Achieving CRD depends on negotiation, contestation and reconciliation of trade-offs among diverse actors, who in turn value preferred outcomes differently with respect to associated climate risks and uncertainties, hence the prospect for deep uncertainty to manifest (Section 18.5). Deep uncertainty also characterises the development process itself, given that fundamental changes and disruptions are part of the transformational changes required to shift towards CRDPs.

The 'keeping options open' approach, i.e. plans that use a series of sequential decisions and actions in the near term to avoid closing off potentially promising future options (Rosenhead, 2001; Section 2.6) or, by using real options, takes near-term actions that create currently unavailable options in the future (Kwakkel, 2020). Deep uncertainty approaches use a wide range of storylines as scenarios to test low-regret options and to provide information relevant for potential thresholds for use in adaptation pathways (Haasnoot et al., 2013; Boxes 11.4, 11.6; Sections 11.7, 17.3).

Deep uncertainty approaches enhance the value of monitoring to detect signals of change in a timely manner (*medium confidence*). Actionable warning can come from climate signals, and socioeconomic indicators/signposts, including drivers of change, vulnerability and impacts, best suited for timely, reliable and convincing signals for decision-making that anticipate future changes and the need for adaptation or the potential to seize opportunities (Hermans et al., 2017; Haasnoot et al., 2018; Stephens et al., 2018; Oppenheimer et al., 2019). For early warning signals to be decision relevant, they need to have institutional connectivity to enable action (Haasnoot et al., 2018; Sections 1.4, 11.4, 11.7; Table 11.18) (*medium confidence*).

Examples and case studies from across the WGII report

There are diverse examples of the practical application of deep uncertainty methods across different climate change hazards in many regions of the world. For instance, low-regret options have been used to address the impacts and risks of landslides and debris flows in mountains (Section CCP5.2.6). Their frequency and magnitude are already widely experienced (Section CCP5.2.6) and projected to increase (Section CCP5.3.2.1). However, managing these associated risks also requires joint consideration of projected vulnerabilities and exposure of people and infrastructure, including the multiple and dynamic non-climate-related factors that are relevant for how the impacts manifest in context, such as population growth and land use planning (CCP5.2.6). Here, context-specific deliberative processes are used that include scenarios to guide and specify preventive measures with higher effectiveness than protective (infrastructure) measures could achieve alone. Low-regret adaptation involves raising awareness and accounting for long planning horizons to address the uncertainties associated with such risks, for instance in mountain regions, including education (Sections CCP5.4.1; CCP5.2.6), with co-benefits such as addressing changes in water availability for supply and demand (CCP5.4.1).

Adaptation pathways have been used to address SLR and changes in extreme rainfall through flood risk and management (Cross-Chapter Box SLR in Chapter 3; CCP2; Sections 13.2, 11.3 and 11.7): for example, adaptive plans in the Netherlands (Van Alphen, 2016; Bloemen et al., 2019), climate resilient development in Bangladesh (Hossain et al., 2018; Zevenbergen et al., 2018), adaptive spatial pathways for infrastructure retreat and for flood risk management in New Zealand (Lawrence et al., 2019a; Kool et al., 2020) and adaptive strategies such as in the cities of London (Ranger et al., 2013; Hall et al., 2019), New York (Rosenzweig and Solecki, 2014) and Los Angeles (Aerts et al., 2018a). This approach is mainstreamed into guidance documents such as the Climate Risk Informed Decision Analysis (CRIDA) (Mendoza et al., 2018), national guidance and policy briefs to address coastal hazards and sea level rise planning in New Zealand (Lawrence et al., 2018; Lawrence et al., 2019b), planning for sea level rise in California (OCP, 2018) and synthesis documents by the government of Canada on marine coasts (Lemmen et al., 2016). Furthermore, examples from the UK, New Zealand and the Netherlands point to the development of monitoring plans to detect signals for climate adaptation (Stephens et al., 2017; Haasnoot et al., 2018; Bloemen et al., 2019).

Cross Chapter Box DEEP (continued)

Climate-smart planning, with a focus on keeping options open, can play a role in reducing species extinction rates (Sections 2.5, 2.6). When and where and for whom particular irreversible impacts will occur is deeply uncertain, for example the extinction of a species. Even at the lowest emissions scenarios, some local species will become extinct, but estimates of extinction risk are highly uncertain, typically varying by factors of two to three even for one species (Section 2.5) (*medium confidence*). Risks of species' extinctions are lowered by reducing emissions, but keeping options open for as long as possible and avoiding irreversible actions are key to developing a climate-resilient adaptive pathway so that real-time climate-driven changes can inform actions. Nature-based solutions (NBS) are emerging as key players for mitigation. With smart planning, NBS offer approaches that not only provide substantial mitigation, but also considerable adaptation benefit to biodiversity, and human health and well-being. Done poorly, such projects can result in large negative impacts on humans and nature. An NBS climate-sensitive decision framework leading to 'win-win' solutions for mitigation and adaptation is shown in Figure 1 Cross-Chapter Box NATURAL in Chapter 2 (see also Sections 2.4.2.5, 2.5, 2.6, 5.4.4.4 and 5.14.1; Cross-Chapter Box ILLNES in Chapter 2; Cross-Chapter Box COVID in Chapter 7).

In view of these multiple and diverse examples, it is evident that the application of deep uncertainty methods is enabling decisions to be made in a timely manner that avoid foreseeable and undesirable outcomes and take opportunities as they arise (*high confidence*).

Prospects for adaptation decision-making

Deep uncertainty is increasingly salient for decision-making as recognition of climate-related risks and related uncertainties has increased (*high confidence*). These risks can compound and cascade to become new risks, increasing the breadth, frequency and severity of climate change impacts and the consequently increasing scale and scope of adaptation (*high confidence*) (Cross-Chapter Box Extremes in Chapter 2; Sections 1.3.1.2, 2.3, 2.5, 2.6, 11.5, 11.7, and CCP5.3.1). Waiting until uncertainties are resolved (if they ever can) may leave little or no time to adapt. The lead time for planning and implementation of adaptation can take decades (Haasnoot et al., 2020b; Cross-Chapter Box SLR in Chapter 3), and socioeconomic developments can lock in undesirable pathways where underlying vulnerabilities and exposure, such as poverty, conflict and their associated displacement of people, remain unaddressed (Sections 5.13.4, 16.5.2.3.8; Cross-Chapter Box Migrate in Chapter 7).

Overall, there is growing evidence that effective implementation of strategies developed for deeply uncertain problems require adequate mandates and funding frameworks, preparedness and disaster response plans, and monitoring and evaluation of the strategy outcomes, against how the future unfolds (*medium confidence*). Collaborative and adaptive governance arrangements, and education and awareness raising, promote learning environments for community engagement, and are essential for the effective implementation of robust adaptation plans (*medium confidence*) (Sections 5.14.1, 17.3 and 11.7).

Cross-Chapter Box FINANCE | Finance for Adaptation and Resilience

Authors: Mark New (South Africa), Madeleine Rawlins (UK), David Viner (UK), Charlene Watson (UK), Lily Burge (UK), Lionel Mok (Canada), Lauren Arendse (South Africa), Vita Karoblyte (UK), Liane Schalatek (USA), Neha Rai (UK), Baysa Naran (Mongolia), So-Min Cheong (Republic of Korea), Nicoletta Giulivi (Italy/Guatemala).

Introduction

This Cross-Chapter Box reports on: (i) new evidence on the finance needed for adaptation and resilience, and uncertainties in these estimates; (ii) the emerging public and private climate finance architecture; (iii) the status of financing for AR, including sources, total flows, regional and sectoral distributions; (iv) equity considerations; (iv) opportunities and challenges for financing adaptation and resilience during and after the coronavirus disease 2019 (COVID-19) pandemic. This Cross-Chapter Box does not focus on finance for mitigation, which is covered in WGIII Chapter 15 (Kreibiel et al., 20122), nor the economic damages of climate change or financial aspects of Loss and Damage, which are covered in Cross-Working Group Box ECONOMIC (Chapter 16) and Cross-Chapter Box LOSS (this chapter), respectively.

Successive reports of the IPCC (Vellinga et al., 2001; Mimura et al., 2008; Yohe et al., 2008; Klein et al., 2014) and the AR6 Special Reports have noted the importance of finance as an enabler for adaptation, across both developed and developing nations. While the UNFCCC and the UNFCCC has yet to arrive at a formally agreed definition of climate finance, numerous overlapping have been suggested and reported (e.g., Falconer and Stadelmann, 2014; UNFCCC, 2014; Roberts and Weikmans, 2017; Munira et al., 2021). However, there is wide agreement across these definitions that climate finance refers to financial resources devoted to addressing climate change, both mitigation and adaptation to current and projected climate change, and that these resources can come from both public and private sources (high confidence). Climate finance includes, but in most definitions is not restricted to, international financial flows to developing countries. Finance can be delivered through a range of instruments including grants, concessional and non-concessional debt, and internal budget reallocations (high confidence) (Watson and Schalatek, 2019). Adaptation and resilience are often used interchangeably in climate finance discussions, although adaptation is a process, while resilience (to climate risk) is the ability to progress towards desired outcomes in the face of impacts from a changing climate (Section 1.2.1).

Box Cross-Chapter Box FINANCE.1 | The 100 Billion Climate Finance Commitment to Developing Countries

At the 16th session of the Conference of the Parties (COP16) in Copenhagen in 2009, developed country parties to the UNFCCC committed to a goal of jointly mobilising USD 100 billion yr^{-1} by 2020 to address the climate change needs of developing countries (UNFCCC, 2009). This was in response to a threat by developing countries to walk out of the negotiations, as they perceived developed country support to be lagging and lacking in ambition (Roberts et al., 2021). The commitment was formalised in the Cancun Agreements (Decision 1/CP.16) in 2010 and was re-affirmed as a key element of the Paris Agreement in 2015 (Article 9, paragraph 4). At the 26th session of the Conference of the Parties (COP26) in 2021, formal deliberations will begin on a new climate finance goal to be adopted in 2025; the current USD 100 billion target will serve as the annual minimum until 2025 (Chhetri et al., 2020).

The '100 Billion' does not represent the total need to respond to climate change in developing countries, nor the global cost across all countries, as is sometimes interpreted in the literature and media. As shown below in this Cross-Chapter Box, the estimated cost of adaptation for developing countries ranges from 15 to 411 billion USD yr^{-1} for climate change impacts out to 2030, with the majority of estimates being well above 100 billion.

Proposed sources for the developed country commitment included '*a wide variety of sources, public and private, bilateral and multilateral, including alternative sources of finance*' and several instruments including grants and loans. Nonetheless, there remain differences of opinion on the types of finance that should count towards this goal, with several issues identified (*high confidence*) (Bodnar et al., 2015; Bhattacharya et al., 2020; Roberts et al., 2021), including: (i) counting non-grant finance, such as market and concessional loans (public and private), where developing countries ultimately have to repay the investment; (ii) what is counted as 'climate' by different funders, especially when climate is not the prime objective; (iii) the extent to which some funds are 'new and additional' rather than a repurposing of development finance.

Progress towards the 100 Billion target has shown an upward trend over the last several years (*high confidence*), but will fall short in 2020, even when the most generous criteria are included (*high confidence*). In 2017/2018, the most recent year for which data have been comprehensively analysed, estimates using different (but overlapping) data sources and methods were in

Cross-Chapter Box FINANCE (continued)

the range 48–75 billion USD yr^{-1}, compared with 45–75 in 2015/2016 and 41–52 in 2013/2014 (Carty et al., 2020; SM17.3; CPI, 2020; OECD, 2020; UNFCCC, 2020). The distribution between adaptation and mitigation has remained strongly weighted towards mitigation, although the proportion allocated to adaptation has increased from 17–25% in 2013/2014 to 19–30% in 2017/2018 (*high confidence*). One analysis that excludes debt repayments indicates that the debt-adjusted flows are about half the total flows reported above, of which circa 31–33% was for adaptation between 2015/2016 and 2017/2018 (Carty et al., 2020).

Adaptation finance needs

Estimates of global, regional or national finance needs for adaptation and resilience vary depending on both analysis approach, the level of climate change, and the geographic and sectoral scope of analysis (*high confidence*) (UNEP, 2016; Chapagain et al., 2020; UNEP, 2020). Recent estimates have adopted one of main approaches: (i) aggregation of individual case studies, along with scaling to generate global or regional costs; (ii) analysis of NDC adaptation cost estimates (Weischer et al., 2016; Hallegatte et al., 2018); (iii) integrated assessment model simulation of impacts and adaptation costs (Markandya and González-Eguino, 2019; Chapagain et al., 2020).

All approaches suffer from limitations that can cause both over- and underestimates, including incomplete coverage of sectors and risks; inability to account for autonomous/unreported adaptation; incorrect cost estimations; soft and hard limits to adaptation; balance between adaptation, mitigation and residual cost; benefits and co-benefits on cost; and learning and innovation as climate change progresses (UNEP, 2020). Global or developing region estimates based on scaling NDC data is particularly uncertain, as most NDCs did not specify how the costs were calculated. Also, scaling from a relatively small set of NDCs with costs to the global scale is not particularly robust, indicating a need for more transparency and better guidance for calculating adaptation costs (Watkiss et al., 2015; Zhang and Pan, 2016; Hallegatte et al., 2018; African Development Bank, 2019).

Most estimates of adaptation cost in the literature are for developing countries. Chapagain et al. (2020) assessed various estimates of adaptation for developing countries, under different emissions scenarios for 2030 and 2050. The median estimates (and range) from these studies are 127 (15–411) and 295 (47–1088) billion USD yr^{-1} for climate change impacts out to 2030 and 2050, respectively (see SM17.3). All but one study report adaptation costs higher than the 70–100 billion estimated in 2010 by the World Bank (World Bank, 2010).

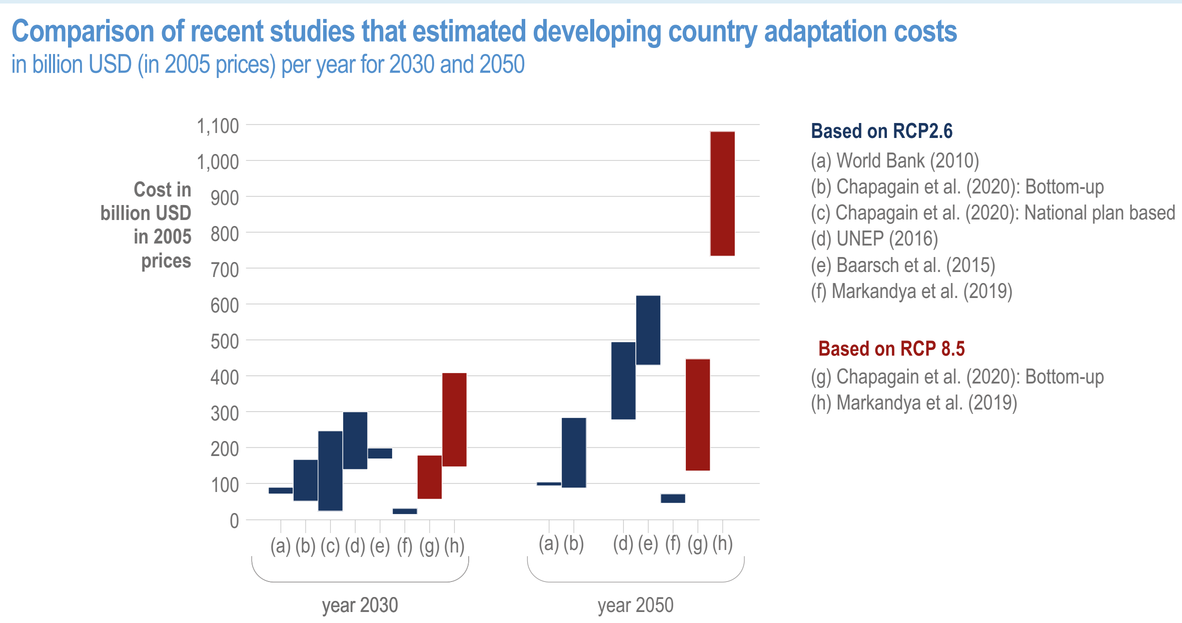


Figure Cross-Chapter Box FINANCE.1 | Comparison of recent studies that estimated developing country adaptation costs in billion USD (in 2005 prices) yr^{-1}, for 2030 and 2050. Figure based on Chapagain et al. (2020). Major studies are World Bank (2010), Chapagain et al. (2020), UNEP (2016), Baarsch et al. (2015) and Markandya and González-Eguino (2019). The solid-coloured bars are based on RCP2.6, and patterned bars are based on RCP 8.5; the width of the bars indicates the range of estimates (maximum and minimum) produced in each study.

Cross-Chapter Box FINANCE (continued)

The cost of adaptation for developed countries is rarely reported; most literature either reports a global cost or developing country costs, or costs for a specific country or sector. Baarsch et al. (2015), using an Integrated Assessment Model (IAM), report adaptation annual costs (2012 prices) in 2030 (and 2050) as 272 (660) billion globally and 205 (521) in developing countries only under the RCP2.6 scenario, indicating that developed country costs are around 25% (21%) of total cost.

In addition to global estimated adaptation costs, there are many studies that have focused on specific regions, countries or sectors, such as estimated adaptation cost for coastal environments, water-related infrastructure, urban infrastructure, agriculture and energy (UNEP, 2014; Watkiss et al., 2015; UNEP, 2016). Examples of such estimates are reported in various chapters in this report and summarised in SM17.3.

Estimating the benefit of adaptation, in terms of damage avoided, remains challenging. For example, Ricke et al. (2018) show that the social cost of carbon (monetary damage per tCO_2 emitted) varies by up to two orders of magnitude depending on country, socioeconomic scenario, damage function, total greenhouse gases (GHG) forcing, and local climate change. In addition, non-monetary benefits such as cultural identity, sacred places, human health and lives are often ignored (Tschakert et al., 2017; Serdeczny, 2019; see also Cross-Working Group Box ECONOMIC in Chapter 16; Cross-Chapter Box LOSS, this Chapter). Recent case studies and global level analyses continue to support the conclusion in IPCC AR5 WGII Chapter 17 (Chambwera et al., 2014) that the benefits of adaptation generally remain larger than the costs (*medium confidence*), but the cost–benefit ratio varies widely by context and assumptions (OECD, 2015; Global Commission on Adaptation, 2019; WRI, 2019)

The climate finance landscape

The adaptation and resilience finance landscape spans multiple sources, intermediaries, instruments and recipients, operating across global to sub-national scales (Buchner et al., 2019; Carter, 2020; Watson and Schalatek, 2021). Public finance is provided by national and sub-national governments and distributed directly by government or intermediaries such as development finance institutions and climate funds, either nationally or internationally. Private finance comes from five main sources: commercial financial institutions (banks), institutional investors (including asset managers, insurance companies and pension funds), other private equity (venture capital and infrastructure funds), non-financial corporations such as renewable energy or water companies, and individual households and communities. Across these different sources, the main instruments used are grants, concessional debt, market debt, internal budget allocation, insurance, as well as personal savings in households (*high confidence*). Public and private sources of funding can be blended into a single instrument, for example for insurance where public funds provide capital for both sovereign catastrophe instruments and micro-insurance (Jarzabkowski et al., 2019) or for concessional loans. Similarly, public finance is often ultimately derived from commercial debt instruments such as bonds.

International public climate finance

International public climate finance flows are realised through bilateral and multi-lateral channels (Watson and Schalatek, 2021) where contributions to these channels are received from Annex II and non-Annex I countries (UNFCCC SCF, 2018; Buchner et al., 2019). Annex II countries contribute as part of their commitments in the Paris Agreement, while non-Annex I countries commit climate finance through these channels on a voluntary basis (Pickering et al., 2015; Roberts and Weikmans, 2017; Egli and Stünzi, 2019). Bilateral intermediaries include development cooperation agencies and national development banks. These institutions often have long-standing development-cooperation experience, and offer climate change projects, facilities and financial instruments based on their differing mandates, structures and priorities (Atteridge et al., 2009; Buchner et al., 2019).

Multi-lateral channels include the UNFCCC financial mechanisms, such as the Green Climate Fund, and the multi-lateral development banks (MDBs), such as the World Bank. Both pool contributor resources before committing such resources for climate change projects and programmes. Funding through multi-lateral channels promotes recipient country engagement in the governance and prioritisation of funding decisions, with concurrent processes in the multi-laterals often existing to support country ownership of funded climate action (Ciplet et al., 2013; Ha et al., 2016).

There are five multi-lateral climate change funds of the UNFCCC and Paris Agreement financial mechanisms. There are further multi-lateral climate change funds that are not governed by the UNFCCC or Paris Agreement, the largest of which is the World Bank governed Climate Investment Funds (Watson and Schalatek, 2021). Some of the major multi-lateral climate change funds have been established with a specific focus on adaptation, while some bilateral donors have thematic or sectoral priorities. Multi-lateral climate change funds operate through accredited implementing entities. These have historically been multi-lateral in nature, such as the development banks, but recent years have seen a rise in the accreditation of national and regional institutions (UNFCCC SCF, 2018). In addition to programming funds

Cross-Chapter Box FINANCE (continued)

from external sources, such as through the multi-lateral climate change funds, the MDBs also raise and programme their own climate finance (UNFCCC SCF, 2018; MDBs, 2019).

Several major multi-lateral climate change funds work through grant-only programmes, whereas others include concessional loan, equity and guarantee instruments. The broader suite of instruments used by the MDBs includes grant, investment loan, equity, guarantee, line of credit, policy-based financing and results-based financing (MDBs, 2019).

Public funding of a concessional nature that flows from Annex II to non-Annex I countries supports research and capacity building and can also facilitate private finance flows into climate action, with the intention to avoid creating a high debt burden in developing countries, in response to climate impacts for which they have little historic responsibility (Watson, 2016; Carter, 2020; Schalatek, 2020). Less concessional public finance flows include other official flows that are not developmental in nature and can be trade related, including, for example, export credits.

Critiques of the public climate finance architecture are aimed at the overlapping mandates of the institutions programming climate finance, particularly the multi-lateral climate funds, and the challenges in accessing funding (Nakhooda et al., 2014; Amerasinghe et al., 2017; Pickering et al., 2017). However, Pickering et al. (2017) further note that institutional fragmentation of climate finance could result in more flexibility, resilience and innovation. There have also been important governance changes leveraged by some of these funds and instruments, such as integration of gender considerations into projects (Schalatek, 2020).

Private financing of adaptation and resilience

There is an increasing focus on the role of the private sector to support large-scale financing of adaptation and resilience (UNEP, 2016; UNEP, 2018). To date, it has been difficult to track adaptation and resilience finance within the private sector (UNEP, 2016) as it is either not disclosed or not easily identifiable, since it is often built into capital and operating expenditure and is not a standalone investment. Several private mechanisms are emerging as important sources of climate finance (Gupta et al., 2014; Eccles and Krzus, 2018; Miller et al., 2019).

Green, social impact and resilience bonds are similar to traditional bonds—fixed-income financial instruments raised on commercial markets by companies, governments or financial institutions—but the proceeds are used to fund activities that have positive environmental, social or climate benefit (Tuhkanen, 2020). Green bonds align to voluntary principles, such as the Green Bond Principles set out by the International Capital Market Association, the Climate Bonds Initiative's Climate Resilience Principles (Sartzetakis, 2020). Given the voluntary nature and lack of standardisation of green bond principles, there are concerns around their additionality, and there is also a lack of data on how green bonds contribute to a scaling up of green projects (Dupre et al., 2018).

Green bond annual issuance reached 260 billion in 2019 (CBI, 2020), but as of 2018, only 3–5% (USD 12 billion) of green bond total proceeds can be explicitly traced to climate-resilience-related efforts (CBI, 2019). Examples of AR focused bonds include those issued by Fiji in 2017, dedicating 91% of spending to adaptation and resilience (Shukla and Peyraud, 2017; Ministry of Economy, 2019), and by the European Bank for Reconstruction and Development's 2019 Climate Resilience Bond for USD 700 million to finance climate-resilient infrastructure, commercial operations, agriculture or ecological systems (EBRD, 2019).

Dedicated investment vehicles are equity funds that are created to invest in products and services that enhance resilience and reduce risks. An example is the Climate Resilience and Adaptation Finance and Technology Transfer Facility that is proposed as a USD 500 million private equity fund to invest in companies providing climate resilience solutions for developing countries. Initial funding has been provided by donors (Miller et al., 2019).

Balance sheet finance occurs when an entity directly invests in resilience and adaptation rather than as a separate project. This source of funding may be from exiting reserves, re-allocation from other budget lines, or via external commercial finance, but the investment is financed by the firm rather than as a separate project (Gupta et al., 2014; Buchner et al., 2019).

Insurance can play an important role in managing residual climate risks at any given level of adaptation, but insurers can also be important r risk assessment and risk reduction as part of any insurance package (Jarzabkowski et al., 2019; Section 11.3.8.3). While traditional indemnity insurance is important for repair and rebuilding of damaged property and infrastructure, parametric insurance has become increasingly popular for supporting rapid post-disaster responses such as drought, hurricane damage and flooding. Examples include sovereign insurance facilities such as African Risk Capacity and the Caribbean Catastrophe Risk Insurance Facility (Broberg, 2019)

Cross-Chapter Box FINANCE (continued)

as well as weather-index insurance targeted at individuals, especially in agriculture (Greatrex et al., 2015; Isakson, 2015; Surminski et al., 2016; Jensen and Barrett, 2017; Fischer, 2019). The role of insurance as a climate risk management option, as well as limitations, is covered in more depth in Section 17.2 and Cross-Chapter Box LOSS (this chapter).

Mainstreaming physical climate risks and resilience in the private sector

The data on tracked climate finance and green bond issuance for adaptation and resilience both show a substantial gap between the adaptation needs and the finance deployed. Scaling up these instruments is unlikely to close this gap given the challenges with financing adaptation projects, particularly from the private sector. There is therefore a need for more systematic action to manage climate risks and mainstream climate change considerations (Miller et al., 2019).

The financial case for mitigation investment can often be demonstrated through revenues from, for example, the sale of renewable electricity. On contrast, the benefits from investment in adaptation and resilience are typically considered in terms of avoided losses and cost benefit ratios. For example, the Global Commission on Adaptation (2019) estimates that the overall rate of return on investments in improved resilience is very high, with benefit–cost ratios ranging from 2:1 to 10:1, and in some cases even higher.

The private sector is becoming increasingly aware of the need to assess physical climate risks to avoid the long-term risks to assets and enhance climate resilience. The task force on climate-related financial disclosures (TCFD) is likely to create additional pressure from investors for companies to identify, manage and reduce risks from climate change (Eccles and Krzus, 2018; ERM and CBEY, 2018; Tuhkanen, 2020).

A key factor for the impact of the TCFD on mainstreaming of physical climate risks and demonstrating the case for investment in adaptation and resilience will be how investors systematically incorporate physical climate risks, adaptation and resilience into their investment decisions. The Coalition for Climate Resilient Investment (DFID et al., 2019) was established to look at this from the private sector viewpoint and is working to systematically incorporate resilience into cash flow modelling and asset valuation practices, so that investors may quantify the investment in resilience for an asset and the benefits associated with reduced costs and more reliable revenue streams.

Recent trends in climate finance flows

Considerable progress has been made in tracking climate finance since AR5, but substantial gaps remain, especially regarding domestic public finance and private sector balance sheet investment in adaptation (Section 17.5.1.5; CPI, 2020; Richmond et al., 2020). The best documented information comes from international climate funds, which provide detail at the project level. Most bilateral and multi-lateral investment institutions report on whether debt, grants and other instruments are for climate projects, but with less detail. Private finance is harder to track, as reporting is voluntary; even for green bonds, where certification identifies the range of sectors a bond aims to cover, reporting of how the bond is spent is infrequent.

The Climate Policy Initiative (CPI) has been tracking climate finance since 2009, allowing for trends to be assessed; however, trends reported are a function of both real changes in finance and changes in methods and information sources (Richmond et al., 2020). Total climate finance tracked by CPI has increased from USD 364 billion yr^{-1} in 2010/2011 to 579 billion in 2017/2018 (SM17.3). Tracked finance remained relatively constant from 2010/2011 to 2013/2014 but has increased steeply in more recent years. The proportion of finance allocated to adaptation has remained small throughout, between 4% and 8% (*high confidence*); a further 1–2% of global finance has been classified as 'multiple-objectives'. The large majority of tracked adaptation finance is from public sources (*high confidence*), with only 2% coming from private sources in 2017/2018 (CPI, 2020). This is at least partly because of the difficulty in demonstrating financial (as opposed to public good and avoided damages) return on investment for adaptation.

The majority of the most recently (2017/18) tracked adaptation and multiple-objective finance was supplied through public donors, largely through grants, concessional and non-concessional instruments (Figure FAR.1). Most finance (44.1%) was spent transregionally (allocated in specific projects to recipients in more than a single region). For regionally specific funding, Sub-Saharan Africa and South Asia, along with the Latin America and Caribbean region, received the largest gross amounts, although Oceania has received the greatest per-capita funding. The largest proportion of AR funding has been allocated to increasing the resilience of infrastructure, energy and the built environment, followed by agriculture, forestry and natural management, and then water and wastewater.

Across financial instruments, Sub-Saharan Africa received the highest relative proportion through grants (38%), followed by the Latin America and Caribbean region (23%), with other non-Organisation for Economic Co-operation and Development (OECD) regions receiving between 16% and 10% (SM17.3). Concessional debt as a proportion of the regional total varies from 84% in South Asia to as low as 29% in Latin America and Caribbean, which has the highest proportion of non-concessional debt (48%).

Cross-Chapter Box FINANCE (continued)

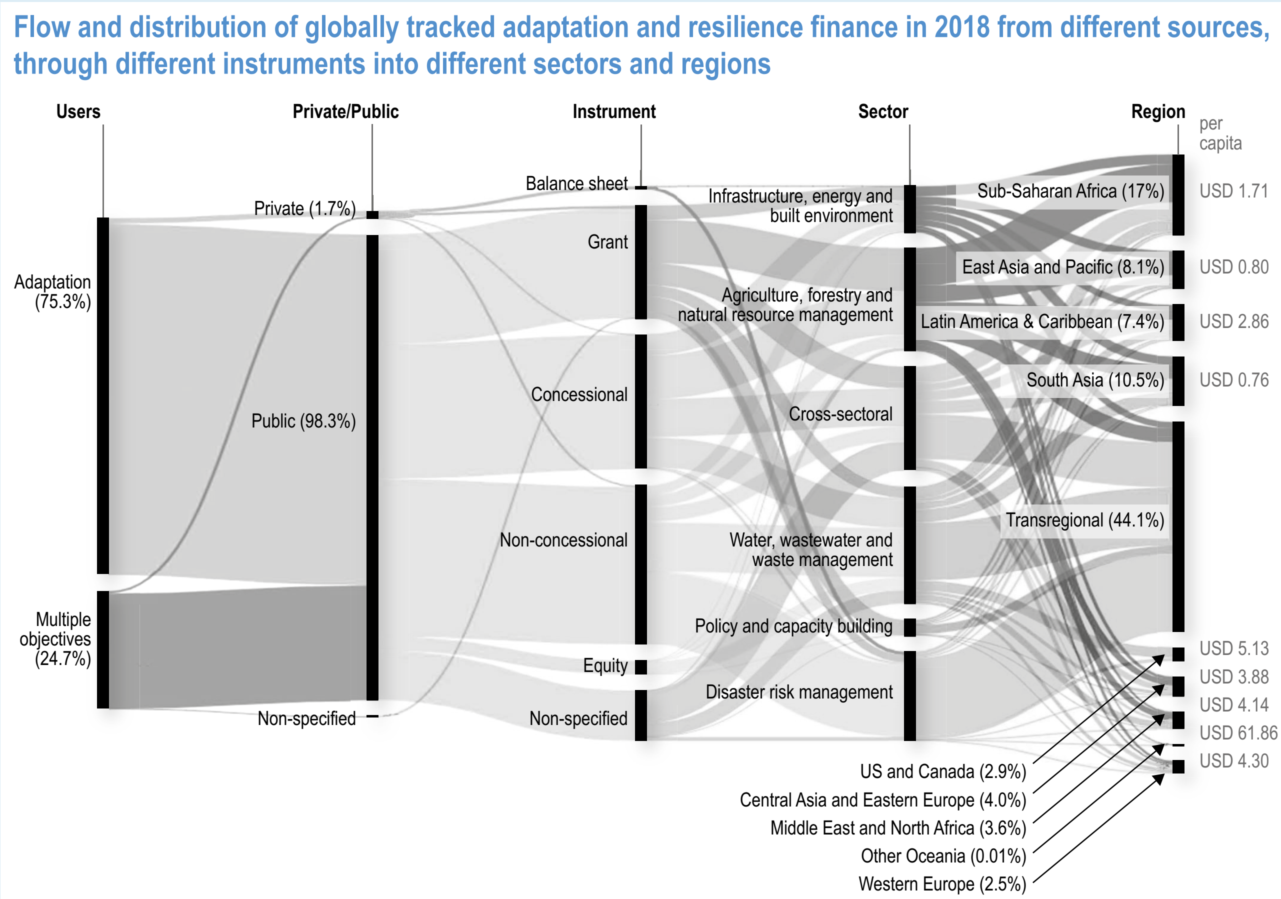


Figure Cross-Chapter Box FINANCE.2 | The flow and distribution of globally tracked adaptation and resilience finance in 2018 from different sources, through different instruments into different sectors and regions. Each strand shows the relative proportion of finance flowing from one category to another (for example, from private or public sources to different instruments). Categories from left to right are: (a) whether the finance is solely for adaptation or for adaptation and other objectives, including mitigation (multiple objectives); (b) whether the finance comes from public or private sources; (c) the financing instrument; (d) the broad sectoral allocation; (e) the geographical distribution of funding (proportion of total in % and per-capita allocation). Based on data collated by CPI (2020).

The importance of public and private finance for adaptation and resilience

Adaptation finance provided by international public mechanisms remains the core source of tracked flows in support of adaptation and resilience to developing countries (Micale et al., 2018; UNEP, 2018), although these public funds alone are insufficient to meet rapidly growing needs and constitute only a minority share of all public climate finance flows (UNEP, 2016; Global Commission on Adaptation, 2019).

Public mechanisms can play a role in leveraging private sector finance for adaptation by addressing real and perceived regulatory, cost and market barriers through blended finance approaches, public–private partnerships or innovative financial instruments and structuring in support of private sector requirements for risk management and guaranteed investment returns (Pillay et al., 2017; Miller et al., 2019).

There is growing agreement on the sectors (such as infrastructure, agriculture or water management) and approaches (contingency finance or insurance) where private sector adaptation investments alone, or leveraged by public mechanisms, might be best targeted, such as by reducing the risk of providing financial services for adaptation investments to domestic micro-, small and medium enterprises or agricultural smallholders, many of them women (Biagini and Miller, 2013; Chambwera et al., 2014; Pauw et al., 2016; Global Commission on Adaptation, 2019; Miller et al., 2019; Resurrección et al., 2019; Richmond et al., 2020). A remaining open question is how to allocate limited public adaptation funds in a way that is equitable, effective and efficient between mobilising private investments and safeguarding adequate financial support for necessary adaptation efforts, such as the provision of public goods, which the private sector will not invest in (Fankhauser and Burton, 2011; Abadie et al., 2013; Baatz, 2018; Omari-Motsumi et al., 2019).

Cross-Chapter Box FINANCE (continued)

Many adaptation interventions in the most vulnerable countries, communities and people provide no adequate financial return on investments and can therefore can only be funded with highly concessional public finance. Grant support is most appropriate for measures such as capacity building, planning, public policy and regulatory reforms, disaster risk management and response, community engagement or support for social safety nets, and for addressing social vulnerabilities, including poverty or gender inequality, which constrain adaptation (Grasso, 2010a; Pillay et al., 2017; Agrawal et al., 2019; Buchner et al., 2019).

Access to adequate adaptation grant finance is further constrained because several public mechanisms provide grants only for the additional costs of adaptation measures compared with a development baseline in the absence of climate impacts. Calculating the incremental costs of adaptation measures imposes additional time and resource burden on the most vulnerable recipients, who are often faced with data gaps or technical capacity constraints (Chambwera et al., 2014; GCF, 2018; UNEP, 2018; Omari-Motsumi et al., 2019).

An exact delineation of respective costs for adaptation and development components is difficult and might be unsuitable as many adaptation measures are intrinsically linked to development. It may also prevent realising necessary synergies between both components (McGray et al., 2007; Smith et al., 2011; Denton et al., 2014; Resch et al., 2017; Micale et al., 2018).

Equality and fairness in climate finance

Climate finance literature recognises that poor and least developed households, communities and countries are most affected and marginalised by climate change, and least responsible for its causes, but receive relatively little financial support for adaptation (Chapters 15, 8; Olsson et al., 2014; Rozenberg and Hallegatte, 2015; Hallegatte et al., 2016; Rai and Fisher, 2017; Shakya and Byrnes, 2017).

While the gap between current financial flows to developing countries and their adaptation needs (see Box Cross-Chapter Box FINANCE.1) is a major factor undermining equity and fairness in financing, several other factors that can also affect fair and just financing in developing countries have been identified in recent literature (Klein et al., 2014; Colenbrander et al., 2018; Mfitumukiza et al., 2019; Khan et al., 2019a; Doshi and Garschagen, 2020). First, financing is skewed in favour of mitigation, and therefore towards fast-growing upper- and middle-income countries offering the biggest gains in emission reductions, especially in Southeast Asia, but also in Sub-Saharan Africa (Rai et al., 2016). Further, as much of current finance uses debt-based instruments, mitigation projects are further preferred as returns are more assured (Lee and Hong, 2018; Carty et al., 2020).

Second, the requirement of many funders for readiness and fiduciary capacity means that least developed countries (LDCs) have been less able to access finance, despite many support mechanisms being offered. Additionally, geopolitical preferences of some countries mean that some developing countries are preferred to others for bilateral funding (Doshi and Garschagen, 2020). This is exacerbated for private sector investment, where lower credit ratings make finance more expensive, and increasing understanding of exposure to physical climate risks could lead to 'capital flight' from most vulnerable countries (Global Commission on Adaptation, 2019; Miller et al., 2019; Cooper, 2020).

Third, within climate-vulnerable countries, very little is channelled to local communities who need it most; the few analyses available suggest that less than 10% of total climate finance supports decentralised actions (Rai et al., 2016; Soanes et al., 2017). Reasons include: (i) lack of consideration of procedural equity in programme design (Grasso, 2010b; Wang and Gao, 2018; Venn, 2019; Khan et al., 2019a); (ii) finance being managed by multi-lateral implementers, rather than agencies that are closer to local communities; (iii) the higher transaction costs of decentralised projects in low-income communities reduce their attractiveness to funders as well as the ability of local organisations to meet the fiduciary standards (Fonta et al., 2018; Omari-Motsumi et al., 2019).

It has been proposed that, as middle-income countries can leverage mitigation finance from the private sector, targeting scarce public finance towards LDCs and SIDS may be necessary to ensure sufficient funds reach these countries (Steele, 2015). Matching domestic climate spending with international support is one way to ensure LDCs get the funds they need (Grasso, 2010b; Bird, 2014). Targeting specific marginalised communities and women within countries can also help make climate finance more effective and fairer, such as the Asian Development Bank's efforts to make lending portfolios more inclusive and pro-poor (ADB, 2018).

Post-COVID recovery packages, debt relief and finance for adaptation and resilience

Recent literature has highlighted the opportunity that COVID recovery packages offer for environmentally sustainable, low-carbon and climate-resilient economic growth (Forster et al., 2020; Hepburn et al., 2020; Hanna et al., 2021). Assessment of whether this is indeed happening is limited, although the few available studies suggest that that this opportunity is not being realised in many nations

Cross-Chapter Box FINANCE (continued)

(O'Callaghan and Murdock, 2021; VIVID Economics, 2021). One study of the Group of Twenty (G20) and 10 other nations suggested that stimulus packages would have net negative environmental impact in two-thirds of these countries (VIVID Economics, 2021), while another showed that around half of G20 recovery investment targeted at energy has had gone towards fossil fuels, rather than to cleaner energy sources (Dibley et al., 2021).

Concerns have also been raised about the interactions between debt service, COVID economic recession and post-COVID recovery in developing countries (Simmons et al., 2021; Volz et al., 2021). Debt service grows as a proportion of national budget during recession, reducing scope for investment in recovery, is a self-reinforcing cycle. It has been suggested that linking debt relief to Paris-aligned objectives can act as an additional source of climate finance (Fenton et al., 2014). The G20 has begun addressing this debt crisis through its Debt Service Suspension Initiative and the Common Framework for Debt Treatments (IMF, 2020). It has been suggested that these initiatives could be expanded to prioritise climate-focused debt-relief instruments and to include more countries (Steele and Patel, 2020; Volz et al., 2021). If debt relief is used to invest in national instrument for green and inclusive recovery, national ownership of the use of the finance can occur, avoiding some of the negative connotations of historical debt restructuring (Volz et al., 2021).

Cross-Chapter Box PROGRESS | Approaches and Challenges to Assess Adaptation Progress at the Global Level

Authors: Matthias Garschagen (Germany), Timo Leiter (Germany/UK), Robbert Biesbroek (the Netherlands), Alexandre K. Magnan (France), Diana Reckien (the Netherlands/Germany), Mark New (South Africa), Lea Berrang-Ford (UK/Canada), So Min Cheong (Republic of Korea), Lisa Schipper (Sweden/USA), Robert Lempert (USA).

This Cross-Chapter Box responds to a growing demand for assessing global climate change adaptation progress, which currently faces the challenge of lacking consensus on how adaptation progress at this level can be tracked (*high confidence*). The box therefore assesses the rationale and methodological approaches for understanding adaptation progress globally across sectors and regions. It discusses strengths and weaknesses of existing approaches and sources of information, with a view towards informing the first Global Stocktake of the Paris Agreement in 2023.

Rationale for assessing adaptation progress at the global level

Global assessments of adaptation are expected to help answer key questions of climate policy (Ford et al., 2015; UNEP, 2017; Adaptation Committee, 2021) (*limited evidence*, *high agreement*), including: Do the observed, collective investments in adaptation lead humanity to being better able to avoid or reduce the negative consequences from climate change? Where is progress being made, and what gaps remain in the global adaptation response to climate risks?

While more than 170 countries have policies that address adaptation (Nachmany et al., 2019b; Section 17.4.2), very few have operational frameworks to track and evaluate implementation and results (Leiter, 2021a; Section 17.5.2.4). In Europe, for example, most countries have adopted a national adaptation plan or strategy, but only few are tracking whether ambitions are realised (EEA, 2020; Section 13.11.2). Moreover, climate risks are interconnected across scales, regions and sectors (Eakin et al., 2009; Challinor et al., 2017; Cross-Chapter Box INTERREG in Chapter 16; Hedlund et al., 2018) (*high confidence*), complicating causal attribution. National assessments of progress usually do not assess private sector and non-governmental adaptation and barely account for climate risks that transcend across borders, for example through supply chains or shared ecosystems (EEA, 2018; Benzie and Persson, 2019). In addition, adaptation action in one place or time can potentially lead to negative effects elsewhere (externalities) (Magnan and Ribera, 2016; Atteridge and Remling, 2018; 17.5.1). Hence, determining the collective adequacy and effectiveness (see Figure 1.7 in Chapter 1) of adaptation responses is different from simple aggregates of national and sub-national information (UNEP, 2017).

Assessing global progress on adaptation is therefore of high relevance to the scientific community, policymakers and other actors. Global assessments serve different information needs than local assessments, and their meaningfulness depends on the chosen approaches and their limitations. Aggregated global assessments of adaptation progress are therefore not meant to substitute place-specific ones but to complement them to enhance the knowledge base on adaptation beyond actions by or within individual countries. The Paris Agreement stipulates a Global Stocktake to be undertaken every 5 years to assess the collective progress towards its long-term goals, including on adaptation (UNFCCC, 2015, Article 14). Yet very few scientific studies have addressed the adaptation-specific aspects of the Global Stocktake (Craft and Fisher, 2018; Tompkins et al., 2018), and there are different views and options on how assessing global progress could take place (*high confidence*).

Considerations in designing global adaptation assessments

A number of key considerations for the design of global adaptation assessment approaches are discussed in the literature (Ford and Berrang-Ford, 2016; Berrang-Ford et al., 2017). Some of these involve trade-offs, such as global applicability versus context specificity, for which there is no simple solution. Design considerations directly depend on the objectives of global adaptation assessments, which can differ between actors and can include, for example, providing transparency, enabling accountability, understanding effectiveness or guiding policy development (Section 17.5.2.1). The underlying objectives determine the suitability of approaches and the data requirements.

Comparability

Global assessments may have the objective to compare adaptation over time and across sectors and regions (Ford et al., 2015). Such comparison requires a consistent definition of concepts (Hall, 2017; Berrang-Ford et al., 2019) and the identification of variables that are both generic enough to be applicable from one context to another and specific enough to illustrate national circumstances. To date, finding such balance has proven to be challenging (Dupuis and Biesbroek, 2013). The context dependence of adaptation outcomes poses limits for meaningful comparisons. Even people exposed to the same climate hazard may be differentially affected due to varying levels of vulnerability and resilience (Jones et al., 2018; Thomas et al., 2019), meaning that perceptions on adaptation outcomes can also differ (Jones and d'Errico, 2019).

Cross-Chapter Box PROGRESS (continued)

Aggregation

The aggregation of data from local or regional to global scales can take different forms ranging from qualitative synthesis to quantitative aggregation, which may involve condensing a diverse set of variables into a single score (Leiter, 2015; Section 17.5.2.3). In contrast to climate change mitigation, adaptation does not have a global reference metric against which adaptation levels could be assessed to identify progress or gaps. Experience from the Global Environment Facility, for example, has shown that mechanical aggregation based on standardised indicators fails to capture what makes the greatest difference on the ground (Chen and Uitto, 2014).

Results: Input, process, output or outcome

Adaptation progress at any spatial scale can in principle be assessed in terms of input (e.g., resources spent), process (i.e., the way adaptation is organised), output (i.e., adaptation capacities and actions) and outcomes (i.e., actual changes induced) (Section 17.5.2.2). Due to the challenges inherent in measuring adaptation outcomes (Sections 16.3, 17.5.1 and 17.5.2.5), most global assessments to date have focused on outputs, such as whether countries have adopted adaptation plans (Berrang-Ford et al., 2021; UNEP, 2021a) (*high confidence*). Understanding the effectiveness of adaptation responses globally requires a way to conceptualise and capture outcomes, for example in terms of effective climate risk reduction, while avoiding simplifications that mask maladaptation at the global level, such as where climate risks are shifted to other countries, sectors or population groups (Cross-Chapter Box INTERREG in Chapter 16, Section 17.5.1).

Data

Global assessments typically require global availability of consistent data, be they quantitative or qualitative, which has proven to be a constraining factor for attempts to assess global adaptation (*high confidence*). For example, many countries face difficulties in reporting adequately on progress in implementing the Sendai Framework and risk-related SDGs (UNDRR, 2019: vi). The availability of data also influences which variables can be eventually selected in an assessment. This limitation can affect the ability to meet the initial objectives and lead to biases in the framing and interpretation of assessment outcomes. For some variables, an alternative to relying on nationally provided data can be to develop new global data sets (Magnan and Chalastani, 2019) or utilise data from Earth Observation (Andries et al., 2018). Adaptation is hence faced with a dilemma between globally available yet generic data and regionally or locally more detailed yet patchy data (*high confidence*).

Assessment of existing approaches to assess adaptation progress at the global level

Only few global assessments of adaptation progress across sectors have been undertaken to date (*high confidence*). They focus, for example, on whether countries have progressed their adaptation policies and actions over time (Lesnikowski et al., 2015; Nachmany et al., 2019b), the extent of implemented adaptation globally (Leiter, 2021a; Leiter, 2021b), and the type and actors of responses (Berrang-Ford et al., 2021), evidence for reduced vulnerability to climate-related hazards (Formetta and Feyen, 2019; UNDRR, 2019) or adaptation planning in cities across the globe (Araos et al., 2016a; Reckien et al., 2018a; Olazabal et al., 2019a). Each of these assessments draws on different approaches and data, and all have particular potential but also limitations (Table Cross-Chapter Box PROGRESS.1) (*high confidence*). The application of differing approaches shows that there is no single 'best' approach or data source to assess global progress on adaptation (*high confidence*). Existing global assessments have provided valuable insights into the extent and types of responses and their level of planning and implementation (Section 16.3.2.4). However, they do not provide comprehensive and robust answers so far on whether climate risk and vulnerability have been reduced (Berrang-Ford et al., 2021) (*high confidence*). As a result, combining different approaches and integrating data on climate risk levels, policy measures, implemented actions and their effects on climate risk reduction is currently regarded as the most robust approach (Berrang-Ford et al., 2019) (*medium evidence*, *high agreement*).

Cross-Chapter Box PROGRESS (continued)

Table Cross-Chapter Box PROGRESS.1 | Key approaches and data sources used for global adaptation assessments.

Approach/data source	Potential added value	Limitations
Systematic assessment of adaptation responses reported in academic literature (e.g., systematic reviews, evidence synthesis, meta-analysis, large-*n* comparative studies) Examples: Berrang-Ford, 2011, Global Adaptation Mapping Initiative, Berrang-Ford et al. (2021)	Provides an indication of the status, trends and gaps in adaptation responses	Not a representative sample; biased towards responses published in scientific literature; excludes grey literature; some topics and regions not well covered; challenges in terms of comparability and aggregation; inconsistency in definitions and use of concepts; English language bias
Self-reported progress documents by countries (e.g., National Communications, Biennial Transparency Reports or domestic progress and evaluation) Examples: Gagnon-Lebrun and Agrawala (2007); Lesnikowski et al. (2015); Lesnikowski et al. (2016); Leiter (2021a)	Context-specific information; official government documents enable assessments of national progress	May only be available every few years; content is sensitive to political and policy changes; possible bias towards positive examples; challenges in terms of comparability and aggregation; inconsistency in definitions and use of concepts
Self-reported information from the private sector (e.g., information on actions taken in response to climate risks within the context of climate-related financial disclosure or in company reports). Examples: Committee on Climate Change (2017); Street and Jude (2019); UNFCCC (2021), responses reported under Climate-related Financial Disclosure	Provides an indication of the status, trends and gaps in adaptation responses by the private sector; complements information published in the scientific literature; could enable better understanding of supply chain risks	Sample biased towards larger companies; challenges in terms of comparability and aggregation; potential inconsistencies in definitions and use of concepts
Project documents and evaluations (e.g., from climate funds or implementing organisations) Examples: Leiter (2021b); Eriksen et al. (2021)	Detailed information on context, intended or achieved results and activities	Actual implementation can differ from what was proposed; fragmented picture of local/regional actions; results may be challenging to aggregate; challenges in terms of comparability and aggregation; inconsistency in definitions and use of concepts
Existing global data sets of mostly quantitative indicators Examples: United Nations (UN, 2016a; UN, 2016b; UN, 2019; UNDRR, 2019)	Comparable information based on globally defined indicators	Global data availability constrains indicator choice; reporting burden for new indicators; trade-off between global applicability and national circumstances; usefulness and meaningfulness of global indicators is contested (Leiter and Pringle, 2018; Lyytimäki et al., 2020; Pauw et al., 2020).
Tracking financial flows Examples: CPI (2019), OECD (2018a), MDBs (2019)	Comparable data on financial flows directed at adaptation; standardised methodologies (e.g., OECD RIO markers; climate finance tracking method of multi-lateral development banks; Section 17.5.2.6; Cross-Chapter Box FINANCE in this Chapter)	No information about implementation of measures and their adaptation effect (Eriksen et al, 2021), i.e., it tracks inputs, not outputs or outcomes; inconsistency in what gets counted as adaptation finance (Donner et al., 2016; Doshi and Garschagen, 2020); evidence of over-reporting (Michaelowa and Michaelowa, 2011; Weikmans et al., 2017)

Conclusion—Combining approaches for assessing adaptation progress at the global level

Understanding to what extent the world is on track to adapt to climate change impacts and risks globally is a pressing question in scientific and policy communities, especially in light of the Global Stocktake under the Paris Agreement. Important considerations for a robust assessment framework (e.g., consistency), as well as the associated scientific challenges (e.g., aggregation, externalities, breadth versus depth of data) and the role of underlying objectives (e.g., on the contested issue of comparability) are increasingly understood (*high confidence*). There is also a growing and diverse body of information on adaptation progress, although most assessments of global progress undertaken to date focus on processes and outputs (e.g., policies and plans) rather than outcomes (i.e., risk reduction). A variety of approaches and data sources are employed, such as systematic reviews of observed adaptation, formal communications by Parties to the UNFCCC, and project documents to international funding agencies. Novel approaches, including big data tools (Ford et al., 2016; Biesbroek et al., 2020), are also being explored but still have to prove their practical value. Each approach and source of information can contribute additional knowledge, but also demonstrates limitations, so that there is no single 'best' approach (*high confidence*). Yet, to date, the international community has not sufficiently explored the relative strengths and weaknesses of different approaches and their applicability and, therefore, their potential synergies in complementing each other. Triangulated assessments have only rarely been applied (*high confidence*) due to multiple conceptual and methodological challenges, despite their potential for increasing the robustness of knowledge. One overarching conclusion of this Cross-Chapter Box therefore is that the combination of different approaches will provide a more comprehensive picture of global adaptation progress than is currently available from individual approaches (*limited evidence*, *high agreement*).

Cross-Chapter Box GENDER | Gender, Climate Justice and Transformative Pathways

Authors: Anjal Prakash (India), Cecilia Conde (Mexico), Ayansina Ayanlade (Nigeria), Rachel Bezner Kerr (Canada/USA), Emily Boyd (Sweden), Martina A Caretta (Sweden), Susan Clayton (USA), Marta G. Rivera Ferre (Spain), Laura Ramajo Gallardo (Chile), Sharina Abdul Halim (Malaysia), Nina Lansbury (Australia), Oksana Lipka (Russia), Ruth Morgan (Australia), Joyashree Roy (India), Diana Reckien (the Netherlands/Germany), E. Lisa F. Schipper (Sweden/UK), Chandni Singh (India), Maria Cristina Tirado von der Pahlen (Spain/USA), Edmond Totin (Benin), Kripa Vasant (India), Morgan Wairiu (Solomon Islands), Zelina Zaiton Ibrahim (Malaysia).

Contributing Authors: Seema Arora-Jonsson (Sweden/India), Emily Baker (USA), Graeme Dean (Ireland), Emily Hillenbrand (USA), Alison Irvine (Canada), Farjana Islam (Bangladesh/ UK), Katriona McGlade (UK/Germany), Hanson Nyantakyi-Frimpong (Ghana), Nitya Rao (UK/India), Federica Ravera (Italy), Emilia Reyes (Mexico), Diana Hinge Salili (Fiji), Corinne Schuster-Wallace (Canada), Alcade C. Segnon (Benin), Divya Solomon (India), Shreya Some (India), Indrakshi Tandon (India), Sumit Vij (India), Katharine Vincent (UK/South Africa), Margreet Zwarteveen (the Netherlands)

Key Messages

- Gender and other social inequities (e.g., racial, ethnic, age, income, geographic location) compound vulnerability to climate change impacts (*high confidence*). Climate justice initiatives explicitly address these multi-dimensional inequalities as part of a climate change adaptation strategy (Box 9.2: Vulnerability Synthesis: Differential Vulnerability by Gender and Age in Chapter 9).
- Addressing inequities in access to resources, assets and services, as well as participation in decision making and leadership is essential to achieving gender and climate justice (*high confidence*).
- Intentional long-term policy and programme measures and investments to support shifts in social rules, norms and behaviours are essential to address structural inequalities and support an enabling environment for marginalised groups to effectively adapt to climate change (*very high confidence*) (Equity and Justice box in Chapter 17).
- Climate adaptation actions are grounded in local realities so understanding links with Sustainable Development Goal (SDG) 5 is important to ensure that adaptive actions do not worsen existing gender and other inequities within society (e.g., leading to maladaptation practices) (*high confidence*). [Section 17.5.1]
- Adaptation actions do not automatically have positive outcomes for gender equality. Understanding the positive and negative links of adaptation actions with gender equality goals, (i.e., SDG 5), is important to ensure that adaptive actions do not exacerbate existing gender-based and other social inequalities [Section 16.1.4.4]. Efforts are needed to change unequal power dynamics and to foster inclusive decision making for climate adaptation to have a positive impact for gender equality (*high confidence*).
- There are very few examples of successful integration of gender and other social inequities in climate policies to address climate change vulnerabilities and questions of social justice (*very high confidence*).

Gender, Climate Justice and Climate Change

This Cross-Chapter Box highlights the intersecting issues of gender, climate change adaptation, climate justice and transformative pathways. A gender perspective does not centre only on women or men but examines structures, processes and relationships of power between and among groups of men and women and how gender, particularly in its non-binary form, intersects with other social categories such as race, class, socioeconomic status, nationality or education to create multi-dimensional inequalities (Hopkins, 2019). A gender transformative approach aims to change structural inequalities. Attention to gender in climate change adaptation is thus central to questions of climate justice that aim for a radically different future (Bhavnani et al., 2019). As a normative concept highlighting the unequal distribution of climate change impacts and opportunities for adaptation and mitigation, climate justice (Wood, 2017; Jafry et al., 2018; Chu and Michael, 2019; Shi, 2020a) calls for transformative pathways for human and ecological well-being. These address the concentration of wealth, unsustainable extraction and distribution of resources (Schipper et al., 2020a; Vander Stichele, 2020) as well as the importance of equitable participation in environmental decision making for climate justice (Arora-Jonsson, 2019).

Research on gender and climate change demonstrates that an understanding of gendered relations is central to addressing the issue of climate change. This is because gender relations mediate experiences with climate change, whether in relation to water (Köhler et al., 2019) (see also Sections 4.7, 4.3.3, 4.6.4, 5.3), forests (Arora-Jonsson, 2019), agriculture (Carr and Thompson, 2014; Balehey et al., 2018; Garcia et al., 2020) (see also Chapter 4, Section 5.4), marine systems (Mcleod et al., 2018; Garcia et al., 2020) (see also Section 5.9) or urban environments (Reckien et al., 2018; Susan Solomon et al., 2021) (see also Chapter 6). Climate change has direct negative impacts on women's livelihoods due to their unequal control over and access to resources (e.g., land, credit) and because they are often the ones with the least formal protection (Eastin, 2018) (see also Box 9.2 in Chapter 9). Women represent 43% of the agricultural labour force globally, but only 15% of agricultural landholders (OECD, 2019b). Gendered and other social inequities also exist with non-land assets and financial services (OECD, 2019b) often due to social norms, local institutions and inadequate social protection (Collins et al., 2019b). Men may experience different adverse impacts due to gender roles and expectations (Bryant and Garnham, 2015; Gonda, 2017). These impacts can lead to irreversible losses and damages from climate change across vulnerability hotspots (Section 8.3).

Cross-Chapter Box GENDER (continued)

Participation in environmental decision making tends to favour certain social groups of men, whether in local environmental committees, international climate negotiations (Gay-Antaki and Liverman, 2018) or the IPCC (Nhamo and Nhamo, 2018). Addressing climate justice reinforces the importance of considering the legacy of colonialism on developing regional and local adaptation strategies. Scholars have criticised climate programmes for setting aside forestland that poor people rely on and appropriating the labour of women in the Global South without compensatory social policy or rights; where women are expected to work with non-timber forest products to compensate for the lack of logging and for global climate goals, but where their work of social reproduction and care is paid little attention (Westholm and Arora-Jonsson, 2015; Arora-Jonsson et al., 2016). A global ecologically unequal exchange, biopiracy, damage from toxic exports or the disproportionate use of carbon sinks and reservoirs by high-income countries enhance the negative impacts of climate change. Women in Least Developed Countries (LDCs) and Small Island Developing States (SIDS) also endure the harshest impacts of the debt crisis due to imposed debt measures in their countries (Appiah and Gbeddy, 2018; Fresnillo Sallan, 2020). The austerity measures derived as conditionalities for fiscal consolidation in public services increases gender-based violence (Castañeda Carney et al., 2020) and brings additional burdens for women in the form of increasing unpaid care and domestic work (Bohoslavsky, 2019).

Gendered Vulnerability

Land, ecosystem and urban transitions to climate resilient development need to address gender and other social inequities to meet sustainability and equity goals, otherwise, marginalised groups may continue to be excluded from climate change adaptation. In the water sector, increasing floods and droughts and diminishing groundwater and runoff have gendered effects on both production systems and domestic use (Sections 4.3.1, 4.3.3, 4.5.3). Climate change is reducing the quantity and quality of safe water available in many regions of the world and increasing domestic water management responsibilities (*high confidence*). In regions with poor drinking water infrastructure, it is forcing, primarily women and girls, to walk long distances to access water, and limiting time available for other activities, including education and income generation (Eakin et al., 2014; Kookana et al., 2016; Yadav and Lal, 2018). Water insecurity and the lack of water, sanitation and hygiene (WASH) infrastructure have resulted in psychosocial distress and gender-based violence, as well as poor maternal and child health and nutrition (Collins et al., 2019a; Wilson et al., 2019; Geere and Hunter, 2020; Islam et al., 2020; Mainali et al., 2020) (Sections 4.3.3 and 4.6.4.4) (*high confidence*). Climate-related extreme events also affect women's health—by increasing the risk of maternal and infant mortality, disrupting access to family planning and prevention of mother to child transmission regimens for human immunodeficiency virus (HIV) positive pregnant women (UNDRR, 2019) (see also Section 7.2). Women and the elderly are also disproportionately affected by heat events (Sections 7.1.7.2.1, 7.1.7.2.3, 13.7.1).

Extreme events impact food prices and reduce food availability and quality, especially affecting vulnerable groups, including low-income urban consumers, wage labourers and low-income rural households who are net food buyers (Green et al., 2013; Fao, 2016) (Section 5.12). Low-income women, ethnic minorities and Indigenous communities are often more vulnerable to food insecurity and malnutrition from climate change impacts, as poverty, discrimination and marginalisation intersect in their cases (Vinyeta et al., 2016; Clay et al., 2018) (Section 5.12). Increased domestic responsibilities of women and youth, due to migration of men, can increase their vulnerability due to their reduced capacity for investment in off-farm activities and reduced access to information (Sugden et al., 2014; O'Neil et al., 2017) (Sections 4.3, 4.6) (*high confidence*).

In the forest sector, the increased frequency and severity of drought, fires, pests and diseases, and changes to growing seasons, has led to reduced harvest revenues, fluctuations in timber supply and availability of wood (Lamsal et al., 2017; Fadrique et al., 2018; Esquivel-Muelbert et al., 2019). Climate programmes in the Global South such as REDD+ have led to greater social insecurity and the conservation of the forests have led to more pressure on women to contribute to household incomes, but without enough supporting market access mechanisms or social policy (Westholm and Arora-Jonsson, 2015; Arora-Jonsson et al., 2016). In countries in the Global North, reduced harvestable wood and revenues have led to employment restructuring that has important gendered effects and negatively affects community transition opportunities (Reed et al., 2014).

Integrating Gender in Climate Policy and Practice

Climate change policies and programmes across regions reveal wide variation in the degree and approach to addressing gender inequities (see Table SMCCB GENDER.2). In most regions where there are climate change policies that consider gender, they inadequately address structural inequalities resulting from climate change impacts, or how gender and other social inequalities can compound risk (*high confidence*). Experiences show that it is more frequent to address specific gender inequality gaps in access to resources. Regionally, Central and South American countries (Section 12.5.8) have a range of gender-sensitive or gender-specific policies such as the intersectoral coordination initiative Gender and Climate Change Action Plans (PAGcc), adopted in Perú, Cuba, Costa Rica and Panamá (Casas Varez, 2017), or the Gender Environmental policy in Guatemala that has a focus on climate change (Bárcena-Martín et al., 2021). However, countries often have limited commitment and capacity to evaluate the impact of such policies (Tramutola, 2019). In North and South America, policies have failed to address how climate change vulnerability is compounded by the intersection of race, ethnicity and gender (Radcliffe, 2014; Vinyeta et al.,

Cross-Chapter Box GENDER (continued)

2016) (see also Section 14.6.3). Gender is rarely discussed in African national policies or programmes beyond the initial consultation stage (Holvoet and Inberg, 2014; Mersha and van Laerhoven, 2019), although there are gender and climate change action strategies in countries such as Liberia, Mozambique, Tanzania and Zambia (Mozambique and IUCN, 2014; Zambia and IUCN, 2017). European climate change adaptation strategies and policies are weak on gender and other social equity issues (Allwood, 2014; Boeckmann and Zeeb, 2014; Allwood, 2020), while in Australasia, there is a lack of gender-responsive climate change policies. In Asia, there are several countries that recognise gendered vulnerability to climate change (Jafry, 2016; Singh et al., 2021b), but policies tend to be gender-specific, with a focus on targeting women, for example in the national action plan on climate change as in India (Roy et al., 2018) or in national climate change plan as in Malaysia (Susskind et al., 2020).

Potential for Change and Solutions

The sexual division of labour, systemic racism and other social structural inequities lead to increased vulnerabilities and climate change impacts for social groups such as women, youth, Indigenous peoples and ethnic minorities. Their marginal positions not only affect their lives negatively but their work in maintaining healthy environments is ignored and invisible in policy affecting their ability to work towards sustainable adaptation and aspirations in the SDGs (Arora-Jonsson, 2019). However, attention to the following has the potential to bring about change:

Creation of new, deliberative policymaking spaces that support inclusive decision making processes and opportunities to (re)negotiate pervasive gender and other social inequalities in the context of climate change for transformation (Tschakert et al., 2016; Harris et al., 2018; Ziervogel, 2019; Garcia et al., 2020) (*high confidence*).

Increased access to reproductive health and family planning services, which contributes to climate change resilience and socioeconomic development through improved health and well-being of women and their children, including increased access to education, gender equity and economic status (Onarheim et al., 2016; Starbird et al., 2016; Lopez-Carr, 2017; Hardee et al., 2018) (Section 7.4) (*high confidence*).

Engagement with women's collectives is important for sustainable environments and better climate decision making whether at the global, national or local levels (Westholm and Arora-Jonsson, 2018; Agarwal, 2020). The work of such collectives in maintaining their societies and environments and in resisting gendered and community violence is unacknowledged (Jenkins, 2017; Arora-Jonsson, 2019) but is indispensable especially when combined with good leadership, community acceptance and long-term economic sustainability (Chu, 2018; Singh, 2019) (Section 4.6.4). Networking by gender experts in environmental organisations and bureaucracies has also been important for ensuring questions of social justice (Arora-Jonsson and Sijapati, 2018).

Investment in appropriate reliable water supplies, storage techniques and climate-proofed WASH infrastructure as key adaptation strategies that reduce both burdens and impacts on women and girls (Alam et al., 2011; Woroniecki, 2019) (Sections 4.3.3, 4.6.44).

Improved gender-sensitive early warning system design and vulnerability assessments to reduce vulnerabilities, prioritising effective adaptation pathways to women and marginalised groups (Mustafa et al., 2019; Tanner et al., 2019; Werners et al., 2021).

Established effective social protection, including both cash and food transfers, such as the universal public distribution system (PDS) for cereals in India, or pensions and social grants in Namibia, that have been demonstrated to contribute towards relieving immediate pressures on survival and support processes at the community level, including climate effects (Kattumuri et al., 2017; Lindoso et al., 2018; Rao et al., 2019a; Carr, 2020).

Strengthened adaptive capacity and resilience through integrated approaches to adaptation that include social protection measures, disaster risk management and ecosystem-based climate change adaptation (*high confidence*), particularly when undertaken within a gender-transformative framework (Gumucio et al., 2018; Bezner Kerr et al., 2019; Deaconu et al., 2019) (Cross-Chapter Box NATURAL in Chapter 2, Sections 5.12, 5.14).

For example, gender-transformative and nutrition-sensitive agroecological approaches strengthen adaptive capacities and enable more resilient food systems by increasing leadership for women and their participation in decision making and a gender-equitable domestic work (*high confidence*) (Gumucio et al., 2018; Bezner Kerr et al., 2019; Deaconu et al., 2019) (Cross-Chapter Box NATURAL in Chapter 2, Sections 5.12, 5.14)

New initiatives, such as the Sahel Adaptive Social Protection Program, represent an integrated approach to resilience that promotes coordination among social protection, disaster risk management and climate change adaptation. Accompanying measures include health, education, nutrition and family planning, among others (Daron et al., 2021).

Cross-Chapter Box GENDER (continued)

Climate Change Adaptation and SDG 5

Adaptation actions may reinforce social inequities, including gender, unless explicit efforts are made to change (Nagoda and Nightingale, 2017; Garcia et al., 2020) (*robust evidence*, *high agreement*). Participation in climate action increases if it is inclusive and fair (Huntjens and Zhang, 2016). Roy et al. (2018) assessed links among various SDGs and mitigation options. Adaptation actions are grounded in local realities, especially in terms of their impacts, so understanding links with the goals of SDG 5 becomes more important to make sure that adaptive actions do not worsen prevalent gender and other social inequities within society (*robust evidence*, *high agreement)*. In the IPCC 1.5°C Special Report, Roy et al. (2018) assessed links between various SDGs and mitigation options, adaptation options were not considered. The current SDG 13 climate action targets do not specifically mention gender as a component for action, which makes it even more imperative to link SDG 5 targets and other gender-related targets to adaptive actions under SDG 13 to ensure that adaptation projects are synergistic rather than maladaptive (Section 16.3.2.6, Table 16.6) (Susan Solomon et al., 2021; Roy et al., Submitted).

This assessment is based on a systematic rapid review of scientific publications (McCartney et al., 2017; Liem et al., 2020) published on adaptation actions in nine sectors from 2014 to 2020 (see Table SMCCB GENDER.1) (Roy et al., Submitted)(Roy et al., Submitted)(Roy et al., Submitted)and how they integrated gender perspectives impacting gender equity. The assessment is based on over 17,000 titles and abstracts that were initially found through keyword search and were reviewed. Finally, 319 relevant papers on case studies, regional assessments and meta-reviews were assessed. Gender impact was classified by various targets under SDG 5. Following the approach taken in Roy et al. (2018) and (Hoegh-Guldberg et al., 2019), the linkages were classified into synergies (positive impacts or co-benefits) and trade-offs (negative impacts) based on the evidence obtained from the literature review which is finally used to develop net impact (positive or negative) scores (see Table Cross-Chapter Box GENDER.1 and Supplementary Material).

Table Cross-Chapter Box GENDER.1 | Inter-relations between SDG5 (gender equality) and adaptation initiatives in nine major sectors

5 GENDER EQUALITY

Sector	Adaptation categories: Ecosystem-based	Technological/ infrastructure/ information	Institutional	Behavioural/ cultural
Terrestrial and freshwater ecosystem	All net positive links (low)	/	All net positive links (low)	/
Ocean and coastal ecosystem	All net positive links (low)	All net positive links (very low)	All net negative links (medium)	/
Mountain ecosystem	Net positive links > net negative links (very low)	All net positive links (low)	All net positive links (very low)	Net negative links > net positive links (low)
Food, fibre and others	All net positive links (low)	/	Net positive links > net negative links (low)	Net negative links > net positive links (low)
Urban water and sanitation	All net positive links (very low)	Net positive links > net negative links (low)	/	Net positive links > net negative links (low)
Poverty, livelihood and sustainable development	/	/	All net negative links (very low)	Net negative links > net positive links (low)
Cities, settlements and key infrastructure	All net positive links (low)	Net negative links > net positive links (low)	All net negative links (low)	All net positive links (medium)
Health, well-being, and changing communities' structure	All net positive links (high)	All net positive links (low)	All net positive links (medium)	All net negative links (low)
Industrial system transition	/	/	All net negative links (low)	All net positive links (medium)

Links with Sustainable Development Goal 5: Gender Equality
- All net positive links
- Net positive links > net negative links
- Net negative links > net positive links
- All net negative links
- / no literature/options

Confidence level
- High
- Medium
- Low
- Very low

Potential net synergies and trade-offs between a sectoral portfolio of adaptation actions and SDG 5 are shown. Colour codes showing the relative strength of net positive and net negative impacts and confidence levels. The strength of net positive and net negative connections across all adaptation actions within a sector are aggregated to show sector-specific links. The links are only one-sided on how adaptation action is linked to gender equality (SDG 5) targets and not vice versa. 22 adaptation options were assessed in ecosystem-based actions, 10 options in technological/infrastructure/information, 17 in institutional and 13 in behavioural/cultural. The assessment presented here is based on literature presenting impacts on gender equality and equity of various adaptation actions implemented in various local contexts and in regional climate change policies (Table SMCCB GENDER.2).

Adaptation actions being implemented in each sector in different local contexts can have positive (synergies) or negative (trade-offs) effects with SDG 5. This can potentially lead to net positive or net negative connections at an aggregate level. How they are finally realised depends on how they are implemented, managed and combined with various other interventions, in particular, place-based circumstances. Ecosystem-based adaptation actions and terrestrial and freshwater ecosystems have higher potential for net positive connections (Roy et al., 2018) (Table Cross-Chapter Box GENDER.1 and Supplementary Material). Adaptation in terrestrial and freshwater ecosystems has the strongest net positive links with all SDG 5 targets (*medium evidence*, *low agreement*). For example, community-based natural resource management increases the participation of women, especially when they are organised into women's groups (Pineda-López

Cross-Chapter Box GENDER (continued)

et al., 2015; de la Torre-Castro et al., 2017) (Supplementary Material). For poverty, livelihood and sustainable development sectors, adaptation actions have generated more net negative scores (*limited evidence*, *low agreement*) (Table Cross-Chapter Box GENDER.1). For example, patriarchal institutions and structural discriminations curtail access to services or economic resources as compared with men, including less control over income, fewer productive assets and lack of property rights, as well as less access to credit, irrigation, climate information and seeds which devaluate women's farm-related adaptation options (Adzawla et al., 2019; Friedman et al., 2019; Ullah et al., 2019) (Supplementary Material).

Among the adaptation actions, ecosystem-based actions have the strongest net positive links with SDG 5 targets (Table Cross-Chapter Box GENDER.1, Table SMCCB GENDER.1). In the health, well-being and changing communities' sector, this is with *robust evidence* and *medium agreement*, while in all other sectors there is *medium evidence* and *low agreement*. Net negative links are most prominent in institutional adaptation actions (Table Cross-Chapter Box GENDER.1). For example, in mountain ecosystems, changes in gender roles in response to climatic and socioeconomic stressors is not supported by institutional practices, mechanisms and policies that remain patriarchal (Goodrich et al., 2019). Additionally, women often have less access to credit for climate change adaptation practices, including post-disaster relief, for example, to deal with salinisation of water or flooding impacts (Hossain and Zaman 2018). Lack of coordination among different city authorities can also limit women's contribution in informal settlements towards adaptation. Women are typically under-represented in decision making on home construction and planning and home-design decisions in informal settlements, but examples from Bangladesh show they play a significant role in adopting climate-resilient measures (e.g., the use of corrugated metal roofs and partitions which is important in protection from heat) (Jabeen, 2014; Jabeen and Guy, 2015; Araos et al., 2017; Susan Solomon et al., 2021).

Towards Climate-Resilient, Gender-Responsive Transformative Pathways

The climate change adaptation and gender literature call for research and adaptation interventions that are 'gender-sensitive' (Jost et al., 2016; Thompson-Hall et al., 2016; Kristjanson et al., 2017; Pearce et al., 2018a) and 'gender-responsive', as established in Article 7 of the Paris Agreement (UNFCCC, 2015). In addition, attention is drawn to the importance of 'mainstreaming' gender in climate/development policy (Alston, 2014; Rochette, 2016; Mcleod et al., 2018; Westholm and Arora-Jonsson, 2018). Many calls have been made to consider gender in policy and practice (Ford et al., 2015; Jost et al., 2016; Rochette, 2016; Thompson-Hall et al., 2016; Kristjanson et al., 2017; Mcleod et al., 2018; Lau et al., 2021; Singh et al., 2021b). Rather than merely emphasising the inclusion of women in patriarchal systems, transforming systems that perpetuate inequality can help to address broader structural inequalities not only in relation to gender, but also other dimensions such as race and ethnicity (Djoudi et al., 2016; Pearse, 2017; Gay-Antaki, 2020). Adaptation researchers and practitioners play a critical role here and can enable gender-transformative processes by creating new, deliberative spaces that foster inclusive decision making and opportunities for renegotiating inequitable power relations (Tschakert et al., 2016; Ziervogel, 2019; Garcia et al., 2020).

To date, empirical evidence on such transformational change is sparse, although there is some evidence of incremental change (e.g., increasing women's participation in specific adaptation projects, mainstreaming gender in national climate policies). Even when national policies attempt to be more gendered, there is criticism that they use gender-neutral language or include gender analysis without proposing how to alter differential vulnerability (Mersha and van Laerhoven, 2019; Singh et al., 2021b). More importantly, the mere inclusion of women and men in planning does not necessarily translate to substantial gender-transformative action, for example in National Adaptation Programmes of Action across sub-Saharan Africa (Holvoet and Inberg, 2014; Nyasimi et al., 2018) and national and sub-national climate action plans in India (Singh et al., 2021b). Importantly, there is often an overemphasis on the gender binary (and household headship as an entry point), which masks complex ways in which marginalisation and oppression can be augmented due to the interaction of gender with other social factors and intra-household dynamics (Djoudi et al., 2016; Thompson-Hall et al., 2016; Rao et al., 2019a; Lau et al., 2021; Singh et al., 2021b).

Climate justice and gender transformative adaptation can provide multiple beneficial impacts that align with sustainable development. Addressing poverty (SDG 1), energy poverty (SDG 7), WaSH (SDG 6), health (SDG 3), education (SDG 4) and hunger (SDG 2)—along with inequalities (SDG 5 and SDG 10)—improves resilience to climate impacts for those groups that are disproportionately affected (women, low-income and marginalised groups). Inclusive and fair decision making can enhance resilience (SDG 16; Section 13.4.4), although adaptation measures may also lead to resource conflicts (SDG 16; Section 13.7). Nature-based solutions attentive to gender equity also support ecosystem health (SDGs 14 and 15) (Dzebo et al., 2019). Gender and climate justice will be achieved when the root causes of global and structural issues are addressed, challenging unethical and unacceptable use of power for the benefit of the powerful and elites (MacGregor, 2014; Wijsman and Feagan, 2019; Vander Stichele, 2020). Justice and equality need to be at the centre of climate adaptation decision-making processes. A transformative pathway needs to include the voice of the disenfranchised (MacGregor, 2020; Schipper et al., 2020a).

Cross-Chapter Box INDIG | The Role of Indigenous Knowledge and Local Knowledge in Understanding and Adapting to Climate Change

Authors: Tero Mustonen (Finland), Sherilee Harper (Canada), Gretta Pecl (Australia), Vanesa Castán Broto (Spain), Nina Lansbury (Australia), Andrew Okem (Nigeria/South Africa), Ayansina Ayanlade (Nigeria), Jackie Dawson (Canada), Pauline Harris (Aotearoa-New Zealand), Pauliina Feodoroff (Finland), Deborah McGregor (Canada)

Indigenous knowledge refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings (UNESCO, 2018; IPCC, 2019a). Local knowledge refers to the understandings and skills developed by individuals and populations, specific to the places where they live (UNESCO, 2018; IPCC, 2019a). Indigenous knowledge and local knowledge are inherently valuable but have only recently begun to be appreciated and in western scientific assessment processes in their own right (Ford et al., 2016). In the past these often endangered ways of knowing have been suppressed or attacked (Mustonen, 2014). Yet these knowledge systems represent a range of cultural practices, wisdom, traditions and ways of knowing the world that provide accurate and useful climate change information, observations and solutions (*very high confidence*) (Table Cross-Chapter Box INDIG.1). Rooted in their own contextual and relative embedded locations, some of these knowledges represent unbroken engagement with the earth, nature and weather for many tens of thousands of years, with an understanding of the ecosystem and climatic changes over longer-term timescales that is held both as knowledge by Indigenous Peoples and local peoples, as well as in the archaeological record (Barnhardt and Angayuqaq, 2005; UNESCO, 2018).

Indigenous Peoples around the world often hold unique worldviews that link today's generations with past generations. In particular, many Indigenous Peoples consider concepts of responsibility through intergenerational equity, thereby honouring both past and future generations (Matsui, 2015; McGregor et al., 2020). This can often be in sharp contrast to environmental valuing and decision making that occurs in Western societies (Barnhardt and Angayuqaq, 2005). Therefore, consideration of Indigenous knowledge and local knowledge needs to be a priority in the assessment of adaptation futures (Nakashima et al., 2012); Ford et al., 2016) (Chapter 1), although adequate indigenous cultural and intellectual property rights require legal and non-legal measures for recognition and protection (Janke, 2018).

Indigenous knowledge and local knowledge are crucial to address environmental impacts, such as climate change, where the uncertainty of outcome is high and a range of responses are required (Mackey and Claudie, 2015). However, working with this knowledge in an appropriate and ethically acceptable way can be challenging. For instance, questions of data 'validity' and the requirement to communicate such knowledge in the dominant language can lead to inaccurate portrayals of Indigenous knowledge as inferior to science. This may overlook the uniqueness of Indigenous knowledge and then lead to the overall devaluation of indigenous political economies, cultural ecologies, languages, educational systems and spiritual practices (Smith, 2013; Sillitoe, 2016; Naude, 2019; Barker and Pickerill, 2020). Furthermore, Indigenous knowledge is too often only sought superficially—focusing only on the 'what', rather than the 'how' of climate change adaptation and/or seen through the lenses of 'romantic glorification' leaving little room for the knowledge to be expressed as authored by the communities and knowledge holders themselves (Yunkaporta, 2019).

Multiple knowledge systems and frameworks

Indigenous knowledge systems include not only the specific narratives and practices to make sense of the world, but also profound sources of ethics and wisdom. They are networks of actors and institutions that organise the production, transfer and use of knowledge (Löfmarck and Lidskog, 2017). There is a pluralism of forms of knowledge that emerge from oral traditions, local engagement with multiple spaces, and Indigenous cultures (Peterson et al., 2018). Recognising such multiplicity of forms of knowledge has long been an important concern within sustainability science (Folke et al., 2016). Less dominant forms of knowledge should not be put aside because they are not comparable or complementary with scientific knowledge (Brattland and Mustonen, 2018; Mustonen, 2018; Ford et al., 2020; Ogar et al., 2020). Instead, Indigenous knowledge and local knowledge can shape how climate change risk is understood and experienced, the possibility of developing climate change solutions grounded in place-based experiences, and the development of governance systems that match the expectations of different Indigenous knowledge and local knowledge holders (*very high confidence*).

Different frameworks that enable the inclusion of Indigenous knowledge have emerged from efforts to utilise more than one knowledge system (*robust evidence*, *high agreement*). For example, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has developed a 'nature's contribution to peoples' framework that provides a common conceptual vocabulary and structural analysis (Díaz et al., 2015; Tengö et al., 2017; Díaz et al., 2018; Peterson et al., 2018). The IPBES approach complements other efforts to study areas of intersection between scientific and indigenous worldviews (Barnhardt and Angayuqaq, 2005; Huaman and Sriraman, 2015) or 'boundaries' that illustrate 'blind spots' in scientific knowledge (Cash et al., 2003; Clark et al., 2016; Brattland and Mustonen, 2018). These frameworks highlight areas of collaboration but provide less guidance in areas where sources of evidence conflict across different knowledge systems (Löfmarck and Lidskog, 2017). These experiences suggest that the inclusion of Indigenous knowledge and local knowledge in international assessments may transform the process of assessment of scientific, technical and

Cross-Chapter Box INDIG (continued)

socioeconomic evidence (*medium evidence*, *high agreement*). These knowledge systems also point to novel discoveries that may be still unknown to the scientific world but have been known by communities for millennia (Mustonen and Feodoroff, 2020).

The importance of free and prior-informed consent

Obtaining free and prior-informed consent is a necessary but not sufficient condition to engage in knowledge production with Indigenous Peoples (Sillitoe, 2016). Self-determination in climate change assessment, response and governance is critical (Chakraborty and Sherpa, 2021), and Indigenous Peoples are actively contributing to respond to climate change (Etchart, 2017). Climate change assessment and adaptation should be self-determined and led by Indigenous Peoples, acknowledge the importance of developing genuine partnerships, respect Indigenous knowledge and ways of knowing, and acknowledge Indigenous Peoples as stewards of their environment (Country et al., 2016; Country et al., 2018; ITK, 2019; Barker and Pickerill, 2020; Chakraborty and Sherpa, 2021). Supporting Indigenous Peoples' leadership and rights in climate adaptation options at the local, regional, national and international levels is an effective way to ensure that such options are adapted to their living conditions and do not pose additional detrimental impacts to their lives (*very high confidence*). Chapter 18 shows that the transformations required to deliver climate-resilient futures will create societal disruptions, with impacts that are most often unevenly experienced by groups with high exposure and sensitivity to climate change, including Indigenous Peoples and local communities (Schipper et al., 2020a). Climate-resilient futures depend on finding strategies to address the causes and drivers of deep inequities (Chapter 18). For example, climate-resilient futures will depend on recognising the socioeconomic, political and health inequities that often affect Indigenous Peoples (Mapfumo et al., 2016; Ludwig and Poliseli, 2018) (*very high confidence*).

International conventions to support and utilise Indigenous knowledge and local knowledge

Several tools within international conventions may support instruments to develop equitable processes that facilitate the inclusion of Indigenous knowledge and leadership in climate change adaptation initiatives. The International Labour Convention 69 recognised Indigenous People's right to self-determination in 1989 (ILO, 1989). The United Nations' Declaration on the Rights of Indigenous Peoples (United Nations, 2007) includes articles on the right to development (Article 23), the right to maintain and strengthen their distinctive spiritual relationship and to uphold responsibilities to future generations (Article 25), and the right to the conservation and protection of the environment and the productive capacity of their territories (Article 29). Article 26 upholds the right to the lands, territories and resources, the right to own, use, develop and control the lands, and legal recognition and protection of these lands, territories and resources. Indigenous Peoples are also recognised within the Sustainable Development Goals as a priority group (Carino and Tamayo, 2019). International events such as the 'Resilience in a time of uncertainty: Indigenous Peoples and Climate Change' conference brought together Indigenous Peoples' representatives and government leaders from around the world to discuss the role of Indigenous Peoples in climate adaptation (UNESCO, 2015).

The value of Indigenous knowledge and local knowledge in climate adaptation planning

There have been increasing efforts to enable Indigenous knowledge holders to participate directly in IPCC assessment reports (Ford et al., 2012; Nakashima et al., 2012; Ford et al., 2016). Adaptation efforts have benefited from the inclusion of Indigenous knowledge and local knowledge (IPCC, 2019e) (*very high confidence*). Moreover, it has been recognised that including Indigenous knowledge and local knowledge in IPCC reports can contribute to overcoming the combined challenges of climate change, food security, biodiversity conservation, and combating desertification and land degradation (IPCC, 2019c) (*high confidence*). Limiting warming to 1.5°C necessitates building the capability of formal assessment processes to respect, include and utilise Indigenous knowledge and local knowledge (IPCC, 2018a) (*medium evidence*, *high agreement*).

However, these efforts have been accompanied by a recognition that 'integration' of Indigenous knowledge and local knowledge cannot mean that those knowledge systems are subsumed or required to be validated through typical scientific means (Gratani et al., 2011; Matsui, 2015). Such a critique of 'validity' can be inappropriate, unnecessary, can disrespect Indigenous Peoples' own identities and histories, limits the advancement and sharing of these perspectives in the formal literature, and overlooks the structural drivers of oppression and endangerment that are associated with Western civilisation (Ford et al., 2016). Moreover, by underutilising Indigenous knowledge and local knowledge systems, opportunities that could otherwise facilitate effective and feasible adaptation action can be overlooked. We should also reserve space for the understanding that each cultural knowledge system, building on linguistic-cultural endemicity, is unique and inherently valuable.

Indigenous Peoples have often constructed their ways of knowing using oral histories as one of the vehicles of mind and memory, observance, governance and maintenance of customary law (Table Cross-Chapter Box INDIG.2). These ways of knowing can also incorporate the relationships between multiple factors simultaneously which adds particular value towards understanding complex systems that is in contrast to the dominant reductionist, Western approach, noting that non-reductionist approaches also exist (Ludwig et al., 2014; Hoagland, 2017).

Cross-Chapter Box INDIG (continued)

For climate research, the role of oral histories as a part of Indigenous knowledge and local knowledge is extremely relevant. For example, ocean adaptation initiatives can be guided by oral historians and keepers of knowledge who can convey new knowledge and baselines of ecosystem change over long-time frames (Nunn and Reid, 2016). Oral histories can also convey cultural indicators and linguistic devices of species identification as a part of a local dialect matrix, and changes in ecosystems and species using interlinkages not available to science (Mustonen, 2013; Frainer et al., 2020). Oral histories attached to maritime place names, especially underwater areas (Brattland and Nilsen, 2011), can position observations relevant for understanding climate change over long ecological timeframes (Nunn and Reid, 2016). Species abundances, well-being and locations are some of the examples present in the ever-evolving oral histories as living ways of knowing. Indigenous knowledge and oral histories may also have the potential to convey governance, moral and ethical frameworks of sustainable livelihoods and cultures (Mustonen and Shadrin, 2020) rooted in the particular Indigenous or local contexts that are not otherwise available in written or published forms.

Climate change research involving Indigenous Peoples and local communities has shown that the generation, innovation, transmission and preservation of Indigenous knowledge is threatened by climate change (Kermoal and Altamirano-Jiménez, 2016; Simonee et al., 2021). This is because Indigenous knowledge is taught, local knowledge is gained through experience, and relationships with the land are sustained through social engagement within and among families, communities and other societies (Tobias J.K, 2014; Kermoal and Altamirano-Jiménez, 2016). The knowledge that has traditionally been passed on in support of identity, language and purpose has been disrupted at an intergenerational level (Lemke and Delormier, 2017). Many of these dynamics have affected local knowledge transfers equally (Mustonen, 2013). This scenario represents a tension for Indigenous Peoples, where Indigenous knowledge in the form of land-based life ways, languages, food security, intergenerational transmission and application are threatened by climate change, yet in parallel, these same practices can enable adaptation and resilience (McGregor et al., 2020).

Table Cross-Chapter Box INDIG.1 | Examples of Indigenous knowledge and local knowledge about climate change used in this Assessment Report

Issue	Examples of Indigenous Peoples’ and local communities’ action	Context, peoples and location	Source
Climate forecasting/ early warning	Phenological cues to forecast and respond to climate change	Smallholder farmers, Delta State, Nigeria	Chapter 9
	Forecasting of weather and climate variation through observation of the natural environment (e.g., changes in insects and wildlife).	Afar pastoralists, north-eastern Ethiopia	
	Observation of wind patterns to plan response to coastal erosion/flooding	Inupiat, Alaska, USA	Chapter 14
	Sky and moon observation to determine the onset of rainy season	Maya, Guatemala	Chapter 12
Fire hazards	Prescribed burning	Indigenous nations in Venezuela, Brazil, Guyana, Canada and USA	Chapter 12 Chapter 14
Crop yield/food security	Water management, native seeds conservation and exchange, crop rotation, polyculture and agroforestry	Mapuche, Chile	Chapter 12
	Crop association (milpa) agroforestry, land preparation and tillage practices, native seed selection and exchange, adjusting planting calendars	Maya, Guatemala	Chapter 12
	Harvesting rainwater and the use of maize landraces by Indigenous farmers to adapt to climate impacts and promote food security in Mexico	Yucatán Peninsula, Mexico	Chapter 14
Livelihood and well-being	Cultural values ingrained in knowledge system: reciprocity, collectiveness, equilibrium and solidarity	Quechua, Cusco, Peru	Chapter 12
Ecosystem degradation	Ecosystem restoration including rewilding	Sámi, Nenets, and Komi, Scandinavia and Siberia	Chapter 13
	Collaboration with researchers, foresters and landowners to manage native black ash deciduous trees against emerald ash borer	Indigenous Nations in Canada and USA	Chapter 14
	Selection and planting of native plants that reduce erosion Whole-of-island approaches that embed Indigenous knowledge and local knowledge in environmental governance	Small Islands States (as defined by Chapter 15)	Chapter 15
Fisheries	Traditional climate-resilient fishing approaches	Indigenous nations across North America and the Arctic	Chapter 14 CCP6
Management of urban resources	Restoration of traditional network of water tanks	Traditional communities and activists in South Indian cities such as Bengaluru	Chapter 6

Cross-Chapter Box INDIG (continued)

Table Cross-Chapter Box INDIG.2 | Case study summary

Region	Summary
Africa	Many rural smallholder farmers in Africa use their ingrained Indigenous knowledge systems to navigate climatic changes as many do not have access to Western systems of weather forecasting. Instead, these farmers have been reported to use observations of clouds and thunderstorms, and migration of local birds to determine the start of the wet season, as well as create temporary walls by rivers to store water during droughts. Indigenous knowledge systems should be incorporated into strategic plans for climate change adaptation policies to help smallholder farmers cope with climate change (Mapfumo et al., 2016).
Arctic	For local Inuit hunters and others who travel across Arctic land, ice and sea, there is evidence that the most accurate approach to reduce risk and enable informed decision making for safe travel is to combine Indigenous knowledge and local observations of weather with official online weather and marine services information that is available nationally (Simonee et al., 2021). Combining Inuit and local knowledge of weather, water, ice and climate information with official forecasts has provided local hunters with more accurate, locally relevant information, and has on several occasions helped to avoid major weather-related accidents.
Latin America	In Venezuela, Brazil and Guyana, Indigenous knowledge systems have led to a lower incidence of wildfires, reducing the risk of rising temperatures and droughts (Mistry et al., 2016). The Mapuche Indigenous Peoples in Chile use various traditional and sustainable agricultural practices, including native seed conservation and exchange (*trafkintu*), crop rotation, polyculture and tree-crop association. They also give thanks to Mother Earth through rituals to nurture socio-ecological sustainability (Parraguez-Vergara et al., 2018). In the rural Cusco Region of Peru, 'cultures values known in Quechua as *ayni* (reciprocity), *ayllu* (collectiveness), *yanantin* (equilibrium) and *chanincha* (solidarity)' have led to successful adaptation to climate change (Walshe and Argumedo, 2016).
Māori (Aotearoa New Zealand)	The traditional calendar system (*maramataka*) used by the Māori in Aotearoa, New Zealand, incorporates ecological, environmental and celestial Indigenous knowledge. Māori practitioners are collaborating with scientists through the Effect of Climate Change on Traditional Māori Calendars project (Harris et al., 2017) to examine if climatic changes are impacting the use of the *maramataka*, which can be used as a framework to identify and explain environmental changes. Observations are being documented across Aotearoa, New Zealand to improve understandings of environmental changes and explore the use of Indigenous Māori knowledge in climate change assessment and adaptation.
Skolt Sámi (Finland)	In 2011, the Skolt Sámi in Finland began the first co-governance initiative where collaborative management and Indigenous knowledge were utilised to effectively manage a river and Atlantic Salmon (*Salmo salar*). This species is culturally and spiritually significant to the Skolt Sámi and has been adversely impacted by rising water temperatures and habitat loss (Brattland and Mustonen, 2018; Feodoroff, 2020; Ogar et al., 2020) (see also CCP Polar). Using Indigenous knowledge, they mapped changes in catchment areas and used cultural indicators to determine the severity of changes. Through collaborative management efforts that utilised both Indigenous knowledge and science, spawning and juvenile habitat areas for trout and grayling were restored, demonstrating the autonomous community capacity (Huntington et al., 2017) of the Indigenous Skolt Sámi and the capacity of Indigenous knowledge to address climate change impacts and detection of very first microplastics pollution together with science (Pecl et al., 2017; Brattland and Mustonen, 2018; Mustonen and Feodoroff, 2020).

Cross-Chapter Box FEASIB | Feasibility Assessment of Adaptation Options: An Update of the SR1.5

Authors: Debora Ley (Guatemala/Mexico), Helen Adams (UK), Malcolm Araos (Canada/USA), Ritwika Basu (India/UK), Amir Bazaz (India), Luigi Conte (Italy), Katy Davis (UK), Constantino Dockendorff (Chile/Germany), James Ford (UK/Canada), Sabine Fuss (Germany), Elisabeth A Gilmore (USA/Canada), Tania Guillén Bolaños (Nicaragua/Germany), Ove Hoegh-Guldberg (Australia), Mark Howden (Australia), Bavisha Kalyan (South Africa/USA), Laura Moro (Italy), Anuszka Mosurska (UK/Poland), Reinhard Mechler (Germany), Joana Portugal-Pereira (Brazil), Aromar Revi (India), Swarnika Sharma (India), Anne J. Sietsma (the Netherlands/UK), Chandni Singh (India), Alessandro Triacca (Italy), Bianca van Bavel (Canada/Ireland/UK), Ivan Villaverde Canosa (Spain/UK), Mustafa Babiker (Sudan/Saudi Arabia), Paolo Bertoldi (Italy), Brett Cohen (South Africa), Annette Cowie (Australia), Kiane de Kleijne (the Netherlands), Jeremy Emmet-Booth (Ireland), Amit Garg (India), Gert-Jan Nabuurs (the Netherlands), André Frossard Pereira de Lucena (Brazil), Adrian Leip (Italy/Germany), Lars J. Nilsson (Sweden), Pete Smith (UK), Linda Steg (the Netherlands), Masahiro Sugiyama (Japan)

Key Messages

The feasibility assessment (FA) presents a systematic framework to assess adaptation and mitigation options organised by system transitions. This Cross-Chapter Box assessed the feasibility of 23 adaptation options across six dimensions: economic, technological, institutional, socio-cultural, environmental-ecological, and geophysical to identify factors within each dimension that present barriers to the achievement of the option. The results are presented below.

For energy systems transitions, the adaptation options of infrastructure resilience, efficient water use and water management, and reliable power systems enable energy systems to work during disasters with reduced costs, demonstrating the synergistic relationships between mitigation and adaptation (*high confidence*). There is high confidence in the high feasibility of infrastructure resilience and reliable power systems as they enable power systems to provide emergency services during disasters, as well as continue these services during recovery periods. New evidence has focused on both options for peri-urban and rural areas through distributed generation and isolated renewable energy systems, which also provide multiple social co-benefits (*medium confidence*). For efficient water use and management, the synergistic potential with mitigation can make processes more efficient and cost effective (*high confidence*). With regards to adaptation feasibility, efficient water use is especially useful in drought-stricken areas and provides better water management for multiple uses (*high confidence*).

There are multiple adaptation options for land and ocean ecosystems. Forest- and biodiversity-based adaptation options are generally promoted on the basis of their positive impacts on adaptive and ecological capacities, increased provision of ecosystem services and goods, with a particularly strong contribution to carbon sequestration (*high confidence*). However, large afforestation projects and the introduction of non-native and fast-growing vegetation reduce water availability, impoverish habitats for wildlife and reduce overall ecological resilience, threatening the achievement of some Sustainable Development Goals (SDGs), and potentially leading to maladaptation (*high confidence*).Over-reliance on forest-based solutions may increase the susceptibility to wildfires, with detrimental consequences both for mitigation and adaptation (*medium confidence*). Over the last decade, forest- and biodiversity-based solutions have gained considerable political traction and social acceptability (*high confidence*), but in countries with economies highly dependent on the export of agricultural commodities, opportunity costs continue to hinder the expansion of these alternatives, particularly against more profitable land uses (*high confidence*). In such cases, government support and innovative financial schemes, including payments for ecosystem services, are fundamental for broader adherence to forest- and biodiversity-based options.

Agro-forestry solutions have strong ecological and adaptive co-benefits (*high confidence*), including improved provision of ecosystem services, synergies with the water–energy–land–food nexus, and positive outcomes in agricultural intensification, job diversification and household income. While broad inclusion of agro-forestry schemes in countries' Nationally Determined Contributions (NDCs) reflect growing international interest in these strategies, insufficient financial support to smallholder farmers continues to limit the expansion of agro-forestry initiatives in developing and tropical countries.

Implementing environmentally and biodiversity sensitive coastal defence options—often as part of Integrated Coastal Zone Management—is limited by economic, environmental, institutional and social barriers. Successful implementation requires a strong socioeconomic framework and can offer diverse social, ecological and economic benefits, as well as sequestering carbon (*high confidence*). There is extensive experience with hard coastal defence structures (e.g., sea walls), which can be cost-effective in economic terms, depending on the location (*medium confidence*); however, they are considered maladaptive and unsustainable in some contexts (*medium confidence*) due to their lack of flexibility or robustness in response to a changing climate, as well as their carbon-intensiveness and potential ecological impacts (*medium confidence*).

Cross-Chapter Box FEASIB (continued)

There is *medium confidence* on the feasibility of sustainable aquaculture and fisheries as adaptation options. There are financial barriers to implementing sustainable aquaculture and fisheries, even though they can improve employment opportunities, especially for local communities (*medium confidence*). Technical resource availability is still lacking and could represent a barrier to implementing sustainable aquaculture and fisheries (*medium confidence*). Robust institutional and legal frameworks are needed to guarantee effective adaptation (*high confidence*). Sustainable aquaculture and fisheries are highly dependent on healthy and resilient ecosystems (*high confidence*). They can provide diverse ecosystem services and support coastal ecosystems restoration (*medium confidence*).

There are a range of strategies to improve livestock system efficiency including improved livestock diets, enhanced animal health, breeding and manure management, and grassland management. This suite of strategies has strong feasibility to build resilience while improving incomes (*medium confidence*) and providing mitigation co-benefits (*high confidence*). While technological and ecological feasibility is high, institutional, market and socio-political acceptability remain significant barriers (*medium confidence*).

Improving water use efficiency and water resource management under land and ecosystem transitions has high technological feasibility (*high confidence*) with positive resilience-building and socioeconomic co-benefits. However, economic and institutional barriers remain and are based on type, scale and location of interventions (*medium confidence*). Notably, inadequate institutional capacities to prepare for changing water availability, especially in the long term, unsustainable and unequal water use and sharing practices, and fragmented water resource management approaches remain critical barriers to feasibility (*high confidence*).

Improved cropland management includes agricultural adaptation strategies such as integrated soil management, no/reduced tillage, conservation agriculture, planting of stress-resistant or early maturing crop varieties, and mulching. These strategies have high economic and environmental feasibility (*high confidence*) and substantial mitigation co-benefits (*medium confidence*). However, high costs, inadequate information and technical know-how, delays between actions and tangible benefits, lack of comprehensive policies, fragmentation across different sectors, inadequate access to credit, and unequal access to resources constrain technological, institutional and socio-cultural feasibility (*medium confidence*).

For urban and infrastructure system transitions, sustainable urban planning can support both adaptation and decarbonisation by mainstreaming climate concerns, including effective land use into urban policies, by promoting resilient and low-carbon infrastructure, and by protecting and integrating carbon-reducing biodiversity and ecosystem services into city planning (*medium confidence*). Urban green infrastructure and ecosystem services have high feasibility to support climate adaptation and mitigation efforts in cities, for example to reduce flood exposure and attenuate the urban heat island (*high confidence*). While green infrastructure options are cost-effective and provide co-benefits in terms of ecosystem services such as improved air quality or other health benefits (*high confidence*), there remains a need for systematically assessing co-benefits, particularly for flood risk management and sustainable material flow analysis. Governments across scales can support urban sustainable water management by undertaking projects to recycle wastewater and runoff through green infrastructure; enabling greater coherence between urban water and riverine basin management; decentralising water systems; supporting networks for sharing best practices in water supply and storm runoff treatment to scale sustainable management; and foregrounding equity and justice concerns, especially through participation involving informal settlement residents (*medium confidence*).

Strong and equitable health systems can protect the health of populations in the face of known and unexpected stressors (*medium confidence*). Health and health systems adaptation is feasible where capacity is well developed, and where options align with national priorities and engage local and international communities (*medium confidence*). Socio-cultural acceptability of health and health systems adaptation is high and there is significant potential for risk-mitigation and social co-benefits where adaptation addresses the needs of vulnerable regions and populations (*medium confidence*). Microeconomic feasibility and socioeconomic vulnerability reduction potentials are also high (*high confidence*), although economic feasibility may pose a significant challenge in low-income settings (*medium confidence*). However, inadequate institutional capacity and resource availability represent major barriers, particularly for health systems struggling to manage current health risks (*high confidence*).

There is strong evidence that disaster risk management (DRM) is highly feasible when supported by strong institutions, good governance, local engagement and trust across actors (*medium confidence*). DRM is constrained by lack of capacity, inadequate institutions, limited coordination across levels of government (*high confidence*), lack of transparency and accountability, and poor communication (*medium confidence).* There is a preference for top-down DRM processes, which can undermine local institutions and perpetuate uneven power relationships (*medium confidence*). However, local integration of worldviews, belief systems and local and

Cross-Chapter Box FEASIB (continued)

Indigenous Knowledge into DRM activities can facilitate successful, disability-inclusive and gender-focused DRM (*medium confidence*). Moves towards community-based and ecosystem-based DRM are promising but uneven and may increase vulnerability if they fail to address underlying and structural determinants of vulnerability (*high confidence*).

Climate services that are demand-driven and context-specific (e.g., to a particular crop or agricultural system) build adaptation capacity and enable short- and longer-term risk management decisions (*high confidence*). Metrics to assess the economic outcomes of climate services remain insufficient to capture longer-term benefits of interventions (*medium confidence*). While technological capacity and political acceptance is high (*medium confidence*), institutional barriers, poor fit with user requirements and inadequate regional coverage constrain the option's overall feasibility.

Risk insurance can be a feasible tool to adapt to climate risks and support sustainable development (*high confidence*). They can reduce both vulnerability and exposure, support post-disaster recovery and reduce financial burden on governments, households and business. Insurance mechanisms enjoy wide legal and regulatory acceptability among policymakers and are institutionally feasible (*high confidence*). However, socio-cultural and financial barriers make insurance spatially and temporally challenging to implement (*high confidence*), even though it can improve the health and well-being of populations (*medium confidence*). The risk of generating maladaptive outcomes can further limit the uptake of insurance, as it can provide disincentives for reducing risk over the long term (*medium confidence*). Expanding the knowledge base on insurance is fundamental to successfully implement insurance among all relevant stakeholders. Ensuring equitable access to and benefits from innovative financial products (e.g., loans) is needed to guarantee successful uptake of insurance across all the population (*high confidence*).

Migration has been used by millions around the world to maintain and improve their well-being in the face of changed circumstances, often as part of labour or livelihood diversification (*very high confidence*). Properly supported and, where levels of agency and assets are high, migration as a climate response can reduce exposure and socioeconomic vulnerability (*medium confidence*). Households and communities in climate-exposed regions experience a range of intersecting stressors. These households can undertake distress migration, which results in negative adaptive and resilience outcomes (*high confidence*). Outcomes can be improved through a systematic examination of the political economy of local and regional sectors that employ precarious communities and by addressing vulnerabilities that pose barriers to *in situ* adaptation and livelihood strategies (*medium confidence*). Migrants and their sending and receiving communities can be supported through temporary labour-migration schemes, improving discourses on migration, and matching existing migration agreements with development objectives (*medium confidence*).

Planned relocation and resettlement have low feasibility as climate responses (*medium confidence*). Previous disaster- and development-related relocation has been expensive, contentious, posed multiple challenges for governments and amplified existing, and generated new, vulnerabilities for the people involved (*high confidence*). Planned relocation will be increasingly required as climate change undermines habitability, especially for coastal areas (*medium confidence*). Full participation of those affected, ensuring human rights-based approaches, preserving cultural, emotional and spiritual bonds to place, and dedicated governance structures and associated funding are associated with improved outcomes (*high confidence*). Improving the feasibility of planned relocation and resettlement is a high priority for managing climate risks (*high confidence*).

CCB FEASIB.1 Scope

The Paris Climate Agreement marked a significant shift for the IPCC AR6 assessment towards a systematic exploration of climate solutions and a suite of linked adaptation and mitigation options (IPCC, 2018b; IPCC, 2019b). This shift was first evidenced in SR1.5, whose plenary-approved outline sought to define feasibility as 'referring to the potential for a mitigation or adaptation option to be implemented. Factors influencing feasibility are context-dependent, temporally dynamic, and may vary between different groups and actors. Feasibility depends on geophysical, environmental-ecological, technological, economic, socio-cultural and institutional factors that enable or constrain the implementation of an option. The feasibility of options may change when different options are combined and increase when enabling conditions are strengthened'. Based on this, SR1.5 identified (with *high confidence*) rapid and far-reaching transitions in four systems: energy, land and other ecosystems, urban and infrastructure (including transport and buildings), and industrial systems, are necessary to enable pathways to limit average global warming to 1.5°C compared with pre-industrial temperatures (Bazaz et al., 2018; IPCC, 2018b). This was deepened for terrestrial systems in SRCCL, while SROCC added additional evidence from ocean and cryosphere systems. The assessment also included the interactions between carbon dioxide removal (CDR) and adaptation outcomes: compared with previous Assessment Reports, it is clear that the ambitious temperature targets agreed upon in Paris in 2015 will require at least some CDR, that is all 1.5°C pathways will eventually feature annual removals at gigaton level (Rogelj et al., 2018a). This necessitates assessing the interactions of CDR with adaptation.

Cross-Chapter Box FEASIB (continued)

This feasibility assessment (FA) of adaptation options is situated within four system transitions identified in SR1.5 (de Coninck et al., 2018b). In this report, feasibility refers to the potential for an adaptation option to be implemented. Twenty-three key adaptation options have been identified in AR6, across these system transitions, and mapped against representative key risks at global scale (Chapter 16) (Figure 1).

This cross-chapter box first presents the methodology for the (FA) of adaptation options (Section 2); findings of the FA (Section 3); presents synergies and trade-offs (S&Ts) of adaptation for mitigation options and mitigation for adaptations (Section 4); and knowledge gaps (Section 5).

Feasibility assessment options mapped against Representative Key Risks (RKR)

Systems transitions RKRs	Energy systems transitions	Land and ecosystems transitions	Urban and infrastructure systems transitions	Overarching adaptation options
Risk to costal socio-ecological systems		• Coastal defense and hardening • Sustainable aquaculture		• Social safety nets • Risk spreading and sharing • Climate services (including EWS) • Disaster risk management • Population health and health systems • Human migration and displacement • Planned relocation and resettlement
Risk to terrestrial and ocean ecosystems		• Integrated coastal zone management including wetland, mangrove conservation • Sustainable forest management and conservation, forestations and afforestation • Biodiversity management and ecosystem connectivity		
Risk associated with critical physical infrastructure, networks, and services	• Resilient power infrastructure • Improved power reliability		• Green infrastructure and ecosystem services • Sustainable land-use land urban planning	
Risk to living standards and equity		• Livelihood diversification		
Risk to human health				
Risk to food security		• Improved cropland management (including integrated soil management, conservation agriculture) • Efficient livestock systems (including improved grazing land management) • Agroforestry		
Risk to water security	• Improve water use efficiency	• Water use efficiency and water resource management	• Sustainable urban water management	
Risk to peace and migration				

Figure Cross-Chapter Box FEASIB.1 | Feasibility assessment option mapped against representative key risks (RKRs)

Cross-Chapter Box FEASIB (continued)

There has been growing research emphasis on synthesising adaptation literature through meta-reviews of adaptation research (Sietsma et al., 2021; Berrang-Ford et al. 2021), adaptation readiness (Ford et al., 2015a; Ford et al., 2017), adaptation progress (Araos et al., 2016a), adaptation barriers and enablers (Biesbroek et al., 2013; Eisenack et al., 2014; Barnett et al., 2015), and adaptation outcomes (Owen, 2020) (Cross-Chapter Box ADAPT in Chapter 1). In particular, understanding which adaptation options are effective, to what risks, and under what conditions, is particularly challenging given the lack of a clearly defined and globally- agreed- adaptation goals, as well as disagreement on the metrics to assess adaptation effectiveness (Berrang-Ford et al., 2019; Singh et al., 2021c) (17.5.2 on Successful Adaptation). Effectiveness studies often use metrics such as reduced risk exposure, damage costs averted, which lend themselves well to infrastructural options (e.g., effectiveness of seawalls in reducing sea level rise [SLR] exposure in coastal cities), but do not translate well to 'soft' adaptation options such as climate services or changing building codes.

CCB FEASIB.2 Methodology: feasibility assessment of adaptation options across key system transitions

The multi-dimensional feasibility of 23 adaptation options is assessed across six dimensions. This multi-dimensional framework goes beyond technical or economic feasibility alone to capture how adaptation is mediated by the political environment, sociocultural norms (Evans et al., 2016), cognitive and motivational factors (van Valkengoed and Steg, 2019), economic incentives and benefits (Masud et al., 2017), and ecological conditions (Biesbroek et al., 2013).

The six feasibility dimensions are underpinned by a set of 20 indicators. Each adaptation option is scored as having *robust*, *medium* or *limited evidence* on barriers based on a review of literature published from 2018 onwards (pre-2018 literature is expected to be covered by SR1.5 but in some cases pre-2018 literature was added) that reports studies that are 1.5°C-relevant. Further details and motivations for this methodology can be found in Singh et al., 2020c.

The scoring process is undertaken by one author and reviewed by at least two more authors to ensure robustness and geographical coverage. While the literature does not support an assessment at different temperature levels or an assessment of how feasibility can change over time, some examples of these spatial and temporal aspects are detailed below.

CCB FEASIB.3 Findings: feasibility assessment of adaptation options across key system transitions

The following sections outline the findings of a 1.5ºC-relevant feasibility assessment of adaptation options by the four system transitions. A synoptic summary of the findings of the multi-dimensional feasibility is shown at the end of this section in Figure Cross-Chapter Box FEASIB.2. The full line of sight can be found in the Supplementary Material (SM).

CCB FEASIB.3.1 Energy systems transitions

The adaptation options assessed for energy system transitions are resilient power infrastructure; water management, focused on water efficiency and cooling, for all types of generation sources; and reliable power systems. Since SR1.5, there has not been significant change in the feasibility of the first two options as they continue to be implemented successfully, allowing for power generation to maintain or increase its reliability during extreme weather events (*high confidence*) (Zhang et al., 2018; Ali and Kumar, 2016; DeNooyer et al., 2016). As in the case of SR1.5, these options are not sufficient for the far-reaching transformations required in the energy sector, which tend to focus on technological transitions from a fossil-based to a renewable energy regime (Erlinghagen and Markard, 2012; Muench et al., 2014; Brand and von Gleich, 2015; Monstadt and Wolff, 2015; Child and Breyer, 2017; Hermwille et al., 2017). The main difference from SR1.5 is that resilient power infrastructure now includes distributed generation utilities, such as microgrids, as there is increasing evidence of its role in reducing vulnerability, especially within underserved populations (*high confidence*).

The option for resilient power infrastructure considers all types generation sources, and transmission and distribution systems. There is *robust evidence* and *high agreement* for the high feasibility of the economic and technological dimensions as the technologies have been used and their cost effectiveness is high, although the latter is dependent upon the generation source and location of each specific generation plant. There is medium institutional feasibility (*medium evidence*, *medium agreement*) as there are insufficient policies for resilient infrastructure, although there is high acceptability for these options.

The option of efficient water use and management also has high feasibility for the economic, technological and environmental dimensions (*robust evidence*, *high agreement*), as this option also has proven that technology and efficient water use can make power generation operations more efficient and cost effective as well as have positive effects on the environment, especially in drought-stricken regions. There is high political acceptability, existence of water use policies, regulations and supporting institutional frameworks to ensure compliance (Ali and Kumar, 2016; DeNooyer et al., 2016; Zhang et al., 2018). There is *medium evidence* and *high agreement* for the medium feasibility of the socio-cultural dimension, especially given the evidence of resilience in distributed generation systems and independent microgrids.

Cross-Chapter Box FEASIB (continued)

Since AR5, the reliability of power systems has gained interest because of the numerous service disruptions during extreme weather events. As with resilient power systems, there is increasing evidence of the feasibility of increased reliability for both existing power plants, independently of the generation source, and for rural landscapes. The option has *high confidence* (*robust evidence*, *high agreement*) for the high feasibility of the technological and social dimensions. As with previous options, the technological means exist to create redundancy in power generation, transmission and distribution systems and their implementation ensures the continuous functionality of emergency services, such as communications, health and water pumping, amongst others, in urban, peri-urban and rural landscapes (*high confidence*). There is high feasibility for the economic, technical and socio-cultural dimensions (the latter more prominently for decentralised systems), and medium feasibility for institutional and geophysical dimensions.

For the three options, some of the indicators within the institutional, social and geophysical dimensions have *limited evidence* as they have not been the focus of dedicated research. For example, when discussing the social co-benefits of energy reliable systems of efficient water use, the literature does not focus on intergenerational or gender issues separately from the broad range of social co-benefits the options provide, but, for example, highlight the need for electricity for communications and health centres.

CCB FEASIB.3.2 Land and ecosystems

CCB FEASIB.3.2.1 Coastal defence and hardening

There is *robust evidence* and *medium agreement* regarding the feasibility of coastal defence and hardening as adaptation options in some circumstances, which here includes grey coastal infrastructure. Economic and social factors may limit the feasibility of these options as they require large investments (both construction, maintenance and monitoring) (Hamin et al., 2018; Magnan and Duvat, 2018; Morris et al., 2018; Morris et al., 2019; Nicholls et al., 2019; Hanley et al., 2020b) (Section CCP2.3). While these costs present challenges for rural areas, coastal defence structures may still be cost-effective in other areas, such as those with larger economies (Aerts, 2018; Lincke and Hinkel, 2018; Tiggeloven et al., 2020; Vousdoukas et al., 2020; Lima and Coelho, 2021). Strong, transparent and inclusive governance is key, suggesting that these measures can occasionally fail to adequately balance competing stakeholder interests. Consequently, they may disproportionately benefit wealthier people and exacerbate existing vulnerability of the poor (Kind et al., 2017; O'Donnell, 2019; Ratter et al., 2019; Siders and Keenan, 2020; Siriwardane-de Zoysa, 2020). They are also potentially maladaptive if they are not flexible or robust in response to a changing climate (Antunes do Carmo, 2018; Hamin et al., 2018; Morris et al., 2019; Baills et al., 2020; Foti et al., 2020; Hanley et al., 2020b) and can have negative impacts on the local environment, habitats, ecosystem services, and communities (Mills et al., 2016; Morris et al., 2018; Morris et al., 2019; Foti et al., 2020; Hanley et al., 2020b).

Recent projects have focused on improving adaptability and increasing ecological and social sustainability by combining both hard engineering and 'softer' nature-based solutions (Morris et al., 2019; Scheres and Schüttrumpf, 2019; Schoonees et al., 2019; Van Loon-Steensma and Vellinga, 2019; Du et al., 2020; Foti et al., 2020; Winters et al., 2020; Ghiasian et al., 2021; Joy and Gopinath, 2021; Tanaya et al., 2021; Waryszak et al., 2021). For example, coastal defence might involve a combination of 'stabilising' ecosystems (e.g., seagrasses, mangroves, salt marshes) and hard human-made structures. Such coastal defence 'mixed' structures can be part of an Integrated Coastal Zone Management (ICZM) strategy, which is covered as a separate option below.

CCB FEASIB.3.2.2 Sustainable aquaculture

There is *medium evidence* with *medium agreement* on the feasibility of sustainable aquaculture as an adaptation measure. Sustainable aquaculture (e.g., integrated multi-trophic aquaculture, polyculture, aquaponics, mangrove-integrated culture) can have socioeconomic benefits for vulnerable communities and small-scale fisheries (Ahmed, 2018; Blasiak et al., 2019; Mustafa et al., 2021; Thomas et al., 2021; Xuan et al., 2021). However, caution is important to guarantee that access to fish supply of local and vulnerable communities is not affected (Chan et al., 2019; Galappaththi et al., 2020). Access to financial resources is often a barrier to implementation, although sustainable aquaculture can increase employment opportunities that are increasingly gender equitable (Alleway et al., 2018; Leakhena et al., 2018; Valenti et al., 2018; Gopal et al., 2020), as well as increasing the resilience of coastal livelihoods to climate change (Shaffril et al., 2017; Blasiak and Wabnitz, 2018). Technological, institutional and socio-cultural factors can form barriers to the feasibility of sustainable aquaculture (e.g., Ahmed et al., 2018; Blasiak et al., 2019; Galappaththi et al., 2019; Boyd et al., 2020; Osmundsen et al., 2020; Stentiford et al., 2020; Mustapha et al., 2021; Xuan et al., 2021).

Sustainable aquaculture depends on healthy ecosystems (Sampantamit et al., 2020; Stentiford et al., 2020; Qurani et al., 2021). At the same time, its implementation can increase or regenerate ecosystem services, enhance ecosystems' adaptive capacity (Shaffril et al., 2017; Freduah et al., 2018; Custódio et al., 2020; Bricknell et al., 2021; Mustafa et al., 2021) and protect nursery grounds and habitats for fish and other important organisms (i.e., many commercial species are associated with mangroves). It may also prevent ecosystem

Cross-Chapter Box FEASIB (continued)

degradation such as deforestation, enhancing land use potential (Ahmed et al., 2018; Stentiford et al., 2020; Turolla et al., 2020; Mustafa et al., 2021).

Environmental and economic aspects are key when assessing the sustainability of aquaculture practices (Ahmed et al., 2018; Aubin et al., 2019; Bohnes et al., 2019; Galappaththi et al., 2019; Boyd et al., 2020; Galappaththi et al., 2020; Osmundsen et al., 2020; Stentiford et al., 2020; Thomas et al., 2021). A global picture of where sustainable aquaculture is possible is needed and desirable (FAO, 2018; Galappaththi et al., 2019; Bricknell et al., 2021), yet there are few new references to its physical feasibility. Adaptation options for existing sustainable aquaculture need to be developed, along with institutional arrangements such as education and technology transfer, focused on developing sustainable industries (Section 8.6.2.3). Sustainable agriculture is likely to receive strong support from many countries but may also experience resistance for several reasons (e.g., competition with existing industries, debates over tolerance to aesthetic changes to coastlines). Literature on this area is growing. Potential barriers at the government and political levels are significant (e.g., Jayanthi et al., 2018; Blasiak et al., 2019; Hargan et al., 2020; Osmundsen et al., 2020; Stentiford et al., 2020; Mustafa et al., 2021; Qurani et al., 2021).

CCB FEASIB.3.2.3 Integrated coastal zone management (ICZM)

ICZM measures such as salt marsh management, re-vegetation of shorelines, community-based coastal adaptation and ecosystem-based adaptation were considered in this assessment. There is *robust evidence* and *high agreement* that ICZM increases ecological and adaptive capacity to climate change (Villamizar et al., 2017; Antunes do Carmo, 2018; Hamin et al., 2018; Le Cornu et al., 2018; Propato et al., 2018; Romañach et al., 2018; Rosendo et al., 2018; Warnken and Mosadeghi, 2018; Morecroft et al., 2019; Morris et al., 2019; Alves et al., 2020; Donatti et al., 2020; Erftemeijer et al., 2020; Foti et al., 2020; Gómez Martín et al., 2020; Hanley et al., 2020b; Jones et al., 2020b; Krauss and Osland, 2020; O'Mahony et al., 2020; Perera-Valderrama et al., 2020; Cantasano et al., 2021).

Diverse socioeconomic co-benefits have been identified, including integration of tourism activities, increased educational opportunities for the reduction in storm damage, maintenance of ecosystems and their services, increasing adaptive capacities of institutions (Romañach et al., 2018; Mestanza-Ramón et al., 2019; Morris et al., 2019; Donatti et al., 2020; Ellison et al., 2020; Erftemeijer et al., 2020; Gómez Martín et al., 2020; Hanley et al., 2020a; Jones et al., 2020b; Martuti et al., 2020; Perera-Valderrama et al., 2020; Telave and Chandankar, 2021); as well as environmental and geophysical co-benefits aspects, including mitigation potential and hazard risk reduction (Propato et al., 2018; Romañach et al., 2018; Ellison et al., 2020; Erftemeijer et al., 2020; Hanley et al., 2020a; Jones et al., 2020b; Martuti et al., 2020; Cantasano et al., 2021).

ICZM measures are generally more cost-effective than 'hard engineering' measures (Antunes do Carmo, 2018; Morecroft et al., 2019; Morris et al., 2019; Donatti et al., 2020; Erftemeijer et al., 2020; Hanley et al., 2020a; Jones et al., 2020b), but implementation pose barriers, especially in low-income countries (Lamari et al., 2016; Villamizar et al., 2017; Rosendo et al., 2018; Mestanza-Ramón et al., 2019; Barragán Muñoz, 2020; Botero and Zielinski, 2020; Caviedes et al., 2020; Martuti et al., 2020; Lin et al., 2021). ICZM implementation requires strong institutional frameworks, where all relevant stakeholders (especially representatives of local communities) are part of decision-making processes (Pérez-Cayeiro and Chica-Ruiz, 2015; Lamari et al., 2016; Hassanali, 2017; Antunes do Carmo, 2018; Hamin et al., 2018; Phillips et al., 2018; Romañach et al., 2018; Rosendo et al., 2018; Warnken and Mosadeghi, 2018; Mestanza-Ramón et al., 2019; Morecroft et al., 2019; Morris et al., 2019; Walsh, 2019; Barragán Muñoz, 2020; Caviedes et al., 2020; Donatti et al., 2020; Ellison et al., 2020; Martuti et al., 2020; O'Mahony et al., 2020; Perera-Valderrama et al., 2020). This aspect is mentioned as a key challenge in developing countries (Pérez-Cayeiro and Chica-Ruiz, 2015; Villamizar et al., 2017; Rosendo et al., 2018; Alves et al., 2020). Similarly, explicitly incorporating gender considerations into ICZM is generally recommended, mainly because women are key knowledge holders in coastal communities; however, this is rarely done in practice, which may lead to sub-optimal or unequal outcomes (Nguyen Mai and Dang Hoang, 2018; Hoegh-Guldberg et al., 2019; Pearson et al., 2019; Barreto et al., 2020). The perception that building 'hard' infrastructure (i.e., coastal defence and hardening) is a more efficient way of reducing coastal risk than the implementation of 'soft' or nature-based solutions (NbS) measures has been challenged in recent studies (Magnan and Duvat, 2018).

CCB FEASIB.3.2.4 Agro-forestry

There is *robust evidence* and *high agreement* that agro-forestry systems can increase ecological and adaptive capacity (Schoeneberger et al., 2012; Smith et al., 2013a; Minang et al., 2014; Apuri et al., 2018; Kmoch et al., 2018; IPCC, 2019b; Jordon et al., 2020). Benefits include preservation of ecosystems services, such as water provision and soil conservation, more efficient use of limited land, alleviation of land degradation, prevention of desertification and improved agricultural output. Agro-forestry solutions also result in co-benefits in the water–energy–land–food nexus, with observed positive outcomes in soil management, crop diversification, water efficiency and alternative sources of energy (De Beenhouwer et al., 2013; Elagib and Al-Saidi, 2020). Further, they can have social and economic benefits

Cross-Chapter Box FEASIB (continued)

and positive synergies between adaptation and mitigation (Section 8.6.2.2) (Coulibaly et al., 2017; Hernández-Morcillo et al., 2018; Tschora and Cherubini, 2020; Duffy et al., 2021).

When locally adapted to fine-scale ecological and social variation, agro-forestry initiatives can improve household income, and provide regular employment and sustainable livelihood to local communities, thereby strengthening peoples' resilience to cope with adverse impacts of changing climate conditions (Coe et al., 2014; Ogada et al., 2020; Sharma et al., 2020; Sollen-Norrlin et al., 2020; Awazi et al., 2021). However, Cechin et al. (2021) questions the financial viability of agro-forestry systems, especially in the case of smallholders in agrarian reform settlements, struggling with high upfront costs. Similarly, insufficient financial support was found to be a major constraint for the implementation of broader agro-forestry initiatives in Southeast Asia and Africa (Sections 8.5.2 and 8.6.2.1) (Dhyani et al., 2021; Williams et al., 2021b).

Over the last decade, agro-forestry schemes have grown in acceptability and political support, most notably observed in their broad inclusion in countries' NDCs and National Adaptation Plans (NAPs). Governance and institutional arrangements, however, have not been conducive to broader implementation of agro-forestry initiatives at the landscape level (Dhyani et al., 2021; Williams et al., 2021b). *Medium evidence* with *medium agreement* suggests that economic and cultural barriers may explain difficulties with the implementation of agro-forestry systems (Coe et al., 2014; Quandt et al., 2017; Cedamon et al., 2018; Hernández-Morcillo et al., 2018; Ghosh-Jerath et al., 2021). Also, unclear land tenure and ownership issues, together with inappropriate mapping and incomplete databases for monitoring vegetation, continue to hinder the adoption of broader agro-forestry strategies, particularly in remote areas and tropical forests (Martin et al., 2020).

Notably, agro-forestry practices are often part of Indigenous and local Knowledge (Santoro et al., 2020), and so far, most literature refers to the evaluation of existing agro-forestry practices or autonomous adaptation, with few studies evaluating the effects of targeted interventions, especially in low- and middle-income countries (Miller, 2020; Castle et al., 2021).

CCB FEASIB.3.2.5 Forest-based adaptation, including sustainable forest management, forest conservation and restoration, avoided deforestation, reforestation and afforestation

There is *robust evidence* and *medium agreement* supporting the overall feasibility of forest-based adaptation options. Regarding its economic feasibility, some studies (Nabuurs et al., 2017b; Chow et al., 2019; Seddon et al., 2020a) highlight that the net benefits of measures such as reforestation, sustainable forest management and ecosystem restoration outweigh the costs of implementation and maintenance. Yet, another strand of literature observes that limited access to financial resources is a major constraint to forest-based initiatives, especially in the face of upfront investment costs and alternative, more profitable land uses, such as agriculture (Bustamante et al., 2019; Ota et al., 2020; Seddon et al., 2020b). In countries with extensive rural areas where forests provide for local communities, government support together with private investments and long-term assurances of maintenance, are considered fundamental for the long-term viability of forest conservation strategies (Bustamante et al., 2019; Seddon et al., 2020b). In rural areas, smallholders can diversify their livelihood and increase household income as a result of improved local forest governance (Bustamante et al., 2019; Fleischman et al., 2020; Ota et al., 2020) Similarly, forest and ecosystem restoration has been found to reduce poverty and improve social inclusion and participation, given that ecosystems can be managed jointly and in traditional ways (Woroniecki et al., 2019). *Robust evidence* (*high agreement*) links forest-based adaptation to job creation, improved health and recreational benefits, most notably for indigenous, rural and remote communities (Muricho et al., 2019b; Rahman et al., 2019; Ambrosino et al., 2020; Bhattarai, 2020; Ota et al., 2020; von Holle et al., 2020; Tagliari et al., 2021). However, Chausson et al. (2020) note that frameworks for assessing the cost-effectiveness of adaptation strategies continue to be tailored to conventional, engineered interventions, which fail to capture the broader array of material and non-material benefits that forest-based interventions might bring.

Forest-based solutions enjoy wide local, regional and international support (Lange et al., 2019; Chausson et al., 2020; Seddon et al., 2020b), and most countries have a basic regulatory framework for environmental protection. However, lack of institutional capacity, deficient inter-agency coordination, and insufficient staff and budget continue to limit broader implementation of forest-based adaptation measures. Limited technical capacity, insufficient production and supply of seeds and seedlings, long transport distances and immature supply chains have also been identified as significant barriers that hinder the expansion of forest-based initiatives (Bustamante et al., 2019; Nunes et al., 2020).

There is *robust evidence* and *medium agreement* that forest-based solutions support ecosystems' capacity to adapt to climate change, including better regulation of microclimate, increased groundwater recharge, improved quality of air and water, reduced soil erosion, improved and climate-adapted biodiversity habitats and expansion of biomass, as well as continuous provision of renewable wood

Cross-Chapter Box FEASIB (continued)

products (Nabuurs et al., 2017b; Chow et al., 2019; Lochhead et al., 2019; Shannon et al., 2019; Weng et al., 2019; von Holle et al., 2020; Dooley et al., 2021; Forster et al., 2021; Tagliari et al., 2021). In well-designed systems, adaptation and mitigation can then go hand in hand, as in climate-smart forestry. What is more, adaptive forest management is already being tested in climate-smart forestry pilots in several temperate regions (Nabuurs et al., 2017b). However, large afforestation and non-native monoculture plantations may negatively impact non-forest ecosystems, such as grasslands, shrublands and peatlands, their water resources and biodiversity (Seddon et al., 2019; Seddon et al., 2020a; Seddon et al., 2020b). Similarly, the International Resource Panel (2019) warns that restoration may also imply trade-offs with other ecological and societal goals.

Regarding risk reduction potential, forest-based strategies are found to protect in-land infrastructure from landslides and coastal infrastructure from storm surges (Seddon et al., 2020a; Seddon et al., 2020b), together with offering a cheaper solution than engineered grey solutions (Chausson et al., 2020). Land availability is a limiting factor for expanding forest-based solutions (Morecroft et al., 2019; Ontl et al., 2020). However, there is *high agreement* and *robust evidence* that reforestation, environmental conservation and NbS result in increased carbon sinks (Griscom et al., 2017b; Nabuurs et al., 2017b; de Coninck et al., 2018b; Fuss et al., 2018; Favretto et al., 2020; Forster et al., 2021). Some authors argue that primary ecosystems and native forests contain larger stocks of carbon than tree plantations (Seddon et al., 2019; Fleischman et al., 2020; Seddon et al., 2020a), while another strain of literature finds that net sequestration rate is lower in mature primary forests than in younger managed forests with their associated wood value chains (Cowie et al., 2021; Forster et al., 2021; Gundersen et al., 2021). There is *robust evidence* and *high agreement* that forest- and ecosystem-based strategies result in hazard risk reduction potential. Environmental restoration can be an effective climate change adaptation alternative, reducing susceptibility to extreme events, improving ecological capacities and increasing overall ecosystems' resilience (Chapter 8, Box 9.7) (Nunes et al., 2020). However, too much reliance on forests and green alternatives might increase water shortages and wildfires (Seddon et al., 2019; Fleischman et al., 2020).

CCB FEASIB.3.2.6 Biodiversity management and ecosystem connectivity

There is *robust evidence* and *medium agreement* supporting the overall feasibility of biodiversity management and ecosystem connectivity as adaptation options. With respect to its economic feasibility, financial constraints continue to hinder broader implementation of biodiversity-based solutions (Lausche et al., 2013; Chausson et al., 2020; Jones et al., 2020a). Seddon et al. (2020a) highlights that only 5% of climate finance goes towards adaptation strategies, and only 1% is destined to disaster risk management including NbS and biodiversity management. Government support via subsidies and fiscal transfers is critical for broader biodiversity management interventions. In addition, REDD+ (Reduced Emissions from Deforestation and Land Degradation) initiatives have been promoted as a profitable mechanism to advance biodiversity conservation strategies while reducing carbon emissions. As far as ecosystem connectivity is concerned, its feasibility will strongly depend on the existence of a regulatory framework that appropriately balances property rights, environmental regulations and monetary incentives to ensure landowners' willingness to participate and maintain ecosystem corridors (Jones et al., 2020b). The demands of commodity-based economies, favouring extractive land uses, present serious barriers to upscaling biodiversity-based adaptation interventions (Seddon et al., 2020a). In addition, integrated assessments have shown how biodiversity-based solutions can deliver jobs from landscape restoration or income from wildlife tourism and how those benefits are fairly distributed (Chausson et al., 2020).

Legal and regulatory instruments are not perceived as major barriers to biodiversity management and ecosystem connectivity projects (Lausche et al., 2013; D'Aloia et al., 2019). A challenge that biodiversity-based measures still face is less acceptance among decision makers because their efficiency and cost-benefit ratio are difficult to determine and most of the measures are only effective in the long term (Lange et al., 2019). Methodologies to determine cost-effectiveness vary substantially between studies, in part because these analyses must be tailored to the socio–ecological context to be meaningful for local governance. This makes it challenging to capture and synthesise the full economic benefits of biodiversity-based solutions in comparison to alternatives (Chausson et al., 2020). In all, biodiversity and nature-based solutions have gained considerable political traction, with the greatest emphasis on the role of ecosystems as carbon sinks (Lange et al., 2019; Chausson et al., 2020; Seddon et al., 2020a).

Several social co-benefits are found to follow from biodiversity management strategies, including improved community health, recreational activities and eco-tourism, in addition to educational, spiritual and scientific benefits (Lausche et al., 2013; Worboys et al., 2016; Seddon et al., 2020a). Lavorel et al. (2020) show how the benefits of biodiversity management are co-produced by harnessing ecological and social capital to promote resilient ecosystems with high connectivity and functional diversity. Furthermore, Chausson et al. (2020) note how properly implemented NBS, including biodiversity management, can strengthen social networks and foster a sense of place, supporting virtuous cycles of community engagement to sustain interventions over time.

There is *high agreement* and *robust evidence* supporting the ecological capacity enhancement of biodiversity-based and ecosystem connectivity strategies (Thompson et al., 2017; Lavorel et al., 2020). Forest management that favours mixed-species rather than non-

Cross-Chapter Box FEASIB (continued)

native monocultures can promote the resilience of timber production and carbon storage while also benefiting biodiversity (Chausson et al., 2020). Similarly, monocultures have been found to impoverish biodiversity and hold less resilient carbon stocks than natural and semi-natural forests (Seddon et al., 2020a).

There is a *relatively high agreement* that ecosystem connectivity has the potential to improve the adaptive capacity of both ecological systems and humans. Krosby et al. (2010), for example, found that planting trees in short distances could increase the probability of range shifts in species that depend on the habitat those trees provide. Likewise, connectivity conservation has benefits for climate change mitigation (Lausche et al., 2013), but empirical evidence of the adaptation benefits for humans is scant. More recently, it has been found that biodiversity conservation reduces the risk of zoonotic diseases when it provides additional habitats for species and reduces the potential contact between wildlife, livestock and humans (Van Langevelde et al., 2020). Ecosystem-based approaches have been promoted to address the risk of increased zoonotic diseases, including the conservation of wildlife corridors (Gibb et al., 2020).

Despite abundant literature on the necessity to implement ecosystem connectivity strategies, many policy recommendations are mostly discursive and not supported by evidence. There is a lack of specificity when referring to the actors that should intervene in the design, implementation and evaluation of policies. What is more, most of the literature comes from the natural sciences and is concerned with co-benefits to wildlife and nature, with very little elaboration on the socioeconomic co-benefits for humans.

CCB FEASIB.3.2.7 Improved cropland management

Improved cropland management, which includes agricultural adaptation strategies such as integrated soil management, no/reduced tillage, conservation agriculture, planting of stress-resistant or early maturing crop varieties, and mulching, has high economic and environmental feasibility (*robust evidence, high agreement*) (AGEGNEHU and AMEDE, 2017; Lalani et al., 2017; Schulte et al., 2017; Thierfelder et al., 2017; Aryal et al., 2018a; Mayer et al., 2018; Prestele et al., 2018; Sova et al., 2018; Gonzalez-Sanchez et al., 2019; Lunduka et al., 2019; McFadden et al., 2019; Shah and Wu, 2019; TerAvest et al., 2019; Adams et al., 2020; Aryal et al., 2020a; Debie, 2020; Mutuku et al., 2020; Somasundaram et al., 2020; Du et al., 2021). Despite higher initial costs in some cases, the economic feasibility of improved cropland management is high through improved productivity, higher net returns and reduced input costs (Aryal, 2020; Mottaleb et al., 2017; Keil et al., 2019; Lunduka et al., 2019; McFadden et al., 2019; Parihar et al., 2020). Self-efficacy is shown to be the most important predictor in technical and non-technical adaptation behaviour (Zobeidi et al., 2021), while subsidies, extension services, training, commercial custom-hire services and strong social connections such as farmer networks are among the factors supporting adoption among farmers (Section 8.5.2.3) (Aryal et al., 2015a; Aryal et al., 2015b; Kannan and Ramappa, 2017; Bedeke et al., 2019; Acevedo et al., 2020). In some regions and for some practices, technological feasibility is constrained by costs and inadequate information and technical know-how on particular practices and their benefits and trade-offs, indicating medium feasibility (Khatri-Chhetri et al., 2016; Bhatta et al., 2017; Dougill et al., 2017; Kannan and Ramappa, 2017; Aryal et al., 2018a; Sova et al., 2018; Findlater et al., 2019). Delays between actions and tangible benefits can reduce public and private acceptability and uptake of improved cropland management practices (e.g., Dougill et al., 2017 in Malawi).

There remain institutional and financial barriers to improved cropland management such as lack of comprehensive policies, inadequate mainstreaming into national policy priorities (e.g., Amjath-Babu et al., 2019 and Reddy et al., 2020 in South Asia), fragmentation across different sectors (Dougill et al., 2017 in Malawi), and inadequate access to credit (Aryal et al., 2018c in India). Adoption of improved cropland management practices is often strongly mediated by gender: structural barriers such as unequal access to land, machinery, inputs, and extension and credit services, constrain adoption by female farmers (Aryal et al., 2018b; Aryal et al., 2018c) Mponela et al., 2016; Van Hulst and Posthumus, 2016; Ntshangase et al., 2018; Somasundaram et al., 2020). Improved cropland management practices have social and ecological co-benefits in terms of better health, education and food security (Agarwal, 2017; Farnworth et al., 2017; Hörner and Wollni, 2020) and better soil health and ecosystem functioning (AGEGNEHU and AMEDE, 2017; Mottaleb et al., 2017; Thierfelder et al., 2017; Zomer et al., 2017; Sarkar et al., 2018; Gonzalez-Sanchez et al., 2019; Shah and Wu, 2019; Du et al., 2020; Mutuku et al., 2020; Somasundaram et al., 2020).

There is *robust evidence* (*medium agreement*) that improved cropland management can have mitigation co-benefits but the exact quantity of emissions reductions and increased removals depend on agro-ecosystem type, climatic factors and cropping practices (VandenBygaart, 2016; Han et al., 2018; Mayer et al., 2018; Prestele et al., 2018; Singh et al., 2018a; Sommer et al., 2018; Gonzalez-Sanchez et al., 2019; Ogle et al., 2019; Shah and Wu, 2019; Adams et al., 2020; Aryal et al., 2020a; Li et al., 2020; Wang et al., 2020b; Shang et al., 2021).

CCB FEASIB.3.2.8 Efficient livestock systems

Enhancing the production efficiency of livestock systems through, for example, improved livestock diets, enhanced animal health, breeding and manure management, can contribute to adaptation and mitigation (Ericksen and Crane, 2018; Accatino et al., 2019; Paul

Cross-Chapter Box FEASIB (continued)

et al., 2020; IPCC WGIII AR6 Section 7.4.3). While the technological and ecological feasibility of improving livestock production systems is high (i.e., measures are technically well established, with different options applicable to a range of livestock production systems and ecological conditions), there are multiple context-specific barriers to adoption. These include the lack of coordinated policy support or governance, potentially high implementation costs and limited access to finance, inadequate advisory, knowledge exchange or infrastructural capacity (Escarcha et al., 2018; Paul et al., 2020), the potential land requirements and associated ecological impacts of adjusting livestock management, lack of context-specific research (Pardo and del Prado, 2020) and socio-cultural barriers limiting access by women or low-income groups to better breeds or feed varieties (Luqman et al., 2018; Salmon et al., 2018), as well as women losing influence in the household in some contexts when farms intensify (Tavenner and Crane, 2018). In dryland livestock systems in Ethiopia and Kenya, Ericksen and Crane (2018) find that low governance capacities to implement improved grazing regimes constrain improved grassland management.

CCB FEASIB.3.2.9 Water use efficiency and water resource management

There is high technological feasibility (*robust evidence*, *high agreement*) of improving water use efficiency as well as of managing water resources at basin and field scales. These approaches include rainwater harvesting, drip irrigation, laser land levelling, drainage management and stubble retention (Dasgupta and Roy, 2017; Khatri-Chhetri et al., 2017; Rahman et al., 2017; Adham et al., 2018; Darzi-Naftchali and Ritzema, 2018; Terêncio et al., 2018; Velasco-Muñoz et al., 2018; Sojka et al., 2019). There is *robust evidence* (*medium agreement*) that such measures have socioeconomic co-benefits and improve adaptive capacities through improved water supply (e.g., through rainwater harvesting, increased infiltration or integrated watershed management) and sustainable water demand management (e.g., reduction of evaporation loss). There is *medium evidence* (*high agreement*) of the option's economic feasibility due to water and energy cost savings enhanced by low-cost monitoring systems in some cases (Kodali and Sarjerao, 2017; Viani et al., 2017). Implementation costs vary widely, with land forming and irrigation infrastructure requiring substantial up-front investment, while mulches and cover crops are low-cost practices. Water management and use efficiency is currently constrained by governance and institutional factors such as inadequate institutional capacities to prepare for changing water availability, especially in the long term; unsustainable and unequal water use and sharing practices, particularly across boundaries; and fragmented and siloed resource management approaches (Lardizabal, 2015; Margerum and Robinson, 2015; Singh et al., 2020a).

CCB FEASIB.3.2.10 Livelihood diversification

Livelihood diversification is a key coping and adaptation strategy to climatic and non-climatic risks (Gautam and Andersen, 2016; Asfaw et al., 2018; Liu, 2015; Goulden et al., 2013; Makate et al., 2016; Orchard et al., 2016; Nyantakyi-Frimpong, 2017; Schuhbauer et al., 2017; Kihila, 2018; Radel et al., 2018; Tian and Lemos, 2018; Buechler and Lutz-Ley, 2019; Salam and Bauer, 2020). There is *robust evidence* (*medium agreement*) that diversifying livelihoods improves incomes and reduces socioeconomic vulnerability, but depending on livelihood type, opportunities and local context, feasibility changes (Section 8.5.1) (Barrett, 2013; Martin and Lorenzen, 2016; Sina et al., 2019). Livelihood diversification has positive and negative outcomes for adaptive capacity, especially in ecologically and resource-stressed regions (e.g. Anderson et al., 2017; Woodhouse and McCabe, 2018; Rosyida et al., 2019; Ojea et al., 2020), with diversification predominantly out of rural farm-based livelihoods on the rise (Rigg and Oven, 2015; Shackleton et al., 2015; Ober and Sakdapolrak, 2020). Key barriers to livelihood diversification include socio-cultural and institutional barriers (including social networks; Goulden et al., 2013) as well as inadequate resources and livelihood opportunities that hinder the full adaptive possibilities of existing livelihood diversification practices (Shackleton et al., 2015; Nightingale, 2017b; Bhowmik et al., 2021; Rahut et al., 2021). Autonomous diversification in the absence of more equitable and harmonised efforts at regional and national scales to facilitate sustainable diversification can further skew development indicators at the sub-national scale in favour of local elites, increased inequality and environmental degradation (Ford et al., 2014; Wilson, 2014; Alobo Loison, 2015; Tanner et al., 2015; Gautam and Andersen, 2016; Baird and Hartter, 2017; Torell et al., 2017; Asfaw et al., 2018; Woodhouse and McCabe, 2018; Brown et al., 2019; Rosyida et al., 2019; Sani Ibrahim et al., 2019; Ojea et al., 2020; Salam and Bauer, 2020).

CCB FEASIB.3.3 Urban and infrastructure system transitions

CCB FEASIB.3.3.1 Sustainable land use and urban planning

Urban planning is a medium feasibility option to support adaptation by prioritising it in city plans, such as land use planning, transportation (Liang et al., 2020), and health and social services (Carter et al., 2015; Araos et al., 2016b); by procuring the design and construction of resilient infrastructure; by promoting community-based adaptation through community-based design and implementation of adaptation activities (Archer, 2016); and by protecting and integrating biodiversity and ecosystem services into city planning. Research since SR1.5 documents the challenging high costs of infrastructure (Georgeson et al., 2016; Woodruff et al., 2018); potential loss of municipal revenue in the case of managed retreat (Shi and Varuzzo, 2020; Siders and Keenan, 2020); and the fraught causal connection between planning

Cross-Chapter Box FEASIB (continued)

and the reduction of socioeconomic vulnerability (Keenan et al., 2018; Anguelovski et al., 2019a; Elliott, 2019; Paganini, 2019; Shokry et al., 2020). However, adaptation benefits could potentially outweigh costs (Carey, 2020). There is financial viability of green infrastructure (Meerow, 2019; Zhang et al., 2019; Van Oijstaeijen et al., 2020; Ossola and Lin, 2021); and availability of technical expertise, although the inequitable planning processes and distribution of those resources remains a significant concern (Serre and Heinzlef, 2018; Szewrański et al., 2018; Fitzgibbons and Mitchell, 2019; Hasan et al., 2019; Heikkinen et al., 2019; Colven, 2020; Goetz et al., 2020; Goh, 2020).

Structural disincentives and institutional arrangements create challenges for planning even where political willingness may be high (Di Gregorio et al., 2019; DuPuis and Greenberg, 2019; Shi, 2019; Zen et al., 2019; Rasmussen et al., 2020). Social resistance may significantly delay or block progress entirely, as vulnerable communities have responded negatively in cases where adaptive urban and land use planning leads to perceived 'resilience gentrification' (Keenan et al., 2018; Anguelovski et al., 2019a), if residents do not perceive themselves as included in the crafting of plans (Araos, 2020; Rasmussen et al., 2020), if the options such as managed retreat are perceived as culturally unacceptable (Ajibade, 2019; Koslov, 2019; Siders, 2019), or if wealthier and advantaged residents benefit from planning at the expense of socially vulnerable groups (Chu and Michael, 2018; Chu et al., 2018; Fainstein, 2018; Rosenzweig et al., 2018; Pelling and Garschagen, 2019a; Ranganathan and Bratman, 2021). Nonetheless, potential social co-benefits related to health and education are high (Raymond et al., 2017; Spaans and Waterhout, 2017; Klinenberg, 2018; Keeler et al., 2019; Meerow, 2019). Finally, the option is highly feasible in relation to ecological and geophysical characteristics, as urban and land use planning's primary tool is to shape the built environment and natural spaces to protect and reduce the vulnerability of residents.

CCB FEASIB.3.3.2 Green infrastructure and ecosystem services

Urban green infrastructure and ecosystem services have high feasibility to support climate adaptation and mitigation efforts in cities, for example to reduce flood exposure and attenuate the urban heat island effect (Perrotti and Stremke, 2018; Belčáková et al., 2019; De la Sota et al., 2019; Stefanakis, 2019). While green infrastructure options are cost-effective and provide co-benefits in terms of ecosystem services such as improved air quality or other health benefits (Depietri and McPhearson, 2017; Morris et al., 2018; Reguero et al., 2018; Escobedo et al., 2019; Filazzola et al., 2019; Hewitt et al., 2020b; Venter et al., 2020; Nieuwenhuijsen, 2021) (*robust evidence, high agreement*), a need remains for systematically assessing co-benefits, particularly for flood risk management (Alves et al., 2019; Stefanakis, 2019) and sustainable material flow analysis (Perrotti and Stremke, 2018). Moreover, while once neglected, rapidly increasing attention has been paid to the equity and justice dimensions of planning and implementing green infrastructure initiatives, such as inclusion of citizens in decision making or the allocation of benefits and impacts of projects (Anguelovski et al., 2019b; Buijs et al., 2019; Langemeyer et al., 2020; Venter et al., 2020)

Institutional barriers constrain the feasibility of urban green infrastructure (*medium confidence*), such as policy resistance to shift priorities from grey to green infrastructure (e.g., Johns, 2019 in Canada) or siloed governance structures (Willems et al., 2021). Further, social and political acceptability of green infrastructure is constrained by lack of confidence in efficacy (Thorne et al., 2018) or issues of accessibility (Biernacka and Kronenberg, 2018).

For flood management, a mix of green, blue and grey infrastructures are found effective, with grey infrastructure reducing the risk of flooding and green infrastructure yielding multiple co-benefits (Alves et al., 2019; Gu et al., 2019; Webber et al., 2020) but catchment-wide solutions are advocated as the best performing strategy (Webber et al., 2020). Recognising and addressing a full range of ecosystem disturbances and disasters over a larger urban spatial scale (Vargas-Hernández and Zdunek-Wielgołaska, 2021) are crucial for planning green infrastructure-based solutions. In some cases, low impact development interventions yield effective flood management outcomes but are adequate only for small flood peaks (Pour et al., 2020), with the major challenge being identifying best practices. NbS hold significant potential to achieve mitigation and adaptation goals in comparison with traditional approaches, but more research is necessary to understand their effectiveness, distribution, implementation at scale, cost-benefit and integration with spatial dimensions of planning (Davies et al., 2019; Dorst et al., 2019; Zwierzchowska et al., 2019; Hobbie and Grimm, 2020).

CCB FEASIB.3.3.3 Sustainable urban water management (blue infrastructure interventions e.g., lake/river restoration; rainwater harvesting)

Governments across scales can support urban sustainable water management with high feasibility by undertaking projects to recycle wastewater and runoff from higher intensity storms, with implications for decarbonisation and adaptation. Green infrastructure, for example, has shown a high potential to reduce water-use footprints and to save potable water for consumption (Liu and Jensen, 2018), and contributing to a 'circular' water system in cities (Oral et al., 2020). Supportive governance can yield positive outcomes such as improved water security (Jensen and Nair, 2019) and there is *medium evidence* and *high agreement* that participation, such as involving

Cross-Chapter Box FEASIB (continued)

informal settlement residents in water management can improve social inclusion (Pelling et al., 2018; Williams et al., 2018; Leigh and Lee, 2019b; Sletto et al., 2019). Green infrastructure can support the planning of 'sponge cities', such as in China, wherein large areas of green space, permeable surfaces and sustainable water sourcing combine to purify urban runoff, attenuate peak runoff and conserve water for consumption (Chan et al., 2018; Nguyen et al., 2019). Similar approaches in Dutch cities focus on designing and planning for the capturing, storing and draining of storm water (Dai et al., 2018). However, some interventions suffer from uncertainties in design, planning and financing (Nguyen et al., 2019). As drought becomes more severe in some regions, physical barriers in the form of reduced availability of water may become pressing (Singh et al., 2021b).

Deployment of decentralised water management through effective local governance frameworks, is an important water management strategy (Herslund and Mguni, 2019; Leigh and Lee, 2019b), but in general, insufficient institutional learning and capacity remains a critical barrier for the uptake of sustainable urban water management practices (Krueger et al., 2019a; Adem Esmail and Suleiman, 2020). Transnational networks of cities for sharing best practices in water supply and storm runoff treatment also hold the potential to scale sustainable management (Feingold et al., 2018). In rapidly growing large urban areas, sustainable water management faces challenges of institutional heterogeneity (Chu et al., 2018), scalar mismatch, particularly between river basin and city scales (van den Brandeler et al., 2019), and equity and justice concerns (Chu et al., 2018; Pelling et al., 2018). Finally, assessing the vulnerability of urban water infrastructures at city scale remains an important knowledge gap (Dong et al., 2020).

CCB FEASIB.3.4 Cross-cutting adaptation options

CCB FEASIB.3.4.1 Social safety nets

Social safety nets contribute to meeting development goals (e.g., poverty alleviation, accessible education and health services) and are increasingly being reconfigured to build adaptive capacities of the most vulnerable (Coirolo et al., 2013; Aleksandrova, 2020; Bowen et al., 2020; Fischer, 2020; Mueller et al., 2020). They include a range of policy and market-based instruments such as public works programmes and conditional or unconditional cash transfers, in-kind transfers, and insurance schemes (Centre, 2019; Aleksandrova, 2020). While there is *robust evidence* (*medium agreement*) that social safety nets can build adaptive capacities, reduce socioeconomic vulnerability and reduce risk linked to hazards (Fischer, 2020; Mueller et al., 2020), macroeconomic, institutional and regulatory barriers such as limited state resources, underdeveloped credit and insurance markets, and economic leakages constrain their feasibility (Singh et al., 2018c; Hansen et al., 2019; Aleksandrova, 2020; Lykke Strøbech and Bordon Rosa, 2020). Social safety nets have strong co-benefits with development goals (Section 8.6) (Castells-Quintana et al., 2018b; Ulrichs et al., 2019; Mueller et al., 2020) but these positive outcomes are constrained by inadequate regional inclusiveness (e.g., limited access in certain remote, rural areas; Singh et al., 2018b; Aleksandrova, 2020; Lykke Strøbech and Bordon Rosa, 2020) or focus on rural areas overlooks urban vulnerable groups (Coirolo et al., 2013).

CCB FEASIB.3.4.2 Risk spreading and sharing

There is *high confidence* on risk spreading and sharing, most commonly arranged through insurance, as an adaptation option, but high to medium feasibility depending on context (e.g., developed versus developing countries). Technological, economic and institutional feasibility is high, as insurance can spread risk, provide a buffer against the impact of climate hazards, support recovery and reduce the financial burden on governments, households and businesses (Wolfrom and Yokoi-Arai, 2015; O'Hare et al., 2016; Glaas et al., 2017; Jenkins et al., 2017; Patel et al., 2017; Kousky et al., 2021). Insurance can shift the mobilisation of financial resources away from *ad hoc* post-event payments, where funding is often unpredictable and delayed, towards more strategic approaches that are set up in advance of disastrous events (Surminski et al., 2016). By pricing risk, insurance can provide incentives for investments and behaviour that reduce vulnerability and exposure (Linnerooth-Bayer and Hochrainer-Stigler, 2015; Shapiro, 2016; Jenkins et al., 2017). Socio-cultural barriers, such as social inclusiveness, socio-cultural acceptability and gender equity constrains feasibility (Bageant and Barrett, 2017; Budhathoki et al., 2019). Insurance can provide disincentives for reducing risk through the transfer of the risk spatially and temporally, distorting incentives for adaptation if the pricing is too low (moral hazard) and is often unaffordable, poorly understood, and not widely utilised in developing nations even when subsidised, possibly leading to maladaptation (García Romero and Molina, 2015; Joyette et al., 2015; Lashley and Warner, 2015; Jin et al., 2016; Müller et al., 2017; Tesselaar et al., 2020). Insurance can reinforce exposure and vulnerability through underwriting a return to the 'status-quo' rather than enabling adaptive behaviour (e.g., through 'no-betterment' principles) (Collier and Cox, 2021). For low-income nations and in the absence of global support, insurance shifts responsibility to those least responsible for climate change (Surminski et al., 2016).

CCB FEASIB.3.4.3 Disaster risk management

There is *robust evidence* (*high agreement*) that DRM aids adaptation decision making, particularly where it is demand-driven, context-specific and supported by strong institutions, good governance, strong local engagement and trust across actors (Hasan et al., 2019; Kim

Cross-Chapter Box FEASIB (continued)

and Marcouiller, 2020; Peng et al., 2020; Smucker et al., 2020; Uddin et al., 2020; Webb, 2020; Ali et al., 2021; Anderson and Renaud, 2021; Glantz and Pierce, 2021; Ji and Lee, 2021; Villeneuve, 2021). These conditions are rarely met, and therefore DRM is often constrained by institutional factors that may even increase vulnerability (Booth et al., 2020; Islam et al., 2020b; Islam et al., 2020c; Marchezini, 2020; Goryushina, 2021; Mena and Hilhorst, 2021). The feasibility of DRM continues to be constrained by limited coordination across levels of government, lack of transparency and accountability, poor communication and a preference for top-down DRM processes that can undermine local institutions and perpetuate uneven power relationships (Atanga, 2020; Booth et al., 2020; Bordner et al., 2020; Bronen et al., 2020; Goryushina, 2021; Mena and Hilhorst, 2021; Son et al., 2021; Yumagulova et al., 2021). However, local integration of worldviews, belief systems and local and Indigenous Knowledge into DRM activities improves feasibility (Bordner et al., 2020; Cuaton and Su, 2020; Hosen et al., 2020; Sharma and Sharma, 2021), including disability-inclusive and gender-focused DRM (Ruszczyk et al., 2020; Crawford et al., 2021). Data access and availability continues to challenge DRM despite advances in data analytics, especially in rapidly growing informal settlements, including population estimates and limited mobility data (Goniewicz and Burkle, 2019; Marchezini, 2020).

Moves towards community-based and ecosystem-based DRMs are promising but uneven (Klein et al., 2019; Seebauer et al., 2019; Almutairi et al., 2020; Bordner et al., 2020; Hosen et al., 2020; Murti et al., 2020; Sharma and Sharma, 2021), and may increase vulnerability if they fail to address underlying, structural determinants of vulnerability, particularly among marginalised groups and by gender (Sections 8.4.4 and 8.4.5) (Seleka et al., 2017; Hossen et al., 2019; Ramalho, 2019b; Atanga, 2020; Cuaton and Su, 2020; Gartrell et al., 2020; Kenney and Phibbs, 2020; Khalil et al., 2020; Ngin et al., 2020; Ruszczyk et al., 2020; Webb, 2020; Ali et al., 2021; Geekiyanage et al., 2021; Villeneuve, 2021).

CCB FEASIB.3.4.4 Climate services, including early warning systems

There is *robust evidence* (*high agreement*) that climate services aid adaptation decision making and build adaptive capacity, particularly where they are demand-driven and context-specific (Vaughan et al., 2018; Bruno Soares and Buontempo, 2019; Daniels et al., 2020; Hewitt et al., 2020a; Findlater et al., 2021). Climate service interventions are constrained by low capacity, inadequate institutions, difficulties in maintaining systems beyond pilot project stage (Vincent et al., 2017; Tall et al., 2018; Bruno Soares and Buontempo, 2019), and poor mapping between climate services and existing user capacities and demands (Williams et al., 2020) (*robust evidence*, *high agreement*). Metrics to assess outcomes of climate services remain project-based and insufficiently capture longer-term economic and non-economic benefits of interventions (Tall et al., 2018; Parton et al., 2019; Perrels, 2020). The technical feasibility of climate services is relatively strong and growing (Vaughan et al., 2016; Kihila, 2017; Findlater et al., 2021) but they can be made more inclusive by focusing on addressing uneven uptake based on location or gender (Amegnaglo et al., 2017; Daly and Dessai, 2018; Tall et al., 2018; Alexander and Dessai, 2019; Vaughan et al., 2019; Gumucio et al., 2020) and a more balanced focus on uptake rather than data production alone (Dorward et al., 2021; Findlater et al., 2021) that values co-production and different knowledge systems (Daniels et al., 2020; Martínez-Barón et al., 2021).

CCB FEASIB.3.4.5 Health and health systems adaptation

Climate change will exacerbate existing health challenges. Strong health systems can protect and promote the health of a population in the face of known and unexpected stressors and pressures (Watts et al., 2021), including climate change. The building blocks of strong health systems engender climate resilience, strong leadership and governance, and effective coordination across sectors, to prioritise the needs of the most vulnerable (Ebi et al., 2020). Options for enhancing current health services include providing access to safe water and sanitation, improving food security, enhancing access to essential services such as vaccinations, developing or strengthening integrated surveillance systems, and changing the timing and location of specific vector-control measures (WHO, 2015; Haines and Ebi, 2019). These measures can reduce the health system's vulnerability to climate change, especially if combined with iterative management that incorporates monitoring of (and resilience against) climate change impacts (Hanefeld et al., 2018; Haines and Ebi, 2019; Linares et al., 2020; Rudolph et al., 2020) (*medium evidence*, *high agreement*).

Health systems can provide sufficient and high-quality healthcare to all where capacity is well developed, and where options are aligned with national priorities, engage local to international communities, and address the needs of particularly vulnerable regions and population groups (Hanefeld et al., 2018; Austin et al., 2019; Nuzzo et al., 2019; Sheehan and Fox, 2020). Microeconomic feasibility and socioeconomic vulnerability reduction potential are high where a system's capacity is well developed. Economic feasibility poses a significant challenge in low-income settings, with many governments projected to require international climate finance for health systems which is not currently available (WHO, 2019; Watts et al., 2021), and where adequate household-level financial security is a cross-cutting barrier (Paudel and Pant, 2020). Risk mitigation potential is high where capacity is well developed, for example through technologies to monitor and alter environmental conditions (Lock-Wah-Hoon et al., 2020; Kouis et al., 2021; Ligsay et al., 2021). Social co-benefits of mainstreaming health and climate change are also present, such as the inclusion of environmental health in medical education curricula training programmes (Kligler et al., 2021). There is growing recognition that lack of institutional capacity and low availability of resources represent major barriers to health system adaptation options, particularly for health systems struggling to manage current health risks

Cross-Chapter Box FEASIB (continued)

(Ebi et al., 2018; Brooke-Sumner et al., 2019; Chersich and Wright, 2019; Gilfillan, 2019; Negev et al., 2019; Hussey and Arku, 2020), for neglected populations (Hanefeld et al., 2018; Negev et al., 2019), and where there are conflicting mandates or poor coordination across ministries (Austin et al., 2019; Fox et al., 2019; Gilfillan, 2019; Kendrovski and Schmoll, 2019; Sheehan and Fox, 2020). Barriers to adapting health systems to climate change include lack of institutional funding, staff and data access (Austin et al., 2019; Schramm et al., 2020; Opoku et al., 2021), inadequate resources for evaluation and management of adaptation (Pascal et al., 2021), competing stakeholder goals and costly technology (Negev et al., 2021). Within the healthcare community, surveillance systems generally lack ways to integrate climate observation data, as well as expertise to critically evaluate these data, limiting their ability to plan and prepare for climate hazards and hospital-associated vulnerabilities (Runkle et al., 2018; Chersich and Wright, 2019; Liao et al., 2019). Although understanding of health vulnerability is growing (Berry et al., 2018), knowledge on the health effects of climate change among health practitioners remains limited (Ebi et al., 2018; Brooke-Sumner et al., 2019; Chersich and Wright, 2019; Fox et al., 2019; Liao et al., 2019; Albright et al., 2020). Mechanisms to ensure transparency and accountability of implementing, monitoring and evaluating adaptation within the health sector are lacking, across scales and contexts (Gostin and Friedman, 2017; Huynh and Stringer, 2018; Parry et al., 2019).

CCB FEASIB.3.4.6 Human migration

Much climate-related migration is associated with labour migration. Rural–urban migrant networks are important channels for remittances and knowledge that help build resilience to hazards in sending areas (Bragg et al., 2018; Obokata and Veronis, 2018; Semenza and Ebi, 2019; Maharjan et al., 2020; Porst et al., 2020). Whether migration reduces vulnerability for migrants depends on levels of control over the migration decision and assets such as wealth, and education of the migrant household (Thober et al., 2018; Cattaneo, 2019; Hoffmann et al., 2020; Maharjan et al., 2020; Sedova and Kalkuhl, 2020). Individuals from households of all levels of wealth migrate. However, poorer households do so with lower levels of choice and often more likely under duress, and in these cases, migration can undermine well-being (Suckall et al., 2016; Mallick et al., 2017; Nawrotzki and DeWaard, 2018; Natarajan et al., 2019). In some cases, migration can increase poverty in sending communities (Jacobson et al., 2019). Women in the sending community can experience an increase or decrease in the vulnerability, depending on the livelihoods people are moving into and existing asset bases (Banerjee et al., 2018; Banerjee et al., 2019b; Goodrich et al., 2019; Maharjan et al., 2020; Rao et al., 2020; Singh and Basu, 2020; Singh et al., 2020b).

Migration has been highly politicised, and climate-related immigration has been conceptualised in public and media discourse as a potential threat which limits adaptation feasibility (Telford, 2018; Honarmand Ebrahimi and Ossewaarde, 2019; McLeman, 2019; Wiegel et al., 2019; Hauer et al., 2020). Existing international agreements provide potential frameworks for climate-related migration to benefit adaptive capacity and sustainable development (Warner, 2018; Kälin, 2019). However, agreements to facilitate temporary or circular migration and remittances are often informal and limited in scope (Webber and Donner, 2017b; Margaret and Matias, 2020) and migrant receiving areas, particularly urban areas, can be better assisted to prepare for population change (Deshpande et al., 2019; Adger et al., 2020; Hauer et al., 2020). Policies and planning are lacking that would ensure that positive migration outcomes for sending and receiving areas and the migrants themselves (Wrathall et al., 2019; Adger et al., 2020; de Salles Cavedon-Capdeville et al., 2020; Hughes, 2020).

Investing in building *in situ* adaptive capacity through climate resilient development is a precondition to supporting high agency migration (Cundill et. al. 2021). Migration only tends to occur when adaptation *in situ* has been exhausted and thresholds for living with risk have been crossed (Sections 8.2.2.1, 8.4.4, 8.4.5) (McLeman, 2018; Adams and Kay, 2019; Semenza and Ebi, 2019). The financial, emotional and social costs of leaving are high (Adams and Kay, 2019; McNamara et al., 2021), there are environmental, health and well-being risks in destination areas (Schwerdtle et al., 2018; Schwerdtle et al., 2020), and existential threats to identity and citizenship (Oakes, 2019; Piguet, 2019; Desai et al., 2021). In receiving areas, without appropriate policies to ensure equitable provision of services, there can be socio-cultural barriers to in-migration where there is the perception of a loss caused by new arrivals, although outcomes are mixed (Koubi et al., 2018; Linke et al., 2018; Spilker et al., 2020; Petrova, 2021).

CCB FEASIB.3.4.7 Planned relocation and resettlement

Few climate-related planned resettlement and relocation initiatives have taken place. However, initial findings, and experience from past development and disaster-related resettlement programmes, show that when implemented in a top-down manner and without the full participation of those affected, resettlement increases vulnerability by undermining livelihoods and negatively impacting health, community cohesion and emotional and psychological well-being (Wilmsen and Webber, 2015; Dannenberg et al., 2019; Piggott-McKellar et al., 2019; Tabe, 2019; Ajibade et al., 2020; Henrique and Tschakert, 2020; Desai et al., 2021). Planned relocation could also redistribute vulnerability for those who do not move (Thomas and Benjamin, 2018; Mach et al., 2019a; Piggott-McKellar et al., 2019; Johnson et al., 2021; Maldonado et al., 2021) and vulnerability generally is reproduced along existing social cleavages often worsening inequality (See and Wilmsen, 2020). Approaches that foreground participation, non-material and socio-cultural factors, livelihoods and local power dynamics can be addressed and adjusted to prevent planned relocation from reproducing inequality (See and Wilmsen, 2020; Alverio et al., 2021).

Cross-Chapter Box FEASIB (continued)

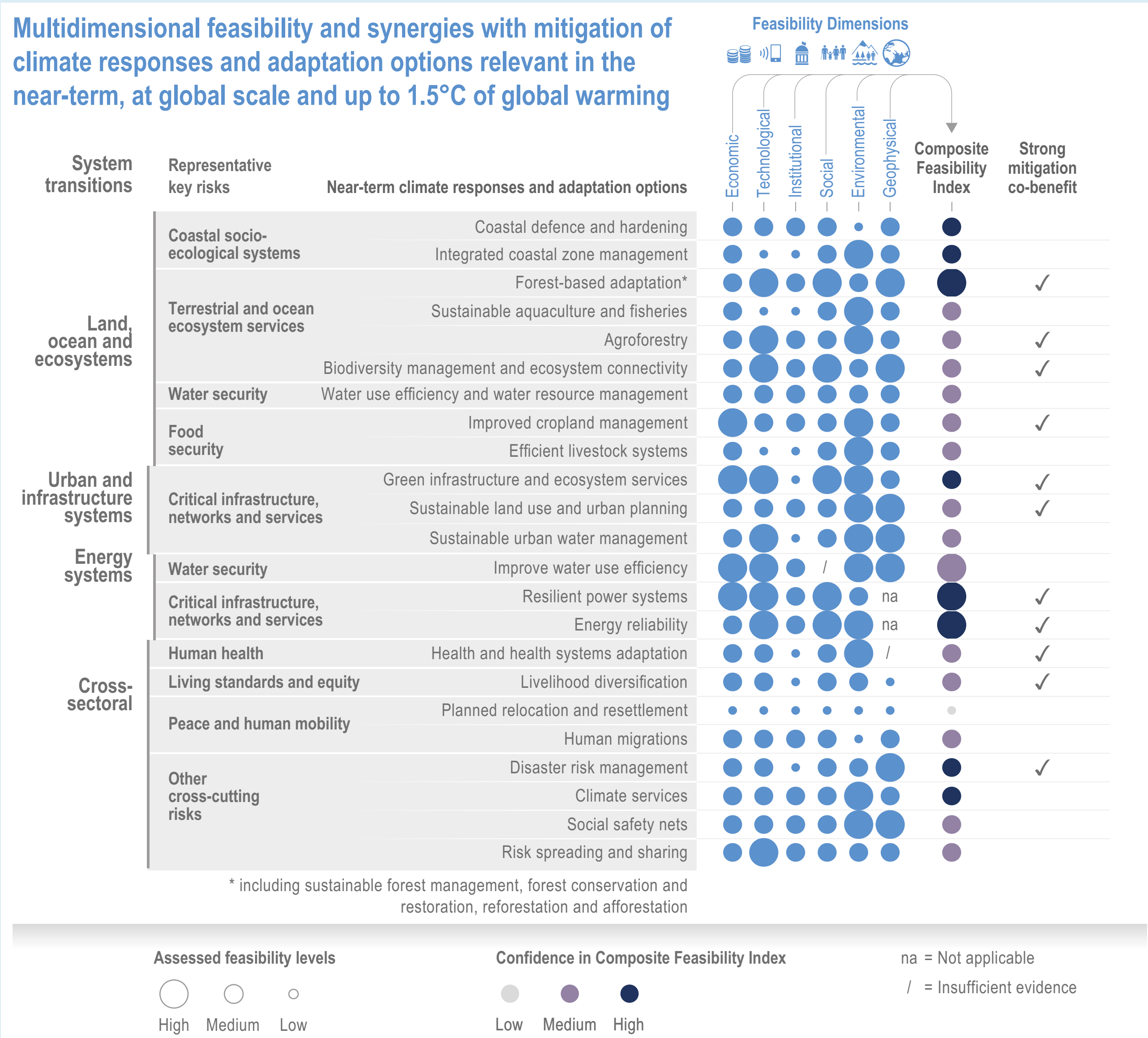


Figure Cross-Chapter Box FEASIB.2 | This figure summarizes the assessment results classifying options by System Transitions and Representative Key Risks. Each option is assessed across six dimensions: economic, technological, institutional, socio-cultural, environmental and geophysical. Each dimension is assessed as high (big circle), medium (medium circle), low (small circle) feasibility, and limited evidence or no evidence (LE/NE, as a dash). Composite feasibility is calculated across the six dimensions following the same key as above, with feasibility levels determined by circle size and confidence levels by shades of colour. The last column shows options with strong synergies with mitigation, which is then broken down in Fig. CCB FEASIB.3.

There is inadequate institutional capacity to enable movement relocation, with global and national policies identified as too abstract and lacking guidance on ensuring equity (Mortreux et al., 2018; Kelman et al., 2019; Ajibade et al., 2020; Hauer et al., 2020; Alverio et al., 2021). Lack of institutional capacity can lead to resettlements being stalled indefinitely. Climate-related resettlement can be facilitated by novel institutional structures that expand the definition of disaster to include slow onset events, adaptive management frameworks that facilitate a continuum of responses from supporting communities to community relocation and approaches that incorporate existing power dynamics (Bronen and Chapin, 2013; See and Wilmsen, 2020). In 2018, the Fiji Government provided a framework for climate change-related relocation and equipped communities with rights in the planned relocation process (McMichael and Katonivualiku, 2020). However, even with guidelines in place, local socio-cultural dynamics complicate planning, and relocation should take place only after cost–benefit analysis of all available adaptation options (Jolliffe, 2016; Bronen and Chapin, 2013; Albert et al., 2017; Mortreux et al., 2018). At a local level, issues around land tenure, a lack of financial support, dedicated governance frameworks and complex planning processes delay action (Albert et al., 2017). Funding for climate-related resettlement is currently not readily available, exacerbated by

Cross-Chapter Box FEASIB (continued)

a lack of appropriate mechanisms through which to deliver that funding (Boston et al., 2021). For example, planned relocation projects cannot access disaster relief funds in the USA because of the slow onset nature of the impacts (Bronen and Chapin, 2013).

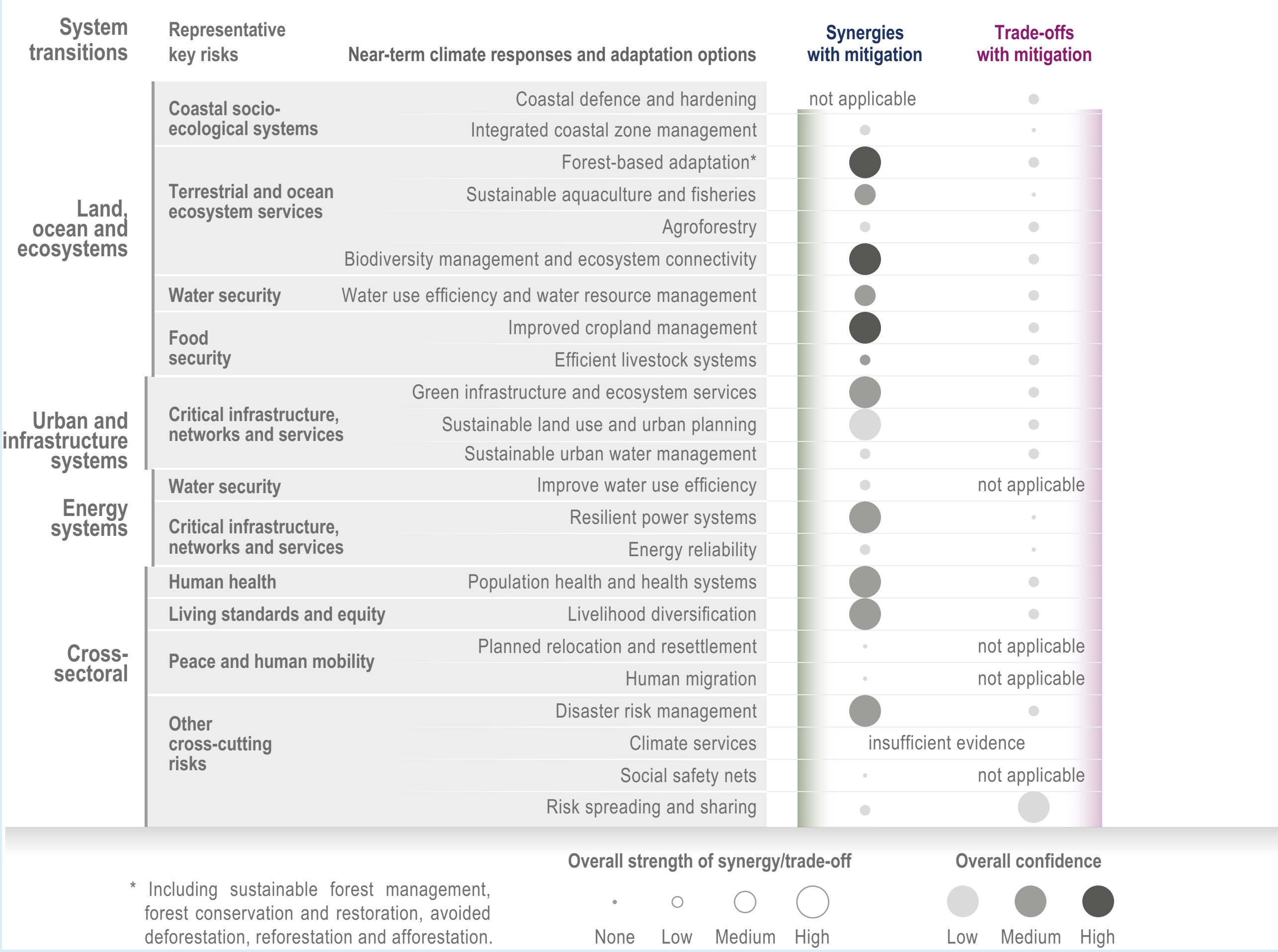
Without consultation, relocated people can experience significant financial and emotional distress as cultural and spiritual bonds to place and livelihoods are disrupted (Neef et al., 2018; Roy et al., 2018b; Piggott-McKellar et al., 2019; Bertana, 2020; McMichael and Katonivualiku, 2020; McMichael et al., 2021; Jain et al. 2021). However, in some places, where climate risks are acute, political acceptance for planned relocation is high (e.g., (McNamara, 2015; Roy et al., 2018b) in Kiribati). Socio-cultural feasibility can be improved by participatory approaches and, where possible, moving within ancestral lands (McNamara, 2015). In this case, voluntary planned relocation can represent the assertion of people living in an area to preserve land and community-based social, cultural and spiritual ties.

A summary of feasible options to enable four 1.5°C-relevant system transitions is presented in Figure Cross-Chapter Box FEASIB.2.

CCB FEASIB.4 Synergies and trade-offs

The feasibility assessment focuses on individual adaptation options. However, systems transitions necessitate assessing how mitigation and adaptation options *interact* to mediate overall feasibility. To capture these linkages, this section reports synergies and trade-offs of (a) adaptation options for mitigation and (b) mitigation options for adaptation (following (de Coninck et al., 2018b) as the outcome of an iterative assessment between WGII and WGIII authors. Also assessed are synergies and trade-offs of adaptation with the SDGs, following (which was done for mitigation alone).

(a) Climate responses and adaptation options and their implications for mitigation



Cross-Chapter Box FEASIB (continued)

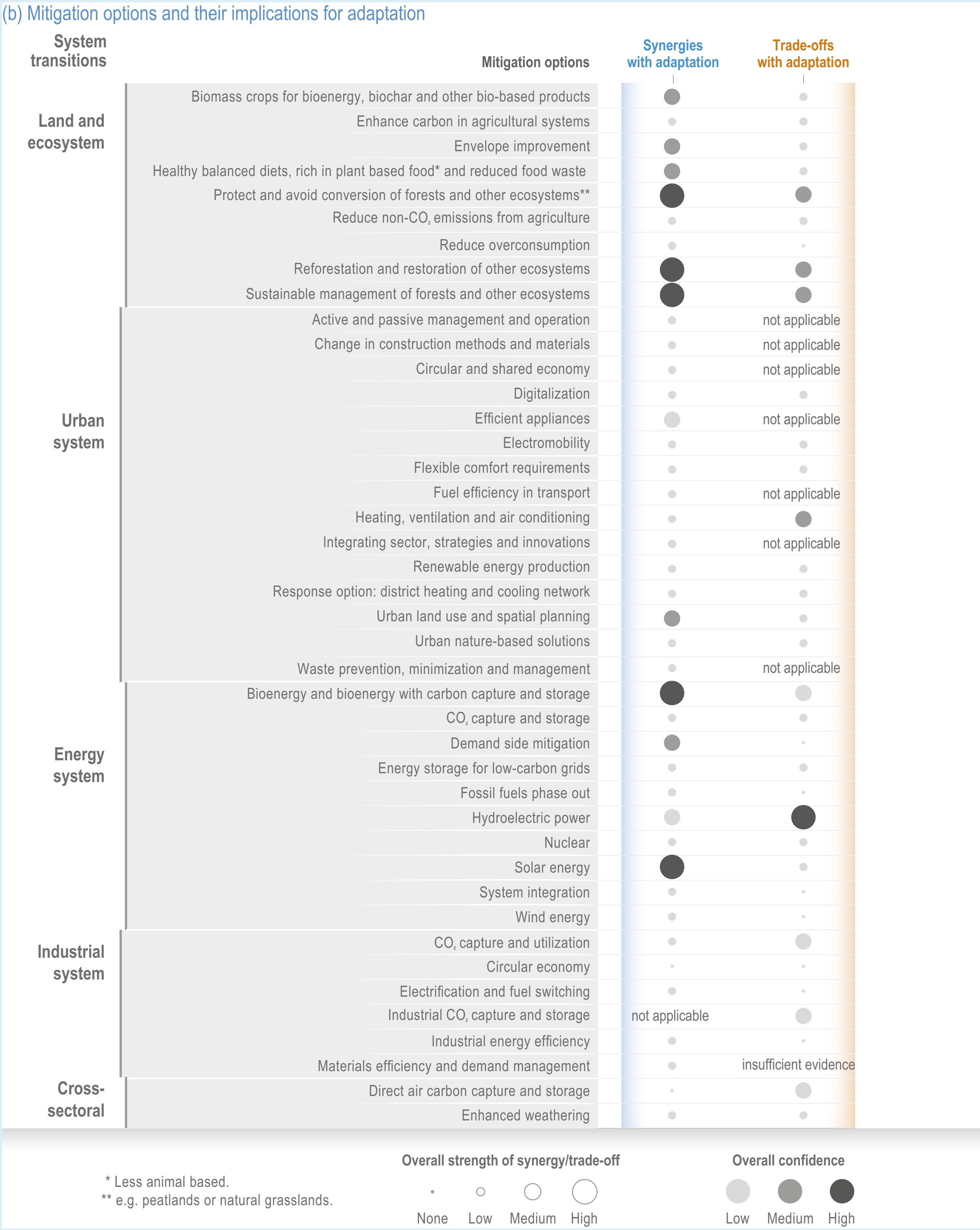


Figure Cross-Chapter Box FEASIB.3 | This figure shows a) adaptation options synergies and trade-offs with mitigation and b) mitigation options synergies and trade-offs with adaptation. The size of the circle denotes the strength of the synergy or trade-offs with big circles meaning strong synergy or trade-off and small circles denoting a weak synergy or trade-off.

Cross-Chapter Box FEASIB (continued)

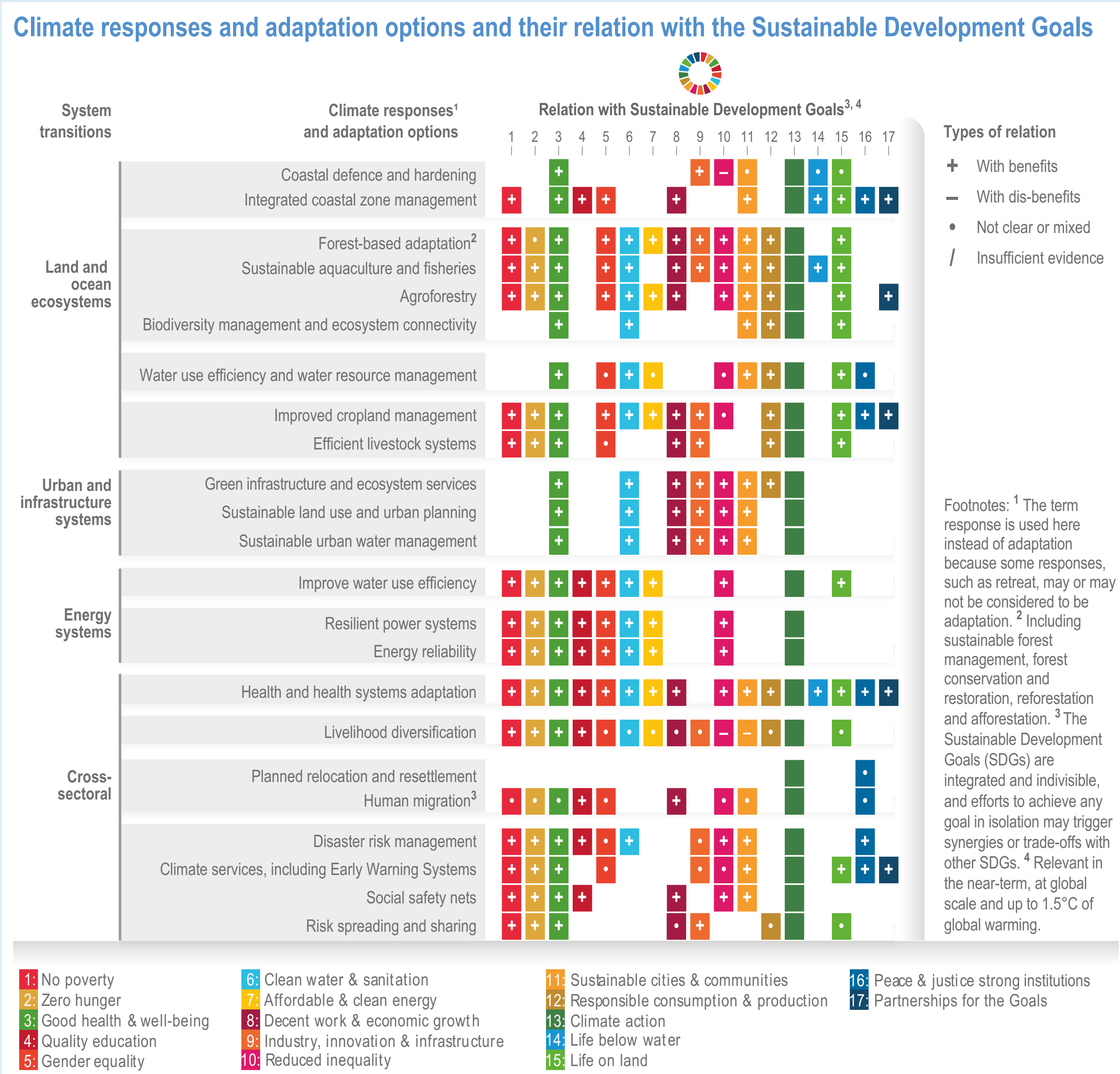


Figure Cross-Chapter Box FEASIB.4 | This figure summarises the assessment of the nexus of each adaptation option considered in this CCB with the 17 Sustainable Development Goals (SDGs). SDGs with which there is a nexus are colored and have a + for positive nexus, – for negative nexus and +/– for mixed nexus. Blank cells either don't have a nexus or there is no or limited evidence of such nexus.

CCB FEASIB.5 Knowledge Gaps

Despite the progress in new evidence since the SR1.5, there remain several knowledge gaps for the assessment of adaptation and mitigation options. They are underlying the Figure Cross-Chapter Box FEASIB.2 through the NE (no evidence) or LE (*limited evidence*).

Within energy system transitions, resilient power infrastructure has knowledge gaps on indicators of transparency and accountability potential, socio-cultural acceptability, social and regional inclusiveness, and intergenerational equity.

Cross-Chapter Box FEASIB (continued)

Under land and ecosystem system transitions, gaps include *limited evidence* for some of the institutional and socio-cultural feasibility dimensions indicators of Integrated Coastal Zone Management. Specifically, there is lack of evidence for transparency and accountability potential and for gender and intergenerational equity. For coastal defence and hardening, there is no or *limited evidence* on the indicators of employment and productivity enhancement, legal and regulatory acceptability, transparency and accountability potential, social and regional inclusiveness, benefits for gender equity, intergenerational equity and land use change enhancement potential. Sustainable aquaculture has knowledge gaps for the indicators of macroeconomic viability, legal and regulatory acceptability, transparency and accountability potential, social and regional inclusiveness, intergenerational equity and land use change enhancement potential. The geographical feasibility for migration and relocation is still an emerging area of research, however, there is *limited evidence* to assess this specific dimension.

The options of forest-based adaptation and biodiversity management and ecosystems connectivity have knowledge gaps for the indicators of risk mitigation potential, legal and regulatory feasibility, and social and regional inclusiveness. The option of improved cropland management has no or *limited evidence* for the indicators of legal and regulatory feasibility, transparency and accountability potential and hazard risk reduction potential. The efficient livestock systems option has no evidence for political acceptability and legal and regulatory feasibility, and *limited evidence* for overall institutional feasibility. Agro-forestry has knowledge gaps for employment and productivity enhancement, transparency and accountability potential and intergenerational equity. There is also *limited evidence* for the economic and technical feasibility dimensions for ecosystem connectivity.

For urban and infrastructure systems, the option of green infrastructure and ecosystem services has *limited evidence* for macroeconomic viability, employment and productivity enhancement, and political acceptability. Sustainable water management has gaps for macroeconomic viability, employment and productivity enhancement, and transparency and accountability potential.

For cross-cutting options, the main knowledge gaps identified are socio-cultural acceptability for social safety nets. While the evidence on resettlement, relocation and migration is large and growing, there is disagreement on several indicators, marking the need for more evidence synthesis. Geophysical feasibility for resettlement, relocation and migration has *limited evidence*, but is an emerging area of research.

In general, throughout most of the options, there is significantly less literature from the regions of Central and South America, and West and Central Asia, as compared with other world regions.

References

Accatino, F., et al., 2019: Trade-offs and synergies between livestock production and other ecosystem services. *Agric Syst*, **168**, 58–72, doi:10.1016/j.agsy.2018.08.002.

Acevedo, M., et al., 2020: A scoping review of adoption of climate-resilient crops by small-scale producers in low- and middle-income countries. *Nat. Plants*, **6**, 1231–1241, doi:10.1038/s41477-020-00783-z.

Adams, A.M., et al., 2020: Long-term effects of integrated soil fertility management practices on soil chemical properties in the Sahel. *Geoderma*, **366**, 114207, doi:10.1016/j.geoderma.2020.114207.

Adams, H. and S. Kay, 2019: Migration as a human affair: Integrating individual stress thresholds into quantitative models of climate migration. *Environ. Sci. Policy*, **93**, 129–138, doi:10.1016/j.envsci.2018.10.015.

Esmail, A. and L. Suleiman, 2020: Analyzing evidence of sustainable urban water management systems: a review through the lenses of sociotechnical transitions. *Sustainability*, **12**(11), doi:10.3390/su12114481.

Adger, W.N., et al., 2020: Urbanization, migration, and adaptation to climate change. *One Earth*, **3**, 396–399, doi:10.1016/j.oneear.2020.09.016.

Adham, A., et al., 2018: A GIS-based approach for identifying potential sites for harvesting rainwater in the Western Desert of Iraq. *Int. Soil Water Conserv. Res.*, **6**(4), 297–304, doi:10.1016/j.iswcr.2018.07.003.

Aerts, J.C.J.H., 2018: *A Review of Cost Estimates for Flood Adaptation*.

Agarwal, P.K. and D. Pandey, 2017, *Impact of pesticide: an overview.* Trends in Biosciences, (10)6, 1341–1344.

Agegnehu, G. and T. Amede, 2017: *Integrated Soil Fertility and Plant Nutrient Management in Tropical Agro-Ecosystems: A Review*. Soil Science Society of China, 662–680.

Ahmed, B., 2018: Who takes responsibility for the climate refugees? *Int. J. Clim. Chang. Strateg. Manag.*, **10**, 5–26, doi:10.1108/IJCCSM-10-2016-0149.

Ahmed, N., et al., 2018: Blue-green water nexus in aquaculture for resilience to climate change. *Rev. Fish. Sci. Aquac.*, **26**, 139–154, doi:10.1080/23308249.2017.1373743.

Ajibade, I., 2019: Planned retreat in global south megacities: disentangling policy, practice, and environmental justice. *Clim. Change*, doi:10.1007/s10584-019-02535-1.

Ajibade, I., M. Sullivan and M. Haeffner, 2020: Why climate migration is not managed retreat: Six justifications. *Glob. Environ. Chang.*, **65**, 102187, doi:10.1016/J.GLOENVCHA.2020.102187.

Cross-Chapter Box FEASIB (continued)

Albert, S., et al., 2017: Winners and losers as mangrove, coral and seagrass ecosystems respond to sea-level rise in Solomon Islands. *Environ. Res. Lett.*, **12**, 94009.

Albright, K., P. Shah, M. Santodomingo and J. Scandlyn, 2020: Dissemination of information about climate change by state and local public health departments: United States, 2019-2020. *Am J Public Health*, **110**, 1184–1190, doi:10.2105/AJPH.2020.305723.

Aleksandrova, M., 2020: Principles and considerations for mainstreaming climate change risk into national social protection frameworks in developing countries. *Clim. Dev.*, **12**, 511–520, doi:10.1080/17565529.2019.1642180.

Alexander, M. and S. Dessai, 2019: What can climate services learn from the broader services literature? *Clim. Change*, **157**, 133–149, doi:10.1007/s10584-019-02388-8.

Ali, B. and A. Kumar, 2016: Development of life cycle water footprints for gas-fired power generation technologies. *Energy Convers. Manag.*, **110**, 386–396, doi:10.1016/j.enconman.2015.12.048.

Ali, T., et al., 2021: Integrating Indigenous perspectives and community-based disaster risk reduction: a pathway for sustainable Indigenous development in Northern Pakistan. *Int. J. Disaster Risk Reduct.*, **59**, 102263, doi:10.1016/j.ijdrr.2021.102263.

Alleway, H.K., et al., 2018: The ecosystem services of marine aquaculture: valuing benefits to people and nature. *BioScience*, **69**, 59–68, doi:10.1093/biosci/biy137.

Almutairi, A., M. Mourshed and R.F.M. Ameen, 2020: *Coastal Community Resilience Frameworks for Disaster Risk Management*. Springer, 595–630.

Alobo Loison, S., 2015: Rural livelihood diversification in Sub-Saharan Africa: a literature review. *J. Dev. Stud.*, **51**, 1125–1138, doi:10.1080/00220388.2015.1046445.

Alverio, G.N., S.H. Hoagland, E.C. Perez and K.J. Mach, 2021: The role of international organizations in equitable and just planned relocation. *J Environ Stud Sci*, 1–12, doi:10.1007/S13412-021-00698-X.

Alves, A., et al., 2019: Assessing the co-benefits of green-blue-grey infrastructure for sustainable urban flood risk management. *J. Environ. Manag.*, **239**, 244–254, doi:10.1016/j.jenvman.2019.03.036.

Alves, B., D.B. Angnuureng, P. Morand and R. Almar, 2020: A review on coastal erosion and flooding risks and best management practices in West Africa: what has been done and should be done. *J. Coast. Conserv.*, **24**, 38, doi:10.1007/s11852-020-00755-7.

Ambrosino, C., et al., 2020: *Integrating climate adaptation, poverty reduction, and environmental conservation in Kwale county, Kenya*. Springer International Publishing, 1–19.

Amegnaglo, C.J., et al., 2017: Contingent valuation study of the benefits of seasonal climate forecasts for maize farmers in the Republic of Benin, West Africa. *Clim. Serv.*, **6**, 1–11, doi:10.1016/j.cliser.2017.06.007.

Amjath-Babu, T.S., P.K. Aggarwal and S. Vermeulen, 2019: Climate action for food security in South Asia? Analyzing the role of agriculture in nationally determined contributions to the Paris Agreement. *Clim. Policy*, **19**, 283–298, doi:10.1080/14693062.2018.1501329.

Anderson, C.C. and F.G. Renaud, 2021: A review of public acceptance of nature-based solutions: the 'why', 'when', and 'how' of success for disaster risk reduction measures. *Ambio*, **50**(8), 1552–1573, doi:10.1007/s13280-021-01502-4.

Anderson, S.C., et al., 2017: Benefits and risks of diversification for individual fishers. *Proc. Natl. Acad. Sci. U.S.A.*, **114**, 10797–10802, doi:10.1073/pnas.1702506114.

Anguelovski, I., et al., 2019a: New scholarly pathways on green gentrification: What does the urban 'green turn' mean and where is it going? *Prog Hum Geogr*, **43**, 1064–1086, doi:10.1177/0309132518803799.

Anguelovski, I., C. Irazábal-Zurita and J.J.T. Connolly, 2019b: Grabbed urban landscapes: Socio-spatial tensions in green infrastructure planning in Medellín. *Int. J. Urban Reg. Res.*, **43**, 133–156, doi:10.1111/1468-2427.12725.

Antunes do Carmo, J.S., 2018: *Climate Change, Adaptation Measures, and Integrated Coastal Zone Management: the New Protection Paradigm for the Portuguese Coastal Zone*. Coastal Education Research Foundation Inc., 687–703.

Apuri, I., K. Peprah and G.T.W. Achana, 2018: Climate change adaptation through agroforestry: The case of Kassena Nankana West District, Ghana. *Environ. Dev.*, **28**, 32–41, doi:10.1016/j.envdev.2018.09.002.

Araos, M., 2020: Democracy underwater: public participation and technical expertise in climate infrastructure planning in New York City. *Soc. Sci. Res. Netw.*

Araos, M., S.E. Austin, L. Berrang-Ford and J.D. Ford, 2016a: Public health adaptation to climate change in large cities: A global baseline. *Int J Health Serv*, **46**, 53–78, doi:10.1177/0020731415621458.

Araos, M., et al., 2016b: Climate change adaptation planning in large cities: A systematic global assessment. *Environ. Sci. Policy*, **66**, 375–382, doi:10.1016/j.envsci.2016.06.009.

Archer, D., 2016: Building urban climate resilience through community-driven approaches to development. *Int. J. Clim. Chang. Strateg. Manag.*, **8**, 654–669, doi:10.1108/IJCCSM-03-2014-0035.

Aryal, J.P., et al., 2018a: Adoption of multiple climate-smart agricultural practices in the Gangetic plains of Bihar, India. *Int. J. Clim. Chang. Strateg. Manag.*, **10**, 407–427, doi:10.1108/IJCCSM-02-2017-0025.

Aryal, J.P., M.B. Mehrotra, M.L. Jat and H.S. Sidhu, 2015a: Impacts of laser land leveling in rice–wheat systems of the north–western Indo-Gangetic plains of India. *Food Sec.*, **7**, 725–738, doi:10.1007/s12571-015-0460-y.

Aryal, J.P., et al., 2018b: Factors determining the adoption of laser land leveling in the irrigated rice–wheat system in Haryana, India. *J. Crop Improv.*, **32**, 477–492, doi:10.1080/15427528.2018.1457584.

Aryal, J.P., D.B. Rahut, S. Maharjan and O. Erenstein, 2018c: Factors affecting the adoption of multiple climate-smart agricultural practices in the Indo-Gangetic plains of India. *Nat Resour Forum*, **42**, 141–158, doi:10.1111/1477-8947.12152.

Cross-Chapter Box FEASIB (continued)

Aryal, J.P., T.B. Sapkota, M.L. Jat and D.K. Bishnoi, 2015b: On-farm economic and environmental impact of zero-tillage wheat: A case of North-West India. *Exp. Agric.*, **51**, 1–16, doi:10.1017/S001447971400012X.

Aryal, J.P., et al., 2020a: Climate change and agriculture in South Asia: adaptation options in smallholder production systems. *Environ. Dev. Sustain.*, **22**, 5045–5075, doi:10.1007/s10668-019-00414-4.

Aryal, J.P., T.B. Sapkota, D.B. Rahut and M.L. Jat, 2020b: Agricultural sustainability under emerging climatic variability: the role of climate-smart agriculture and relevant policies in India. *Int. J. Innov. Sustain. Dev.*, **14**, 219–245.

Asfaw, S., G. Pallante and A. Palma, 2018: Diversification strategies and adaptation deficit: evidence from rural communities in Niger. *World Dev*, **101**, 219–234, doi:10.1016/j.worlddev.2017.09.004.

Atanga, R.A., 2020: The role of local community leaders in flood disaster risk management strategy making in Accra. *Int. J. Disaster Risk Reduct.*, **43**, doi:10.1016/j.ijdrr.2019.101358.

Aubin, J., et al., 2019: Implementing ecological intensification in fish farming: definition and principles from contrasting experiences. *Rev. Aquac.*, **11**, 149–167, doi:10.1111/raq.12231.

Austin, S.E., et al., 2019: Enabling local public health adaptation to climate change. *Soc. Sci. Med.*, **220**, 236–244, doi:10.1016/j.socscimed.2018.11.002.

Awazi, N.P., M.N. Tchamba and L.F. Temgoua, 2021: Climate-smart practices of smallholder farmers in Cameroon confronted with climate variability and change: the example of agroforestry. *Agric. Res.*, **10**, 83–96, doi:10.1007/s40003-020-00477-0.

Bageant, E.R. and C.B. Barrett, 2017: Are there gender differences in demand for index-based livestock insurance? *J. Dev. Stud.*, **53**, 932–952, doi:10.1080/00220388.2016.1214717.

Baills, A., M. Garcin and T. Bulteau, 2020: Assessment of selected climate change adaptation measures for coastal areas. *Ocean. Coast. Manag.*, **185**, 105059, doi:10.1016/j.ocecoaman.2019.105059.

Baird, T.D. and J. Hartter, 2017: Livelihood diversification, mobile phones and information diversity in Northern Tanzania. *Land Use Policy*, **67**, 460–471, doi:10.1016/j.landusepol.2017.05.031.

Banerjee, S., et al., 2018: Assessing vulnerability of remittance-recipient and nonrecipient households in rural communities affected by extreme weather events: Case studies from S outh-W est. *Wiley Online Libr.*, **25**, doi:10.1002/psp.2157.

Banerjee, S., A. Hussain, S. Tuladhar and A. Mishra, 2019: Building capacities of women for climate change adaptation: insights from migrant-sending households in Nepal. *Clim. Change*, **157**, 587–609, doi:10.1007/S10584-019-02572-W.

Barnett, J., et al., 2015: From barriers to limits to climate change adaptation: Path dependency and the speed of change. *Ecol. Soc.*, **20**, doi:10.5751/ES-07698-200305.

Barragán Muñoz, J.M., 2020: Progress of coastal management in Latin America and the Caribbean. *Ocean. Coast. Manag.*, **184**, 105009, doi:10.1016/j.ocecoaman.2019.105009.

Barreto, G.C., M. Di Domenico and R.P. Medeiros, 2020: Human dimensions of marine protected areas and small-scale fisheries management: A review of the interpretations. *Mar. Policy.*, **119**, 104040, doi:10.1016/j.marpol.2020.104040.

Barrett, S., 2013: Local level climate justice? Adaptation finance and vulnerability reduction. *Glob. Environ. Change*, **23**(6), 1819–1829, doi:10.1016/j.gloenvcha.2013.07.015.

Bazaz, A., et al. (ed.), *Summary for Urban Policymakers – What the IPCC Special Report on 1.5C Means for Cities*.

Bedeke, S., et al., 2019: Adoption of climate change adaptation strategies by maize-dependent smallholders in Ethiopia. *Njas - Wageningen J. Life Sci.*, **88**, 96–104, doi:10.1016/j.njas.2018.09.001.

Belčáková, I., M. Świąder and M. Bartyna-Zielińska, 2019: The green infrastructure in cities as a tool for climate change adaptation and mitigation: Slovakian and Polish experiences. *Atmosphere*, **10**(9), doi:10.3390/atmos10090552.

Berrang-Ford, L., et al., 2019: Tracking global climate change adaptation among governments. *Nature Clim Change*, **9**, 440–449, doi:10.1038/s41558-019-0490-0.

Berry, P., et al., 2018: *Assessing Health Vulnerabilities and Adaptation to Climate Change: a Review of International Progress*. MDPI AG.

Bertana, A., 2020: The role of power in community participation: Relocation as climate change adaptation in Fiji. *Environ. Plan. C Polit. Space*, **38**(5), 902–919, doi:10.1177/2399654420909394.

Bhatta, G.D., et al., 2017: Agricultural innovation and adaptation to climate change: empirical evidence from diverse agro-ecologies in South Asia. *Environ. Dev. Sustain.*, **19**, 497–525, doi:10.1007/s10668-015-9743-x.

Bhattarai, B., 2020: How do gender relations shape a community's ability to adapt to climate change? Insights from Nepal's community forestry. *Clim. Dev.*, **12**, 876–887, doi:10.1080/17565529.2019.1701971.

Bhowmik, J., H.M. Irfanullah and S.A. Selim, 2021: Empirical evidence from Bangladesh of assessing climate hazard-related loss and damage and state of adaptive capacity to address them. *Clim. Risk Manag.*, **31**, 100273, doi:10.1016/j.crm.2021.100273.

Biernacka, M. and J. Kronenberg, 2018: Classification of institutional barriers affecting the availability, accessibility and attractiveness of urban green spaces. *Urban For. Urban Green.*, **36**, 22–33, doi:10.1016/j.ufug.2018.09.007.

Biesbroek, G.R., J.E.M. Klostermann, C.J.A.M. Termeer and P. Kabat, 2013: On the nature of barriers to climate change adaptation. *Reg Environ Change*, **13**, 1119–1129, doi:10.1007/s10113-013-0421-y.

Blasiak, R. and C.C.C. Wabnitz, 2018: Aligning fisheries aid with international development targets and goals. *Mar. Policy*, **88**, 86–92, doi:10.1016/j.marpol.2017.11.018.

Blasiak, R., et al., 2019: Towards greater transparency and coherence in funding for sustainable marine fisheries and healthy oceans. *Mar. Policy*, **107**, 103508, doi:10.1016/j.marpol.2019.04.012.

Bohnes, F.A., M.Z. Hauschild, J. Schlundt and A. Laurent, 2019: Life cycle assessments of aquaculture systems: a critical review of reported findings with recommendations for policy and system development. *Rev. Aquac.*, **11**, 1061–1079, doi:10.1111/raq.12280.

Cross-Chapter Box FEASIB (continued)

Booth, L., et al., 2020: Simulating synergies between climate change adaptation and disaster risk reduction stakeholders to improve management of transboundary disasters in europe. *Int. J. Disaster Risk Reduct.*, **49**, 101668, doi:10.1016/j.ijdrr.2020.101668.

Bordner, A.S., C.E. Ferguson and L. Ortolano, 2020: Colonial dynamics limit climate adaptation in Oceania: perspectives from the Marshall Islands. *Glob. Environ. Change*, **61**, 102054, doi:10.1016/j.gloenvcha.2020.102054.

Boston, J., A. Panda and S. Surminski, 2021: Designing a funding framework for the impacts of slow-onset climate change — insights from recent experiences with planned relocation. *Curr. Opin. Environ. Sustain.*, **50**, 159–168, doi:10.1016/j.cosust.2021.04.001.

Botero, C.M. and S. Zielinski, 2020: The implementation of a world-famous tourism ecolabel triggers political support for beach management. *Tour. Manag. Perspect.*, **35**, 100691, doi:10.1016/j.tmp.2020.100691.

Bowen, T., et al., 2020: *Adaptive Social Protection: Building Resilience to Shocks*. doi:10.1596/978-1-4648-1575-1. Adaptive Social Protection: Building Resilience to Shocks.

Boyd, C.E., et al., 2020: Achieving sustainable aquaculture: Historical and current perspectives and future needs and challenges. *J. World Aquac. Soc.*, **51**, 578–633, doi:10.1111/jwas.12714.

Bragg, C., et al., 2018: Remittances as aid following major sudden-onset natural disasters. *Disasters*, **42**, 3–18, doi:10.1111/DISA.12229.

Brand, U. and A. von Gleich, 2015: Transformation toward a secure and precaution-oriented energy system with the guiding concept of resilience – implementation of low-Exergy solutions in northwestern Germany. *Energies*, **8**, 6995–7019, doi:10.3390/en8076995.

Bricknell, I.R., et al., 2021: Resilience of cold water aquaculture: a review of likely scenarios as climate changes in the Gulf of Maine. *Rev. Aquac.*, **13**, 460–503, doi:10.1111/RAQ.12483.

Bronen, R. and F.S. Chapin, 2013: Adaptive governance and institutional strategies for climate-induced community relocations in Alaska. *Proc. Natl. Acad. Sci.*, **110**, 9320–9325, doi:10.1073/pnas.1210508110.

Bronen, R., et al., 2020: Usteq: integrating indigenous knowledge and social and physical sciences to coproduce knowledge and support community-based adaptation. *Polar Geogr.*, **43**(2-3), 188–205, doi:10.1080/1088937X.2019.1679271.

Brooke-Sumner, C., et al., 2019: 'Doing more with less': a qualitative investigation of perceptions of south African health service managers on implementation of health innovations. *Health Policy Plan.*, **34**, 132–140, doi:10.1093/heapol/czz017.

Brown, B., I. Nuberg and R. Llewellyn, 2017: Negative evaluation of conservation agriculture: perspectives from African smallholder farmers. *Int. J. Agric. Sustain.*, **15**, 467–481, doi:10.1080/14735903.2017.1336051.

Brown, P.R., et al., 2019: Constraints to the capacity of smallholder farming households to adapt to climate change in South and Southeast Asia. *Clim. Dev.*, **11**, 383–400, doi:10.1080/17565529.2018.1442798.

Bruno Soares, M. and C. Buontempo, 2019: Challenges to the sustainability of climate services in Europe. *WIREs Clim. Change*, **10**(4), e587, doi:10.1002/wcc.587.

Budhathoki, N.K., J.A. Lassa, S. Pun and K.K. Zander, 2019: Farmers' interest and willingness-to-pay for index-based crop insurance in the lowlands of Nepal. *Land Use Policy*, **85**, 1–10, doi:10.1016/j.landusepol.2019.03.029.

Buechler, S. and A. Lutz-Ley, 2019: Livelihoods with multiple stressors: Gendered youth decision-making under global change in rural Northwest Mexico. *Environ. Plan. E: Nat. Space*, **3**(4), 1096–1119, doi:10.1177/2514848619878603.

Buijs, A., et al., 2019: Mosaic governance for urban green infrastructure: Upscaling active citizenship from a local government perspective. *Urban For. Urban Green.*, **40**, 53–62, doi:10.1016/J.UFUG.2018.06.011.

Bustamante, M.M.C., et al., 2019: *Ecological restoration as a strategy for mitigating and adapting to climate change: lessons and challenges from Brazil*. Springer Netherlands, 1249–1270.

Butler, J.R.A., et al., 2020: How feasible is the scaling-out of livelihood and food system adaptation in Asia-Pacific islands? *Front. Sustain. Food Syst.*, **4**, 43, doi:10.3389/fsufs.2020.00043.

Cantasano, N., et al., 2021: Can ICZM contribute to the mitigation of erosion and of human activities threatening the natural and cultural heritage of the coastal landscape of Calabria? *Sustainability*, **13**, doi:10.3390/su13031122.

Carey, J., 2020: Core concept: managed retreat increasingly seen as necessary in response to climate change's fury. *Proc. Natl. Acad. Sci.*, **117**, 202008198, doi:10.1073/pnas.2008198117.

Carter, J.G., et al., 2015: Climate change and the city: Building capacity for urban adaptation. *Prog. Plann.*, **95**, 1–66, doi:10.1016/j.progress.2013.08.001.

Castells-Quintana, D., M.P. d. Lopez-Uribe and T.K.J. McDermott, 2018: Adaptation to climate change: A review through a development economics lens. *World Dev*, **104**, 183–196, doi:10.1016/j.worlddev.2017.11.016.

Castle, S.E., et al., 2021: The impacts of agroforestry interventions on agricultural productivity, ecosystem services, and human well-being in low- and middle-income countries: A systematic review. *Campbell Syst. Rev.*, **17**, e1167, doi:10.1002/CL2.1167.

Cattaneo, C., 2019: Migrant networks and adaptation. *Nature Clim Change*, **9**, 907–908, doi:10.1038/s41558-019-0646-y.

Caviedes, V., P. Arenas-Granados and J.M. Barragán-Muñoz, 2020: Regional public policy for integrated coastal zone management in Central America. *Ocean. Coast. Manag.*, **186**, 105114, doi:10.1016/j.ocecoaman.2020.105114.

Cechin, A., A. da Silva and L. Amand, 2021: Exploring the synergy between community supported agriculture and agroforestry: institutional innovation from smallholders in a Brazilian rural settlement. *J Rural Stud*, **81**, 246–258, doi:10.1016/j.jrurstud.2020.10.031.

Cedamon, E., I. Nuberg, B.H. Pandit and K.K. Shrestha, 2018: Adaptation factors and futures of agroforestry systems in Nepal. *Agrofor. Syst.*, **92**, 1437–1453, doi:10.1007/s10457-017-0090-9.

Centre, F. a. R. C. R. C. C. (ed.), *Managing Climate Risks Through Social Protection Reducing Rural Poverty and Building Resilient Agricultural Livelihoods*. Rome, ISBN 978-9251318843.

Chan, C.Y., et al., 2019: *Prospects and challenges of fish for food security in Africa*. Elsevier B.V., 17–25.

Cross-Chapter Box FEASIB (continued)

Chan, F.K.S., et al., 2018: "Sponge city" in China—A breakthrough of planning and flood risk management in the urban context. *Land Use Policy*, **76**, 772–778, doi:10.1016/J.LANDUSEPOL.2018.03.005.

Chausson, A., et al., 2020: Mapping the effectiveness of nature-based solutions for climate change adaptation. *Glob Change Biol*, **26**, 6134–6155, doi:10.1111/gcb.15310.

Chersich, M.F. and C.Y. Wright, 2019: *Climate change adaptation in South Africa: a case study on the role of the health sector*. BioMed Central Ltd.

Child, M. and C. Breyer, 2017: Transition and transformation: A review of the concept of change in the progress towards future sustainable energy systems. *Energy Policy*, **107**, 11–26, doi:10.1016/j.enpol.2017.04.022.

Chow, J., T. Khanom, R. Hossain and J. Khadim, 2019: Forest management for climate change adaptation in Bangladesh. In: Springer, Cham, pp. 39–50.

Chu, E. and K. Michael, 2018: Recognition in urban climate justice: marginality and exclusion of migrants in Indian cities. *SAGE journal.* **31**(1), 139–156, https://doi.org/10.1177%2F0956247818814449.

Chu, E., T. Schenk and J. Patterson, 2018: The dilemmas of citizen inclusion in urban planning and governance to enable a 1.5°C climate change scenario. *Urban Plan.*, **3**, 128–140, doi:10.17645/up.v3i2.1292.

Coe, R., F. Sinclair and E. Barrios, 2014: Scaling up agroforestry requires research 'in' rather than 'for' development. *Curr. Opin. Environ. Sustain.*, **6**, 73–77, doi:10.1016/j.cosust.2013.10.013.

Coirolo, C., S. Commins, I. Haque and G. Pierce, 2013: Climate change and social protection in Bangladesh: Are existing programmes able to address the impacts of climate change? *Dev Policy Rev*, **31**(o74), o90, doi:10.1111/dpr.12040.

Collier, S.J. and S. Cox, 2021: Governing urban resilience: insurance and the problematization of climate change. *Econ. Soc.*, **50**(2), 275–296, doi:10.1080/03085147.2021.1904621.

Colven, E., 2020: Thinking beyond success and failure: Dutch water expertise and friction in postcolonial Jakarta. *Environ. Plan. C: Polit. Space*, **38**, 961–979, doi:10.1177/2399654420911947.

Coulibaly, J.Y., B. Chiputwa, T. Nakelse and G. Kundhlande, 2017: Adoption of agroforestry and the impact on household food security among farmers in Malawi. *Agric. Syst.*, **155**, 52–69, doi:10.1016/j.agsy.2017.03.017.

Cowie, A.L., et al., 2021: Applying a science-based systems perspective to dispel misconceptions about climate effects of forest bioenergy. *GCB Bioenergy*, **13**(8), 1210–1231, doi:10.1111/gcbb.12844.

Crawford, T., et al., 2021: Disability inclusive disaster risk reduction with culturally and linguistically diverse (CALD) communities in the Hawkesbury-Nepean region: A co-production approach. *Int. J. Disaster Risk Reduct.*, **63**, 102430, doi:10.1016/j.ijdrr.2021.102430.

Cuaton, G.P. and Y. Su, 2020: Local-indigenous knowledge on disaster risk reduction: insights from the Mamanwa indigenous peoples in Basey, Samar after Typhoon Haiyan in the Philippines. *Int. J. Disaster Risk Reduct.*, **48**, 101596, doi:10.1016/j.ijdrr.2020.101596.

Custódio, M., S. Villasante, R. Calado and A.I. Lillebø, 2020: Valuation of ecosystem services to promote sustainable aquaculture practices. *Rev. Aquac.*, **12**, 392–405, doi:10.1111/raq.12324.

D'Aloia, C.C., et al., 2019: Coupled networks of permanent protected areas and dynamic conservation areas for biodiversity conservation under climate change. *Front. Ecol. Evol.*, **7**, 27, doi:10.3389/fevo.2019.00027.

Dai, L., R. Wörner and H.F.M.W. van Rijswick, 2018: Rainproof cities in the Netherlands: approaches in Dutch water governance to climate-adaptive urban planning. *Int. J. Water Resour. Dev.*, **34**, 652–674, doi:10.1080/07900627.2017.1372273.

Daly, M. and S. Dessai, 2018: Examining the goals of the regional climate outlook forums: what role for user engagement? *Weather Clim. Soc.*, **10**(4), 693–708, doi:10.1175/WCAS-D-18-0015.1.

Daniels, E., et al., 2020: Refocusing the climate services lens: Introducing a framework for co-designing "transdisciplinary knowledge integration processes" to build climate resilience. *Clim. Serv.*, **19**, 100181, doi:10.1016/j.cliser.2020.100181.

Dannenberg, A.L., H. Frumkin, J.J. Hess and K.L. Ebi, 2019: Managed retreat as a strategy for climate change adaptation in small communities: public health implications. *Clim. Change*, **153**(1), 1–14, doi:10.1007/s10584-019-02382-0.

Darzi-Naftchali, A. and H. Ritzema, 2018: Integrating irrigation and drainage management to sustain agriculture in northern Iran. *Sustainability*, **10**(6), doi:10.3390/su10061775.

Dasgupta, S. and J. Roy, 2017: Analysing energy intensity trends and decoupling of growth from energy use in Indian manufacturing industries during 1973–1974 to 2011–2012. *Energy Effic.*, **10**, 925–943, doi:10.1007/s12053-016-9497-9.

Davies, C.M., et al., 2019: *Potential of precision livestock farming in small ruminant farming systems*. Wageningen Academic Publishers. 717 pp.

De Beenhouwer, M., R. Aerts and O. Honnay, 2013: A global meta-analysis of the biodiversity and ecosystem service benefits of coffee and cacao agroforestry. *Agric. Ecosyst. Environ.*, **175**, 1–7, doi:10.1016/j.agee.2013.05.003.

de Coninck, H., A. Revi, M. Babiker, P. Bertoldi, M. Buckeridge, A. Cartwright, W. Dong, J. Ford, S. Fuss, J.-C. Hourcade, D. Ley, R. Mechler, P. Newman, A. Revokatova, S. Schultz, L. Steg, and T. Sugiyama, 2018: Strengthening and Implementing the Global Response. 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, 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.)]. In Press.

De la Sota, C., V.J. Ruffato-Ferreira, L. Ruiz-García and S. Alvarez, 2019: Urban green infrastructure as a strategy of climate change mitigation. A case study in northern Spain. *Urban For. Urban Green.*, **40**, 145–151, doi:10.1016/j.ufug.2018.09.004.

de Salles Cavedon-Capdeville, F., et al., 2020: *Climate change, extreme events and human mobility in Latin America: exploring the links through national laws and policies*.

Cross-Chapter Box FEASIB (continued)

Debie, E., 2020: Multi-criteria evaluation of soil conservation practices to sustainable cropland management in northwest highlands of Ethiopia. *Authorea Prepr.*, doi:10.22541/AU.159221547.73795848.

DeNooyer, T.A., J.M. Peschel, Z. Zhang and A.S. Stillwell, 2016: Integrating water resources and power generation: The energy-water nexus in Illinois. *Appl Energy*, **162**, 363–371, doi:10.1016/j.apenergy.2015.10.071.

Depietri, Y. and T. McPhearson, 2017: *Integrating the Grey, Green, and Blue in Cities: Nature-Based Solutions for Climate Change Adaptation and Risk Reduction*.

Desai, B., et al., 2021: Addressing the human cost in a changing climate. *Science*, **372**, 1284–1287, doi:10.1126/SCIENCE.ABH4283.

Deshpande, T., K. Michael and K. Bhaskara, 2019: Barriers and enablers of local adaptive measures: a case study of Bengaluru's informal settlement dwellers. *Local Environ.*, **24**, 167–179, doi:10.1080/13549839.2018.1555578.

Dhyani, S., et al., 2021: *Agroforestry to achieve global climate adaptation and mitigation targets: are South Asian countries sufficiently prepared?* MDPI AG. 303 pp.

Di Gregorio, M., et al., 2019: Multi-level governance and power in climate change policy networks. *Glob. Environ. Chang.*, **54**, 64–77, doi:10.1016/j.gloenvcha.2018.10.003.

Donatti, C.I., et al., 2020: Indicators to measure the climate change adaptation outcomes of ecosystem-based adaptation. *Clim Change*, **158**, 413–433, doi:10.1007/s10584-019-02565-9.

Dong, X., et al., 2020: Vulnerability of urban water infrastructures to climate change at city level. *Resour. Conserv. Recycl.*, **161**, doi:10.1016/J.RESCONREC.2020.104918.

Dooley, K., E. Harrould-Kolieb and A. Talberg, 2021: Carbon-dioxide removal and biodiversity: a threat identification framework. *Glob Policy*, **12**, 34–44, doi:10.1111/1758-5899.12828.

Dorst, H., A. van der Jagt, R. Raven and H. Runhaar, 2019: Urban greening through nature-based solutions – key characteristics of an emerging concept. *Sustain. Cities Soc.*, **49**, 101620, doi:10.1016/j.scs.2019.101620.

Dorward, P., G. Clarkson, S. Poskitt and R. Stern, 2021: Putting the farmer at the center of climate services. *One Earth*, **4**(8), 1059–1061, doi:10.1016/j.oneear.2021.08.004.

Dougill, A.J., et al., 2017: Mainstreaming conservation agriculture in Malawi: Knowledge gaps and institutional barriers. *J. Environ. Manag.*, **195**, 25–34, doi:10.1016/j.jenvman.2016.09.076.

Du, S., et al., 2020: Hard or soft flood adaptation? Advantages of a hybrid strategy for Shanghai. *Glob. Environ. Change*, **61**, 102037, doi:10.1016/j.gloenvcha.2020.102037.

Du, X., J. Jian, C. Du and R.D. Stewart, 2021: Conservation management decreases surface runoff and soil erosion. *Int. Soil Water Conserv. Res.*, doi:10.1016/j.iswcr.2021.08.001.

Duffy, C., et al., 2021: Agroforestry contributions to smallholder farmer food security in Indonesia. *Agrofor. Syst.*, **95**(6), 1109–1124, doi:10.1007/S10457-021-00632-8.

DuPuis, E.M. and M. Greenberg, 2019: The right to the resilient city: progressive politics and the green growth machine in New York City. *J Environ Stud Sci*, **9**, 352–363, doi:10.1007/s13412-019-0538-5.

Ebi, K.L., et al., 2018: Stress testing the capacity of health systems to manage climate change-related shocks and stresses. *IJERPH*, **15**, doi:10.3390/ijerph15112370.

Ebi, K.L., et al., 2020: Transdisciplinary research priorities for human and planetary health in the context of the 2030 agenda for sustainable development. *IJERPH*, **17**(23), doi:10.3390/ijerph17238890.

Eisenack, K., et al., 2014: Explaining and overcoming barriers to climate change adaptation. *Nature Clim Change*, **4**, 867–872, doi:10.1038/nclimate2350.

Elagib, N.A. and M. Al-Saidi, 2020: *Balancing the benefits from the water–energy–land–food nexus through agroforestry in the Sahel*. Elsevier B.V. 140509 pp.

Elliott, R., 2019: 'Scarier than another storm': values at risk in the mapping and insuring of US floodplains. *Br. J. Sociol.*, **70**, 1067–1090, doi:10.1111/1468-4446.12381.

Ellison, A.M., A.J. Felson and D.A. Friess, 2020: Mangrove rehabilitation and restoration as experimental adaptive management. *Front. Mar. Sci.*, **7**, 327, doi:10.3389/fmars.2020.00327.

Erftemeijer, P.L.A., et al., 2020: Mangrove planting on dredged material: Three decades of nature-based coastal defence along a causeway in the Arabian Gulf. *Mar. Freshw. Res.*, **71**, 1062–1072, doi:10.1071/MF19289.

Ericksen, P. and T. Crane (eds.), *The feasibility of low emissions development interventions for the East African livestock sector: Lessons from Kenya and Ethiopia*. International Livestock Research Institute, ISBN 978-9291465422. The feasibility of low emissions development interventions for the East African livestock sector: Lessons from Kenya and Ethiopia.

Erlinghagen, S. and J. Markard, 2012: Smart grids and the transformation of the electricity sector: ICT firms as potential catalysts for sectoral change. *Energy Policy*, **51**, 895–906, doi:10.1016/j.enpol.2012.09.045.

Escarcha, J.F., J.A. Lassa and K.K. Zander, 2018: Livestock under climate change: A systematic review of impacts and adaptation. *Climate*, **6**, 54, doi:10.3390/cli6030054.

Escobedo, F.J., et al., 2019: Urban forests, ecosystem services, green infrastructure and nature-based solutions: Nexus or evolving metaphors? *Urban For. Urban Green.*, **37**, 3–12, doi:10.1016/J.UFUG.2018.02.011.

Evans, L.S., et al., 2016: Structural and psycho-social limits to climate change adaptation in the Great Barrier Reef region. *PLoS ONE*, **11**, e150575.

Fainstein, S.S., 2018: Resilience and justice: planning for New York City. *Urban. Geogr.*, 1–8, doi:10.1080/02723638.2018.1448571.

FAO (ed.), *The State of World Fisheries and Aquaculture 2018*. Rome, Italy. 227 pp.

Cross-Chapter Box FEASIB (continued)

Farnworth, C.R., et al., 2017: Gender and inorganic nitrogen: what are the implications of moving towards a more balanced use of nitrogen fertilizer in the tropics? *Int. J. Agric. Sustain.*, **15**, 136–152, doi:10.1080/14735903.2017.1295343.

Favretto, N., et al., 2020: Delivering climate-development co-benefits through multi-stakeholder forestry projects in Madagascar: opportunities and challenges. *Land*, **9**, 157, doi:10.3390/land9050157.

Feingold, D., S. Koop and K. van Leeuwen, 2018: The city blueprint approach: Urban water management and governance in cities in the U.S. *Environ Manage*, **61**, 9–23, doi:10.1007/S00267-017-0952-Y.

Filazzola, A., N. Shrestha and J.S. MacIvor, 2019: The contribution of constructed green infrastructure to urban biodiversity: A synthesis and meta-analysis. *J Appl Ecol*, **56**, 2131–2143, doi:10.1111/1365-2664.13475.

Findlater, K., S. Webber, M. Kandlikar and S. Donner, 2021: Climate services promise better decisions but mainly focus on better data. *Nat. Clim. Change*, **11**(9), 731–737, doi:10.1038/s41558-021-01125-3.

Findlater, K.M., M. Kandlikar and T. Satterfield, 2019: Misunderstanding conservation agriculture: Challenges in promoting, monitoring and evaluating sustainable farming. *Environ. Sci. Policy*, **100**, 47–54, doi:10.1016/j.envsci.2019.05.027.

Fischer, H.W., 2020: Policy innovations for pro-poor climate support: social protection, small-scale infrastructure, and active citizenship under India's MGNREGA. *Clim. Dev.*, **12**, 689–702, doi:10.1080/17565529.2019.1676690.

Fitzgibbons, J. and C. Mitchell, 2019: Just urban futures? Exploring equity in "100 Resilient Cities". *World Dev*, **122**, 648–659, doi:10.1016/j.worlddev.2019.06.021.

Fleischman, F., et al., 2020: Pitfalls of tree planting show why we need people-centered natural climate solutions. *BioScience*, **70**, 947–950, doi:10.1093/biosci/biaa094.

Ford, J.D., et al., 2015: Adaptation tracking for a post-2015 climate agreement. *Nature Clim Change*, **5**, 967–969, doi:10.1038/nclimate2744.

Ford, J.D., J. Labbé, M. Flynn and M. Araos, 2017: Readiness for climate change adaptation in the Arctic: a case study from Nunavut, Canada. *Clim Change*, **145**, 85–100, doi:10.1007/s10584-017-2071-4.

Ford, J.D., et al., 2014: Adapting to the effects of climate change on Inuit health. *Am J Public Health*, **104**, e9–e17, doi:10.2105/AJPH.2013.301724.

Forster, E.J., J.R. Healey, C. Dymond and D. Styles, 2021: Commercial afforestation can deliver effective climate change mitigation under multiple decarbonisation pathways. *Nat Commun*, **12**(1), 3831, doi:10.1038/s41467-021-24084-x.

Foti, E., R.E. Musumeci and M. Stagnitti, 2020: Coastal defence techniques and climate change: a review. *Rendiconti Lincei*, **31**, 123–138, doi:10.1007/s12210-020-00877-y.

Fox, M., et al., 2019: *Integrating public health into climate change policy and planning: State of practice update*. MDPI AG.

Freduah, G., P. Fidelman and T.F. Smith, 2018: Mobilising adaptive capacity to multiple stressors: Insights from small-scale coastal fisheries in the western region of Ghana. *Geoforum*, **91**, 61–72, doi:10.1016/j.geoforum.2018.02.026.

Fuss, S., et al., 2018: Negative emissions – Part 2: Costs, potentials and side effects. *Environ. Res. Lett.*, **13**, 63002, doi:10.1088/1748-9326/aabf9 f.

Galappaththi, E.K., J.D. Ford and E.M. Bennett, 2019: *A framework for assessing community adaptation to climate change in a fisheries context*. Elsevier Ltd, 17–26.

Galappaththi, E.K., et al., 2020: Climate change adaptation in aquaculture. *Rev. Aquac.*, **12**, 2160–2176, doi:10.1111/raq.12427.

García Romero, H. and A. Molina (eds.), *Agriculture and Adaptation to Climate Change: The Role of Insurance in Risk Management: The Case of Colombia*. Inter-American Development Bank (IDB), Washington DC, USA. 49 pp.

Gartrell, A., E. Calgaro, G. Goddard and N. Saorath, 2020: Disaster experiences of women with disabilities: barriers and opportunities for disability inclusive disaster risk reduction in Cambodia. *Glob. Environ. Change*, **64**, 102134, doi:10.1016/j.gloenvcha.2020.102134.

Gautam, Y. and P. Andersen, 2016: Rural livelihood diversification and household well-being: Insights from Humla, Nepal. *J Rural Stud*, **44**, 239–249, doi:10.1016/j.jrurstud.2016.02.001.

Geekiyanage, D., K. Keraminiyage, T. Fernando and T. Jayawickrama, 2021: Factors influencing acceptance or rejection regarding being the host community for post-disaster resettlements in developing countries. *Int. J. Disaster Risk Reduct.*, **53**, 101973, doi:10.1016/J.IJDRR.2020.101973.

Georgeson, L., M. Maslin, M. Poessinouw and S. Howard, 2016: Adaptation responses to climate change differ between global megacities. *Nature Clim Change*, **6**, 584–588, doi:10.1038/nclimate2944.

Ghiasian, M., et al., 2021: Dissipation of wave energy by a hybrid artificial reef in a wave simulator: implications for coastal resilience and shoreline protection. *Limnol. Oceanogr. Methods*, **19**(1), 1–7, doi:10.1002/lom3.10400.

Ghosh-Jerath, S., et al., 2021: Pathways of climate change impact on agroforestry, food consumption pattern, and dietary diversity among indigenous subsistence farmers of Sauria Paharia tribal community of India: a mixed methods study. *Front. Sustain. Food Syst.*, **0**, 174, doi:10.3389/FSUFS.2021.667297.

Gibb, R., L.H.V. Franklinos, D.W. Redding and K.E. Jones, 2020: Ecosystem perspectives are needed to manage zoonotic risks in a changing climate. *BMJ*, **371**, doi:10.1136/bmj.m3389.

Gilfillan, D., 2019: The health sector's role in governance of climate change adaptation in Myanmar. *Clim. Dev.*, **11**, 574–584, doi:10.1080/17565529.2018.1510364.

Glaas, E., E.C.H. Keskitalo and M. Hjerpe, 2017: Insurance sector management of climate change adaptation in three Nordic countries: the influence of policy and market factors. *J. Environ. Plan. Manag.*, **60**, 1601–1621, doi:10.1080/09640568.2016.1245654.

Glantz, M.H. and G.E. Pierce, 2021: Forecast hesitancy: why are people reluctant to believe, accept, or respond to various weather, water, and climate hazard-related forecasts? *Int. J. Disaster Risk Sci.*, **12**(4), 600–609, doi:10.1007/s13753-021-00353-7.

Goetz, E. G., R.A. Williams and A. Damiano, 2020: *Whiteness and Urban Planning*. Routledge, 142–156.

Cross-Chapter Box FEASIB (continued)

Goh, K., 2020: Flows in formation: The global-urban networks of climate change adaptation. *Urban Stud.*, **57**, 2222–2240, doi:10.1177/0042098018807306.

Gómez Martín, E., M. Máñez Costa and K. Schwerdtner Máñez, 2020: An operationalized classification of nature based solutions for water-related hazards: from theory to practice. *Ecol. Econ.*, **167**, 106460, doi:10.1016/j.ecolecon.2019.106460.

Goniewicz, K. and F.M. Burkle, 2019: Challenges in implementing Sendai framework for disaster risk reduction in Poland. *Int. J. Environ. Res. Public Health*, **16**(14), doi:10.3390/ijerph16142574.

Gonzalez-Sanchez, E.J., et al., 2019: meta-analysis on carbon sequestration through conservation agriculture in Africa. *Soil Tillage Res.*, **190**, 22–30, doi:10.1016/j.still.2019.02.020.

Goodrich, C.G., A. Prakash and P.B. Udas, 2019: Gendered vulnerability and adaptation in Hindu-Kush Himalayas: Research insights. *Environ. Dev.*, **31**, 1–8, doi:10.1016/J.ENVDEV.2019.01.001.

Gopal, N., et al., 2020: Expanding the horizons for women in fisheries and aquaculture. *Gend. Technol. Dev.*, **24**, 1–9, doi:10.1080/09718524.2020.1736353.

Goryushina, E.M., 2021: Challenges of the Sendai framework for disaster risk reduction adaption in Russia. *IOP Conf. Ser. Earth Environ. Sci.*, **720**(1), 12101, doi:10.1088/1755-1315/720/1/012101.

Gostin, L.O. and E.A. Friedman, 2017: Global health: a pivotal moment of opportunity and peril. *Health Aff.*, **36**(1), 159–165, doi:10.1377/hlthaff.2016.1492.

Goulden, M.C., W.N. Adger, E.H. Allison and D. Conway, 2013: Limits to resilience from livelihood diversification and social capital in lake social–ecological systems. *Ann. Assoc. Am. Geogr.*, **103**, 906–924, doi:10.1080/00045608.2013.765771.

Griscom, B.W., et al., 2017: Natural climate solutions. *Proc. Natl. Acad. Sci.*, **114**, 11645–11650, doi:10.1073/pnas.1710465114.

Gu, L., et al., 2019: The contribution of internal climate variability to climate change impacts on droughts. *Sci. Total. Environ.*, **684**, 229–246, doi:10.1016/j.scitotenv.2019.05.345.

Gumucio, T., J. Hansen, S. Huyer and T. van Huysen, 2020: Gender-responsive rural climate services: a review of the literature. *Clim. Dev.*, **12**(3), 241–254, doi:10.1080/17565529.2019.1613216.

Gundersen, P., et al., 2021: Old-growth forest carbon sinks overestimated. *Nature*, **591**(7851), E21–E23, doi:10.1038/s41586-021-03266-z.

Gutiérrez, J.M., R.G. Jones, G.T. Narisma, L.M. Alves, M. Amjad, I. V. Gorodetskaya, M. Grose, N.A.B. Klutse, S. Krakovska, J. Li, D. Martínez-Castro, L.O. Mearns, S.H. Mernild, T. Ngo-Duc, B. van den Hurk, and J.-H. Yoon, 2021: Atlas. 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 (eds.)]. Available from http://interactive-atlas.ipcc.ch/.

Haines, A. and K. Ebi, 2019: The imperative for climate action to protect health. *N. Engl. J. Med.*, 380, 263–273, 10.1056/nejmra1807873.

Hamin, E., et al., 2018: Pathways to coastal resiliency: the adaptive gradients framework. *Sustainability*, **10**, 2629, doi:10.3390/su10082629.

Han, D., et al., 2018: Large soil organic carbon increase due to improved agronomic management in the North China Plain from 1980s to 2010s. *Glob Change Biol*, **24**, 987–1000, doi:10.1111/gcb.13898.

Hanefeld, J., et al., 2018: Towards an understanding of resilience: Responding to health systems shocks. *Health Policy Plan.*, **33**, 355–367, doi:10.1093/heapol/czx183.

Hanley, M. E., T.J. Bouma and H.L. Mossman, 2020a: The gathering storm: Optimizing management of coastal ecosystems in the face of a climate-driven threat. *Ann Bot*, **125**, 197–212, doi:10.1093/aob/mcz204.

Hanley, M. E., T.J. Bouma and H.L. Mossman, 2020b: *The gathering storm: Optimizing management of coastal ecosystems in the face of a climate-driven threat*. Oxford University Press, 197–212.

Hansen, J., et al., 2019: Climate risk management and rural poverty reduction. *Agric Syst*, **172**, 28–46, doi:10.1016/j.agsy.2018.01.019.

Hargan, K.E., et al., 2020: Understanding the fate of shrimp aquaculture effluent in a mangrove ecosystem: Aiding management for coastal conservation. *J Appl Ecol*, **57**, 754–765, doi:10.1111/1365-2664.13579.

Hasan, M.R., M. Nasreen and M. A. Chowdhury, 2019: *Gender-inclusive disaster management policy in Bangladesh: A content analysis of national and international regulatory frameworks*. Elsevier Ltd.

Hassanali, K., 2017: Challenges in mainstreaming climate change into productive coastal sectors in a Small Island State – The case of Trinidad and Tobago. *Ocean. Coast. Manag.*, **142**, 136–142, doi:10.1016/j.ocecoaman.2017.04.001.

Hauer, M. E., et al., 2020: Sea-level rise and human migration. *Nat. Rev. Earth Environ.*, **1**, 28–39, doi:10.1038/s43017-019-0002-9.

Heikkinen, M., T. Ylä-Anttila and S. Juhola, 2019: Incremental, reformistic or transformational: what kind of change do C40 cities advocate to deal with climate change? *J. Environ. Policy Plan.*, **21**, 90–103, doi:10.1080/1523908X.2018.1473151.

Henrique, K.P. and P. Tschakert, 2020: Pathways to urban transformation: From dispossession to climate justice. *Prog Hum Geogr*, **0**(0), doi:10.1177/0309132520962856. 0309132520962856.

Hermwille, L., W. Obergassel, H.E. Ott and C. Beuermann, 2017: UNFCCC before and after Paris – what's necessary for an effective climate regime? *Clim. Policy*, **17**, 150–170, doi:10.1080/14693062.2015.1115231.

Hernández-Morcillo, M., et al., 2018: Scanning agroforestry-based solutions for climate change mitigation and adaptation in Europe. *Environ. Sci. Policy*, **80**, 44–52, doi:10.1016/j.envsci.2017.11.013.

Herrero, M., et al., 2016: Climate change and pastoralism: impacts, consequences and adaptation. *Rev. Sci. Tech. Off. Int. Epiz*, **35**, 417–433, doi:10.20506/rst/35.2.2533.

Herslund, L. and P. Mguni, 2019: Examining urban water management practices – Challenges and possibilities for transitions to sustainable urban water management in Sub-Saharan cities. *Sustain. Cities Soc.*, **48**, doi:10.1016/J.SCS.2019.101573.

Hewitt, C.D., et al., 2020a: Making society climate resilient: international progress under the global framework for climate services. *Bull. Am. Meteorol. Soc.*, **101**(2), E237–E252, doi:10.1175/BAMS-D-18-0211.1.

Cross-Chapter Box FEASIB (continued)

Hewitt, C.N., K. Ashworth and A.R. MacKenzie, 2020b: Using green infrastructure to improve urban air quality (GI4AQ). *Ambio*, **49**, 62–73, doi:10.1007/S13280-019-01164-3.

Hobbie, S.E. and N.B. Grimm, 2020: Nature-based approaches to managing climate change impacts in cities. *Philos. Trans. Royal Soc. B Biol. Sci.*, **375**(1794), 20190124, doi:10.1098/rstb.2019.0124.

Hoegh-Guldberg, O., et al. (ed.), *The Ocean as a Solution to Climate Change: Five Opportunities for Action*.

Hoffmann, R., et al., 2020: A meta-analysis of country-level studies on environmental change and migration. *Nat. Clim. Chang.*, **10**(10), 904–912, doi:10.1038/s41558-020-0898-6.

Honarmand Ebrahimi, S. and M. Ossewaarde, 2019: Not a security issue: How policy experts de-politicize the climate change-migration nexus. *Soc Sci*, **8**, 214, doi:10.3390/socsci8070214.

Hörner, D. and M. Wollni, 2020: *RTG 1666 GlobalFood Transformation of Global Agri-Food Systems: Trends, Driving Forces, and Implications for Developing Countries Does Integrated Soil Fertility Management increase returns to land and labor? Plot-level evidence from Ethiopia*.

Hosen, N., H. Nakamura and A. Hamzah, 2020: Adaptation to climate change: does traditional ecological knowledge hold the key? *Sustainability*, **12**(2), doi:10.3390/su12020676.

Hossen, et al., 2019: Governance challenges in addressing climatic concerns in coastal Asia and Africa. *Sustainability*, **11**, 2148, doi:10.3390/su11072148.

Hughes, S., 2020: Principles, drivers, and policy tools for just climate change adaptation in legacy cities. *Environ. Sci. Policy*, **111**, 35–41, doi:10.1016/j.envsci.2020.05.007.

Hussey, L.K. and G. Arku, 2020: Are we ready for it? Health systems preparedness and capacity towards climate change-induced health risks: perspectives of health professionals in Ghana. *Clim. Dev.*, **12**, 170–182, doi:10.1080/17565529.2019.1610350.

Huynh, L.T.M. and L.C. Stringer, 2018: Multi-scale assessment of social vulnerability to climate change: an empirical study in coastal Vietnam. *Clim. Risk Manag.*, **20**, 165–180, doi:10.1016/j.crm.2018.02.003.

IPCC, 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.)]. In Press.

IPCC, 2019: *Clim. Chang.*, 1–864.

Islam, S., C. Chu and J.C.R. Smart, 2020a: Challenges in integrating disaster risk reduction and climate change adaptation: Exploring the Bangladesh case. *Int. J. Disaster Risk Reduct.*, **47**, doi:10.1016/j.ijdrr.2020.101540.

Islam, S., C. Chu, J.C.R. Smart and L. Liew, 2020b: *Integrating disaster risk reduction and climate change adaptation: a systematic literature review*. Taylor and Francis Ltd., 255–267.

Jacobson, C., S. Crevello, C. Chea and B. Jarihani, 2019: When is migration a maladaptive response to climate change? *Reg Environ Change*, **19**, 101–112, doi:10.1007/s10113-018-1387-6.

Jayanthi, M., S. Thirumurthy, M. Muralidhar and P. Ravichandran, 2018: Impact of shrimp aquaculture development on important ecosystems in India. *Glob. Environ. Chang.*, **52**, 10–21, doi:10.1016/j.gloenvcha.2018.05.005.

Jenkins, K., S. Surminski, J. Hall and F. Crick, 2017: Assessing surface water flood risk and management strategies under future climate change: Insights from an Agent-Based Model. *Sci. Total. Environ.*, **595**, 159–168, doi:10.1016/j.scitotenv.2017.03.242.

Jensen, O. and S. Nair, 2019: Integrated urban water management and water security: A comparison of Singapore and Hong Kong. *Water (switzerland)*, **11**, doi:10.3390/W11040785.

Ji, H. and D. Lee, 2021: Disaster risk reduction, community resilience, and policy effectiveness: the case of the Hazard Mitigation Grant Program in the United States. *Disasters*, **45**, 378–402, doi:10.1111/disa.12424.

Jin, J., W. Wang and X. Wang, 2016: Farmers' risk preferences and agricultural weather index insurance uptake in rural China. *Int. J. Disaster Risk Sci.*, **7**, 366–373, doi:10.1007/s13753-016-0108-3.

Johnson, K., S. Mortensen, C. Gueguen-Teil and A.R. Torre, 2021: Displaced by climate and disaster-induced relocations: Experiences of cascading displacement in Fiji and the Philippines. *Disasters*, doi:10.1111/DISA.12475.

Jolliffe, J., 2016: *Economic dimensions of relocation as an adaptation strategy to climate change: A case study of the Narikoso Relocation Project, Fiji*.

Jones, H.P., et al., 2020a: Global hotspots for coastal ecosystem-based adaptation. *PLoS ONE*, **15**, e233005, doi:10.1371/journal.pone.0233005.

Jones, K.W., K. Powlen, R. Roberts and X. Shinbrot, 2020b: Participation in payments for ecosystem services programs in the Global South: A systematic review. *Ecosyst. Serv.*, **45**, 101159, doi:10.1016/j.ecoser.2020.101159.

Jordon, M.W., et al., 2020: Implications of temperate agroforestry on sheep and cattle productivity, environmental impacts and enterprise economics. A systematic evidence map. *Forests*, **11**, 1321, doi:10.3390/F11121321.

Joy, A. and A. Gopinath, 2021: *The Application of Reefs in Shoreline Protection*, 295–315.

Joyette, A.R.T., L.A. Nurse and R.S. Pulwarty, 2015: Disaster risk insurance and catastrophe models in risk-prone small Caribbean islands. *Disasters*, **39**, 467–492, doi:10.1111/disa.12118.

Kälin, W., 2019: The Global Compact on Migration: A Ray of Hope for Disaster-Displaced Persons. *Int. J. Refug. Law*, **30**, 664–667, doi:10.1093/ijrl/eey047.

Kannan, E. and K.B. Ramappa, 2017: Analysis of farm-level adoption of soil nutrient management technology by paddy farmers in Karnataka, India. *Environ. Dev. Sustain.*, **19**, 2317–2331, doi:10.1007/s10668-016-9858-8.

Keeler, B.L., et al., 2019: *Social-ecological and technological factors moderate the value of urban nature*. Nature Publishing Group, 29–38.

Keenan, J.M., T. Hill and A. Gumber, 2018: Climate gentrification: from theory to empiricism in Miami-Dade county, Florida. *Environ. Res. Lett.*, **13**, doi:10.1088/1748-9326/aabb32.

Cross-Chapter Box FEASIB (continued)

Keil, A., A. Mitra, A.K. Srivastava and A. McDonald, 2019: Social inclusion increases with time for zero-tillage wheat in the Eastern Indo-Gangetic Plains. *World Dev.*, **123**, 104582, doi:10.1016/j.worlddev.2019.06.006.

Kelman, I., et al., 2019: Does climate change influence people's migration decisions in Maldives? *Clim Change*, **153**, 285–299, doi:10.1007/s10584-019-02376-y.

Kendrovski, V. and O. Schmoll, 2019: *Priorities for protecting health from climate change in the WHO European region: recent regional activities*. Springer Verlag, 537–545.

Kenney, C. and S. Phibbs, 2020: Indigenous peoples and climate change: situating culture, identity, and place in climate change risk mitigation and resilience. In: *Handbook of Climate Change Management: Research, Leadership, Transformation* [Leal Filho, W., J. Luetz and D. Ayal(eds.)]. Springer International Publishing, Cham, pp. 1–27. ISBN 978-3030227593.

Khalil, M.B., B.C. Jacobs, K. McKenna and N. Kuruppu, 2020: Female contribution to grassroots innovation for climate change adaptation in Bangladesh. *Clim. Dev.*, **12**(7), 664–676, doi:10.1080/17565529.2019.1676188.

Khatri-Chhetri, A., P.K. Aggarwal, P.K. Joshi and S. Vyas, 2017: Farmers' prioritization of climate-smart agriculture (CSA) technologies. *Agric Syst*, **151**, 184–191, doi:10.1016/j.agsy.2016.10.005.

Khatri-Chhetri, A., J.P. Aryal, T.B. Sapkota and R. Khurana, 2016: Economic benefits of climate-smart agricultural practices to smallholder farmers in the Indo-Gangetic Plains of India. *Curr. Sci.*, **110**, 1251–1256, doi:10.18520/cs/v110/i7/1251-1256.

Kihila, J.M., 2017: Indigenous coping and adaptation strategies to climate change of local communities in Tanzania: a review. *Clim. Dev.*, 1–11, doi:10.1080/17565529.2017.1318739.

Kihila, J.M., 2018: *Indigenous coping and adaptation strategies to climate change of local communities in Tanzania: a review*. Taylor and Francis Ltd., 406–416.

Kim, H. and D.W. Marcouiller, 2020: Making sense of resilience planning and policy in the pursuit of sustainable development and disaster risk reduction. *Clim. Dev.*, **12**, 228–240, doi:10.1080/17565529.2019.1613215.

Kind, J., W. Botzen and J.C.J.H. Aerts, 2017: Accounting for risk aversion, income distribution and social welfare in cost-benefit analysis for flood risk management. *Wires Clim. Chang.*, **8**, e446, doi:10.1002/wcc.446.

Klein, J.A., et al., 2019: An integrated community and ecosystem-based approach to disaster risk reduction in mountain systems. *Environ. Sci. Policy*, **94**, 143–152, doi:10.1016/j.envsci.2018.12.034.

Kligler, B., et al., 2021: The impact of integrating environmental health into medical school curricula: a survey-based study. *BMC Med. Educ.*, **21**(1), 40, doi:10.1186/s12909-020-02458-x.

Klinenberg, E., 2018: *Palaces for the people : how social infrastructure can help fight inequality, polarization, and the decline of civic life*. ISBN 978-1524761165. 1524761168 9781524761172 1524761176 9781984822413 1984822411.

Kmoch, L., T. Pagella, M. Palm and F. Sinclair, 2018: Using local agroecological knowledge in climate change adaptation: A study of tree-based options in Northern Morocco. *Sustain. (switzerland)*, **10**, 3719, doi:10.3390/su10103719.

Kodali, R. K. and B. S. Sarjerao (eds.), A low cost smart irrigation system using MQTT protocol. 2017 IEEE Region 10 Symposium (TENSYMP), 14-16 July 2017, 1-5 pp.

Koslov, L., 2019: Avoiding climate change: "agnostic adaptation" and the politics of public silence. *Ann. Am. Assoc. Geogr.*, **109**, 568–580, doi:10.1080/24694452.2018.1549472.

Koubi, V., et al., 2018: *The Determinants of Environmental Migrants' Conflict Perception*. cambridge.org.

Kouis, P., et al., 2021: The MEDEA childhood asthma study design for mitigation of desert dust health effects: implementation of novel methods for assessment of air pollution exposure and lessons learned. *BMC Pediatr.*, **21**(1), 13, doi:10.1186/s12887-020-02472-4.

Kousky, C., H. Wiley and L. Shabman, 2021: Can parametric microinsurance improve the financial resilience of low-income households in the United States? *Econ. Disasters Clim. Chang.*, doi:10.1007/s41885-021-00088-1.

Krauss, K.W. and M.J. Osland, 2020: Tropical cyclones and the organization of mangrove forests: A review. *Ann Bot*, **125**, 213–234, doi:10.1093/aob/mcz161.

Krosby, M., J. Tewksbury, N.M. Haddad and J. Hoekstra, 2010: Ecological connectivity for a changing climate. *Conserv. Biol.*, **24**, 1686–1689, doi:10.1111/j.1523-1739.2010.01585.x.

Krueger, E., P.S.C. Rao and D. Borchardt, 2019: Quantifying urban water supply security under global change. *Glob. Environ. Chang.*, **56**, 66–74, doi:10.1016/J.GLOENVCHA.2019.03.009.

Lalani, B., P. Dorward and G. Holloway, 2017: Farm-level economic analysis - is conservation agriculture helping the poor? *Ecol. Econ.*, **141**, 144–153, doi:10.1016/j.ecolecon.2017.05.033.

Lamari, M., J. Bouchard, J. Jacob and L. Poulin-Larivière, 2016: *Monitoring and Evaluation of Climate Change Adaptation in Coastal Zones: Overview of the Indicators in Use*. Springer, 3–20.

Lange, W., et al., 2019: *Ecosystem-based approaches for disaster risk reduction and climate change adaptation in Rio de Janeiro state*. Springer, Cham, 345–359.

Langemeyer, J., et al., 2020: Creating urban green infrastructure where it is needed – A spatial ecosystem service-based decision analysis of green roofs in Barcelona. *Sci. Total. Environ.*, **707**, 135487, doi:10.1016/j.scitotenv.2019.135487.

Lardizabal, C.C., 2015: Basin comanagement plans – A participative approach to water governance: a case study in Honduras, Central America. *Sustain. Integr. Water Resour. Manag. Water Gov. Clim. Ecohydrol.*, 345–363, doi:10.1007/978-3-319-12194-9_19.

Lashley, J.G. and K. Warner, 2015: Evidence of demand for microinsurance for coping and adaptation to weather extremes in the Caribbean. *Clim Change*, **133**, 101–112, doi:10.1007/s10584-013-0922-1.

Lausche, B., et al. (ed.), *The Legal Aspects of Connectivity Conservation A Concept Paper*.

Cross-Chapter Box FEASIB (continued)

Lavorel, S., B. Locatelli, M.J. Colloff and E. Bruley, 2020: Co-producing ecosystem services for adapting to climate change. *Philos. Trans. Royal Soc. B: Biol. Sci.*, **375**, doi:10.1098/rstb.2019.0119.

Le Cornu, E., et al., 2018: Spatial management in small-scale fisheries: A potential approach for climate change adaptation in Pacific Islands. *Mar. Policy.*, **88**, 350–358, doi:10.1016/j.marpol.2017.09.030.

Leakhena, C., et al., 2018: *Aiming for Improved Gender Equity in Cambodian Aquaculture*.

Leigh, N.G. and H. Lee, 2019: Sustainable and resilient urban water systems: The role of decentralization and planning. *Sustain. (switzerland)*, **11**, doi:10.3390/SU11030918.

Li, Z., et al., 2020: Biochar-supported nanoscale zero-valent iron as an efficient catalyst for organic degradation in groundwater. *J. Hazard. Mater.*, **383**, doi:10.1016/j.jhazmat.2019.121240.

Liang, Y., M. Du, X. Wang and X. Xu, 2020: Planning for urban life: A new approach of sustainable land use plan based on transit-oriented development. *Eval Program Plann*, **80**, 101811, doi:10.1016/j.evalprogplan.2020.101811.

Liao, W., et al., 2019: Preparing the next generation of health professionals to tackle climate change: Are China's medical students ready? *Environ. Res.*, **168**, 270–277, doi:10.1016/j.envres.2018.10.006.

Ligsay, A., O. Telle and R. Paul, 2021: Challenges to mitigating the urban health burden of mosquito-borne diseases in the face of climate change. *Int. J. Environ. Res. Public Health*, **18**(9), doi:10.3390/ijerph18095035.

Lima, M. and C. Coelho, 2021: Integrated methodology for physical and economic assessment of coastal interventions impacts. *J. Model. Optim.*, **13**, 22–43, doi:10.32732/jmo.2021.13.1.22.

Lin, T.Y., V.M.V. Onselen and L.P. Vo, 2021: Coastal erosion in Vietnam: Case studies and implication for integrated coastal zone management in the Vietnamese south-central coastline. *Iop Conf. Series: Earth Environ. Sci.*, **652**, 12009, doi:10.1088/1755-1315/652/1/012009.

Linares, C., et al., 2020: *Impacts of climate change on the public health of the Mediterranean Basin population - Current situation, projections, preparedness and adaptation*. Academic Press Inc.

Lincke, D. and J. Hinkel, 2018: Economically robust protection against 21st century sea-level rise. *Glob. Environ. Chang.*, **51**, 67–73, doi:10.1016/j.gloenvcha.2018.05.003.

Linke, A., F. Witmer and J. O. L.-E. … and u., 2018: *The consequences of relocating in response to drought: human mobility and conflict in contemporary Kenya*. iopscience.iop.org.

Linnerooth-Bayer, J. and S. Hochrainer-Stigler, 2015: Financial instruments for disaster risk management and climate change adaptation. *Clim Change*, **133**, 85–100, doi:10.1007/s10584-013-1035-6.

Liu, L. and M.B. Jensen, 2018: Green infrastructure for sustainable urban water management: Practices of five forerunner cities. *Cities*, **74**, 126–133, doi:10.1016/j.cities.2017.11.013.

Lochhead, K., S. Ghafghazi, V. LeMay and G.Q. Bull, 2019: Examining the vulnerability of localized reforestation strategies to climate change at a macroscale. *J. Environ. Manag.*, **252**, 109625, doi:10.1016/j.jenvman.2019.109625.

Lock-Wah-Hoon, J., et al., 2020: Exploring vector-borne disease surveillance and response systems in Beijing, China: a qualitative study from the health system perspective. *Int. J. Environ. Res. Public Health*, **17**(22), doi:10.3390/ijerph17228512.

Lunduka, R.W., K.I. Mateva, C. Magorokosho and P. Manjeru, 2019: Impact of adoption of drought-tolerant maize varieties on total maize production in south Eastern Zimbabwe. *Clim. Dev.*, **11**, 35–46, doi:10.1080/17565529.2017.1372269.

Luqman, M., et al., 2018: Socio-economic impacts of agro-forestry on livelihoods of rural households in southern region of the Punjab, Pakistan. *SJA*, **34**, doi:10.17582/journal.sja/2018/34.4.880.887.

Strøbech, L. and R. Bordon, 2020: *Addressing the risk of Maladaptation in Social Protection: The case of World Food Programme*.

Mach, K.J., et al., 2019: Managed retreat through voluntary buyouts of flood-prone properties. **5**, doi:10.1126/SCIADV.AAX8995.

Magnan, A.K. and V.K.E. Duvat, 2018: Unavoidable solutions for coastal adaptation in Reunion Island (Indian Ocean). *Environ. Sci. Policy*, **89**, 393–400, doi:10.1016/j.envsci.2018.09.002.

Maharjan, A., et al., 2020: Migration and household adaptation in climate-sensitive hotspots in south Asia. *Curr Clim Change Rep*, **6**, doi:10.1007/S40641-020-00153-Z.

Makate, C., R. Wang, M. Makate and N. Mango, 2016: Crop diversification and livelihoods of smallholder farmers in Zimbabwe: Adaptive management for environmental change. *SpringerPlus*, **5**, 1–18, doi:10.1186/s40064-016-2802-4.

Maldonado, J., et al., 2021: Addressing the challenges of climate-driven community-led resettlement and site expansion: knowledge sharing, storytelling, healing, and collaborative coalition building. *J Environ Stud Sci*, 1–11, doi:10.1007/S13412-021-00695-0.

Mallick, B., B. Ahmed and J. V.-. Environments and u., 2017: *Living with the risks of cyclone disasters in the south-western coastal region of Bangladesh*. mdpi.com.

Marchezini, V., 2020: "What is a sociologist doing here?" an unconventional people-centered approach to improve warning implementation in the Sendai framework for disaster risk reduction. *Int. J. Disaster Risk Sci.*, **11**(2), 218–229, doi:10.1007/s13753-020-00262-1.

Margaret, D. and S. Matias, 2020: Climate humanitarian visa: international migration opportunities as post-disaster humanitarian intervention. *Clim Change*, **160**, 143–156, doi:10.1007/s10584-020-02691-9.

Margerum, R.D. and C.J. Robinson, 2015: Collaborative partnerships and the challenges for sustainable water management. *Curr. Opin. Environ. Sustain.*, **12**, 53–58, doi:10.1016/j.cosust.2014.09.003.

Martin, G., et al., 2020: Potential of multi-species livestock farming to improve the sustainability of livestock farms: A review. *Agric Syst*, **181**, 102821, doi:10.1016/j.agsy.2020.102821.

Martin, S.M. and K. Lorenzen, 2016: Livelihood diversification in rural Laos. *World Dev*, **83**, 231–243, doi:10.1016/j.worlddev.2016.01.018.

Cross-Chapter Box FEASIB (continued)

Martínez-Barón, D., et al., 2021: *Strengthening the climate services chain in Central America*.

Martuti, N.K.T., R. Pribadi, W.A.B.N. Sidiq and D.P. Mutiatari, 2020: *Community-Based Integrated Coastal Management Strategy in Tugurejo Subdistrict, Semarang*. Atlantis Press, 73–80.

Masud, M.M., et al., 2017: Adaptation barriers and strategies towards climate change: Challenges in the agricultural sector. *J Clean Prod*, **156**, 698–706, doi:10.1016/j.jclepro.2017.04.060.

Mayer, A., Z. Hausfather and W. Silver, 2018: The potential of agricultural land management to contribute to lower global surface temperatures. *Sci. Adv.*, **4**, doi:10.1126/sciadv.aaq0932.

McFadden, J., D. Smith, S. Wechsler and S. Wallander (eds.), *Development, Adoption, and Management of Drought-Tolerant Corn in the United States*.

McLeman, R., 2018: Migration and displacement risks due to mean sea-level rise. *Bull. At. Sci.*, **74**(3), 148–154, doi:10.1080/00963402.2018.1461951.

McLeman, R., 2019: International migration and climate adaptation in an era of hardening borders. *Nat. Clim. Chang.*, **9**(12), 911–918, doi:10.1038/s41558-019-0634-2.

McMichael, C., et al., 2021: Rising seas, immobilities, and translocality in small island states: case studies from Fiji and Tuvalu. *Popul Environ*, **43**(1), 82–107, doi:10.1007/s11111-021-00378-6.

McMichael, C. and M. Katonivualiku, 2020: Thick temporalities of planned relocation in Fiji. *Geoforum*, **108**, 286–294, doi:10.1016/j.geoforum.2019.06.012.

McNamara, K.E., 2015: Cross-border migration with dignity in Kiribati. *Forced Migr. Rev.*, **49**, 62.

McNamara, K.E., R. Westoby and A. Chandra, 2021: Exploring climate-driven non-economic loss and damage in the Pacific Islands. *Curr. Opin. Environ. Sustain.*, **50**, 1–11, doi:10.1016/j.cosust.2020.07.004.

Meerow, S., 2019: A green infrastructure spatial planning model for evaluating ecosystem service tradeoffs and synergies across three coastal megacities. *Environ. Res. Lett.*, **14**, doi:10.1088/1748-9326/ab502c.

Mena, R. and D. Hilhorst, 2021: The (im)possibilities of disaster risk reduction in the context of high-intensity conflict: the case of Afghanistan. *Environ. Hazards*, **20**(2), 188–208, doi:10.1080/17477891.2020.1771250.

Mestanza-Ramón, C., M.S. Capa, H.F. Saavedra and J.R. Paredes, 2019: Integrated coastal zone management in continental Ecuador and Galapagos Islands: Challenges and opportunities in a changing tourism and economic context. *Sustainability*, **11**, 6386, doi:10.3390/su11226386.

Miller, F., 2020: Exploring the consequences of climate-related displacement for just resilience in Vietnam. *Urban Stud.*, **57**, 1570–1587, doi:10.1177/0042098019830239.

Mills, M., et al., 2016: Reconciling development and conservation under coastal squeeze from rising sea level. *CONSERVATION LETTERS*, **9**, 361–368, doi:10.1111/conl.12213.

Minang, P.A., et al., 2014: *Prospects for agroforestry in REDD+ landscapes in Africa*. Elsevier, 78–82.

Monstadt, J. and A. Wolff, 2015: Energy transition or incremental change? Green policy agendas and the adaptability of the urban energy regime in Los Angeles. *Energy Policy*, **78**, 213–224, doi:10.1016/j.enpol.2014.10.022.

Morecroft, M.D., et al., 2019: Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. *Science*, **366**, doi:10.1126/science.aaw9256.

Morris, R., et al., 2019: Developing a nature-based coastal defence strategy for Australia. *Aust. J. Civ. Eng.*, **17**, 167–176, doi:10.1080/14488353.2019.1661062.

Morris, R.L., T.M. Konlechner, M. Ghisalberti and S. Swearer, 2018: *From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence*. Blackwell Publishing Ltd, 1827–1842.

Mortreux, C., et al., 2018: Political economy of planned relocation: A model of action and inaction in government responses. *Glob. Environ. Chang.*, **50**, 123–132, doi:10.1016/j.gloenvcha.2018.03.008.

Mottaleb, K. A., et al., 2017: Benefits of the development and dissemination of climate-smart rice: ex ante impact assessment of drought-tolerant rice in South Asia. *Mitig Adapt Strateg Glob Change*, **22**, 879–901, doi:10.1007/s11027-016-9705-0.

Mponela, P., et al., 2016: Determinants of integrated soil fertility management technologies adoption by smallholder farmers in the Chinyanja Triangle of Southern Africa. *Land Use Policy*, **59**, 38–48, doi:10.1016/j.landusepol.2016.08.029.

Mueller, V., C. Gray, S. Handa and D. Seidenfeld, 2020: Do social protection programs foster short-term and long-term migration adaptation strategies? *Envir. Dev. Econ.*, **25**, 135–158, doi:10.1017/S1355770X19000214.

Muench, S., S. Thuss and E. Guenther, 2014: What hampers energy system transformations? The case of smart grids. *Energy Policy*, **73**, 80–92, doi:10.1016/j.enpol.2014.05.051.

Müller, B., L. Johnson and D. Kreuer, 2017: Maladaptive outcomes of climate insurance in agriculture. *Glob. Environ. Chang.*, **46**, 23–33, doi:10.1016/j.gloenvcha.2017.06.010.

Muricho, D.N., D.J. Otieno, W. Oluoch-Kosura and M. Jirström, 2019: Building pastoralists' resilience to shocks for sustainable disaster risk mitigation: lessons from west Pokot county, Kenya. *Int. J. Disaster Risk Reduct.*, **34**, 429–435, doi:10.1016/j.ijdrr.2018.12.012.

Murti, R., S.L. Mathez-Stiefel, V.R. Garcia and S. Rist, 2020: *Engaging national policy makers in ecosystem based disaster risk reduction through social learning: Lessons from workshops in Africa, oceania, Latin America and the Caribbean*. Elsevier Ltd.

Mustafa, S., et al., 2021: Technological applications and adaptations in aquaculture for progress towards sustainable development and seafood security. *(Tall et al.) Conf. Series: Earth Environ. Sci.*, **718**, 12041, doi:10.1088/1755-1315/718/1/012041.

Mustapha, U.F., A.-W. Alhassan, D.-N. Jiang and G.-L. Li, 2021: Sustainable aquaculture development: a review on the roles of cloud computing, internet of things and artificial intelligence (CIA). *Rev. Aquac.*, doi:10.1111/raq.12559.

Mutuku, E.A., et al., 2020: Maize production under combined conservation agriculture and integrated soil fertility management in the sub-humid and semi-arid regions of Kenya. *Field Crop. Res.*, **254**, 107833, doi:10.1016/j.fcr.2020.107833.

Cross-Chapter Box FEASIB (continued)

Nabuurs, G.-J., et al., 2017: By 2050 the mitigation effects of EU forests could nearly double through climate smart forestry. *Forests*, **8**(12), doi:10.3390/f8120484.

Natarajan, N. and K.B.-E.P. a. … u, 2019: Climate change adaptation and precarity across the rural–urban divide in Cambodia: Towards a 'climate precarity' approach. **2**, 899–921, doi:10.1177/2514848619858155. journals.sagepub.com.

Nawrotzki, R.J. and J. DeWaard, 2018: Putting trapped populations into place: climate change and inter-district migration flows in Zambia. *Reg. Environ. Change*, **18**, 533–546, doi:10.1007/S10113-017-1224-3.

Neef, A., et al., 2018: Climate adaptation strategies in Fiji: the role of social norms and cultural values. *World Dev.*, **107**, 125–137, doi:10.1016/j.worlddev.2018.02.029.

Negev, M., et al., 2021: Regional lessons from the COVID-19 outbreak in the Middle East: from infectious diseases to climate change adaptation. *Sci. Total Environ.*, **768**, 144434, doi:10.1016/j.scitotenv.2020.144434.

Negev, M., et al., 2019: Adaptation of health systems to climate-related migration in Sub-Saharan Africa: Closing the gap. *Int J Hyg Environ Health*, **222**, 311–314, doi:10.1016/j.ijheh.2018.10.004.

Ngin, C., J.H. Grayman, A. Neef and N. Sanunsilp, 2020: The role of faith-based institutions in urban disaster risk reduction for immigrant communities. *Nat. Hazards*, **103**(1), 299–316, doi:10.1007/s11069-020-03988-9.

Nguyen Mai, T.H. and D. Hoang, 2018: Gender role in mangrove resource management: case study in Trieu Phong district of Quang Tri province, Vietnam. *J. Vietnamese Environ.*, **9**(2), doi:10.13141/jve.vol9.no2.pp92-98.

Nguyen, T.T., et al., 2019: Implementation of a specific urban water management - sponge city. *Sci. Total. Environ.*, **652**, 147–162, doi:10.1016/J.SCITOTENV.2018.10.168.

Nicholls, R., J. Hinkel, D. Lincke and T.D. van der Pol, 2019: *Global Investment Costs for Coastal Defense Through the 21st Century*. *World Bank Policy Research Working Paper Series*.

Nieuwenhuijsen, M.J., 2021: Green Infrastructure and Health. *Annu. Rev. Public Health*, **42**(1), 317–328, doi:10.1146/annurev-publhealth-090419-102511.

Nightingale, A.J., 2017: Power and politics in climate change adaptation efforts: Struggles over authority and recognition in the context of political instability. *Geoforum*, **84**, 11–20, doi:10.1016/j.geoforum.2017.05.011.

Ntshangase, N.L., B. Muroyiwa and M. Sibanda, 2018: Farmers' perceptions and factors influencing the adoption of no-till conservation agriculture by small-scale farmers in Zashuke, KwaZulu-Natal province. *Sustain. (switzerland)*, **10**, 555, doi:10.3390/su10020555.

Nunes, S., et al., 2020: *Challenges and opportunities for large-scale reforestation in the Eastern Amazon using native species*. Elsevier B.V. 118120 pp.

Nuzzo, J.B., et al., 2019: What makes health systems resilient against infectious disease outbreaks and natural hazards? Results from a scoping review. *Bmc Public Health*, **19**, doi:10.1186/s12889-019-7707-z.

Nyantakyi-Frimpong, H., 2017: Agricultural diversification and dietary diversity: A feminist political ecology of the everyday experiences of landless and smallholder households in northern Ghana. *Geoforum*, **86**, 63–75, doi:10.1016/j.geoforum.2017.09.003.

O'Donnell, T., 2019: Contrasting land use policies for climate change adaptation: A case study of political and geo-legal realities for Australian coastal locations. *Land Use Policy*, **88**, doi:10.1016/J.LANDUSEPOL.2019.104145.

O'Mahony, C., S. Gray, J. Gault and V. Cummins, 2020: ICZM as a framework for climate change adaptation action – Experience from Cork Harbour, Ireland. *Mar. Policy.*, **111**, 102223, doi:10.1016/j.marpol.2015.10.008.

O'Hare, P., I. White and A. Connelly, 2016: Insurance as maladaptation: resilience and the 'business as usual' paradox. *Environ. Plan. C Gov. Policy*, **34**, 1175–1193, doi:10.1177/0263774X15602022.

Oakes, R., 2019: Culture, climate change and mobility decisions in Pacific small island developing states. *Popul. Environ.*, **40**, 480–503, doi:10.1007/s11111-019-00321-w.

Ober, K. and P. Sakdapolrak, 2020: Whose climate change adaptation 'barriers'? Exploring the coloniality of climate change adaptation policy assemblages in Thailand and beyond. *Singap J Trop Geogr*, **41**(1), 86–104, doi:10.1111/sjtg.12309.

Obokata, R. and L. Veronis, 2018: Transnational approaches to remittances, risk reduction, and disaster relief: evidence from post-Typhoon Haiyan experiences of Filipino immigrants in Canada. In: *Routledge Handbook of Environmental Displacement and Migration*, pp. 270–276. doi:10.4324/9781315638843-21.

Ogada, M.J., et al., 2020: Climate-smart agriculture, household income and asset accumulation among smallholder farmers in the Nyando basin of Kenya. *World Dev. Perspect.*, **18**, 100203–100203, doi:10.1016/j.wdp.2020.100203.

Ogle, S.M., et al., 2019: Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. *Sci. Rep.*, **9**, 1–8, doi:10.1038/s41598-019-47861-7.

Ojea, E., S.E. Lester and D. Salgueiro-Otero, 2020: *Adaptation of Fishing Communities to Climate-Driven Shifts in Target Species*. Cell Press, 544–556.

Ontl, T.A., et al., 2020: Forest management for carbon sequestration and climate adaptation. *J. For.*, **118**, 86–101, doi:10.1093/jofore/fvz062.

Opoku, S.K., W.L. Filho, F. Hubert and O. Adejumo, 2021: Climate change and health preparedness in Africa: analysing trends in six African countries. *Int. J. Environ. Res. Public Health*, **18**(9), doi:10.3390/ijerph18094672.

Oral, H.V., et al., 2020: A review of nature-based solutions for urban water management in European circular cities: a critical assessment based on case studies and literature. *Blue-green Syst.*, **2**, 112–136, doi:10.2166/BGS.2020.932.

Orchard, S.E., L.C. Stringer and C.H. Quinn, 2016: Mangrove system dynamics in Southeast Asia: linking livelihoods and ecosystem services in Vietnam. *Reg. Environ. Change*, **16**(3), 865–879, doi:10.1007/s10113-015-0802-5.

Osmundsen, T.C., et al., 2020: The operationalisation of sustainability: Sustainable aquaculture production as defined by certification schemes. *Glob. Environ. Chang.*, **60**, 102025, doi:10.1016/j.gloenvcha.2019.102025.

Ossola, A. and B.B. Lin, 2021: *Making nature-based solutions climate-ready for the 50°C world*. Elsevier Ltd, 151–159.

Cross-Chapter Box FEASIB (continued)

Ota, L., J. Herbohn, N. Gregorio and S. Harrison, 2020: Reforestation and smallholder livelihoods in the humid tropics. *Land Use Policy*, **92**, 104455, doi:10.1016/j.landusepol.2019.104455.

Owen, G., 2020: What makes climate change adaptation effective? A systematic review of the literature. *Glob. Environ. Chang.*, **62**, 102071, doi:10.1016/j.gloenvcha.2020.102071.

Paganini, Z., 2019: Underwater: Resilience, racialized housing, and the national flood insurance program in Canarsie, Brooklyn. *Geoforum*, **104**, 25–35, doi:10.1016/j.geoforum.2019.06.003.

Pardo, G. and A. del Prado, 2020: Guidelines for small ruminant production systems under climate emergency in Europe. *Small Rumin. Res.*, **193**, 106261, doi:10.1016/j.smallrumres.2020.106261.

Parihar, C.M., et al., 2020: Soil quality and carbon sequestration under conservation agriculture with balanced nutrition in intensive cereal-based system. *Soil Tillage Res.*, **202**, 104653, doi:10.1016/j.still.2020.104653.

Parry, L., et al., 2019: The (in)visible health risks of climate change. *Soc. Sci. Med.*, **241**, 112448, doi:10.1016/j.socscimed.2019.112448.

Parton, K. A., J. Crean and P. Hayman, 2019: The value of seasonal climate forecasts for Australian agriculture. *Agric. Syst.*, **174**, 1–10, doi:10.1016/j.agsy.2019.04.005.

Pascal, M., et al., 2021: Evolving heat waves characteristics challenge heat warning systems and prevention plans. *Int. J. Biometeorol.*, doi:10.1007/s00484-021-02123-y.

Patel, R., G. Walker, M. Bhatt and V. Pathak, 2017: The demand for disaster microinsurance for small businesses in urban slums: the results of surveys in three Indian cities. *Plos Curr. Disasters*, **9**.

Paudel, U. and K.P. Pant, 2020: Estimation of household health cost and climate adaptation cost with its health related determinants: empirical evidences from western Nepal. *Heliyon*, **6**(11), e5492, doi:10.1016/j.heliyon.2020.e05492.

Paul, S., et al., 2020: Development of an indicator based composite measure to assess livelihood sustainability of shifting cultivation dependent ethnic minorities in the disadvantageous Northeastern region of India. *Ecol Indic*, **110**, 105934, doi:10.1016/j.ecolind.2019.105934.

Pearson, J., K.E. McNamara and P.D. Nunn, 2019: Gender-specific perspectives of mangrove ecosystem services: Case study from Bua Province, Fiji Islands. *Ecosyst. Serv.*, **38**, 100970, doi:10.1016/j.ecoser.2019.100970.

Pelling, M. and M. Garschagen, 2019: *Put equity first in climate adaptation*. Nature Publishing Group, 327–329.

Pelling, M., et al., 2018: Africa's urban adaptation transition under a 1.5° climate. *Curr. Opin. Environ. Sustain.*, **31**, 10–15, doi:10.1016/j.cosust.2017.11.005.

Peng, L.L.H., et al., 2020: Cooling effects of block-scale facade greening and their relationship with urban form. *Build. Environ.*, **169**, 106552, doi:10.1016/j.buildenv.2019.106552.

Perera-Valderrama, S., et al., 2020: Increasing marine ecosystems conservation linking marine protected areas and integrated coastal management in southern Cuba. *Ocean. Coast. Manag.*, **196**, 105300, doi:10.1016/j.ocecoaman.2020.105300.

Pérez-Cayeiro, M.L. and J.A. Chica-Ruiz, 2015: Evaluation of a programme of integrated coastal zone management: the Ecoplata programme (Uruguay). *Mar. Policy.*, **51**, 527–535, doi:10.1016/j.marpol.2014.09.008.

Perrels, A., 2020: Quantifying the uptake of climate services at micro and macro level. *Clim. Serv.*, **17**, 100152, doi:10.1016/j.cliser.2020.100152.

Perrotti, D. and S. Stremke, 2018: Can urban metabolism models advance green infrastructure planning? Insights from ecosystem services research. **47**(4), 678–694, doi:10.1177/2399808318797131. doi:10.1177/2399808318797131.

Petrova, K., 2021: Natural hazards, internal migration and protests in Bangladesh. *J Peace Res*, **58**, 33–49, doi:10.1177/0022343320973741.

Phillips, M.R., A.L. Jones and T. Thomas, 2018: Climate change, coastal management and acceptable risk: consequences for tourism. *J. Coast. Res.*, **85**, 1411–1415, doi:10.2112/SI85-283.1.

Piggott-McKellar, A.E., K.E. McNamara, P.D. Nunn and S.T. Sekinini, 2019: Moving people in a changing climate: Lessons from two case studies in Fiji. *Soc Sci*, **8**, 133, doi:10.3390/socsci8050133.

Piguet, E., 2019: Climatic statelessness: risk assessment and policy options. *Popul. Dev. Rev.*, **45**(4), 865–883, doi:10.1111/padr.12295.

Porst, L., P.S. Population, S. Place and u, 2020: Gendered translocal connectedness: Rural–urban migration, remittances, and social resilience in Thailand. *Wiley Online Libr.*, **26**, doi:10.1002/psp.2314.

Pour, S.H., et al., 2020: Low impact development techniques to mitigate the impacts of climate-change-induced urban floods: current trends, issues and challenges. *Sustain. Cities Soc.*, **62**, 102373, doi:10.1016/j.scs.2020.102373.

Prestele, R., et al., 2018: A spatially explicit representation of conservation agriculture for application in global change studies. *Glob. Change Biol.*, **24**, 4038–4053, doi:10.1111/gcb.14307.

Propato, M., J.S. Clough and A. Polaczyk, 2018: Evaluating the costs and benefits of marsh-management strategies while accounting for uncertain sea-level rise and ecosystem response. *PLoS ONE*, **13**, e200368, doi:10.1371/journal.pone.0200368.

Quandt, A., H. Neufeldt and J.T. McCabe, 2017: The role of agroforestry in building livelihood resilience to floods and drought in semiarid Kenya. *Ecol. Soc.*, **22**, 10, doi:10.5751/ES-09461-220310.

Qurani, I.Z., N.I. Fawzi, R. Fadilah and W. Kismorodati, 2021: Empowering fish-farmer through coastal field school: towards sustainable aquaculture practice. *Iop Conf. Series: Earth Environ. Sci.*, **750**, 12054, doi:10.1088/1755-1315/750/1/012054.

Radel, C., B. Schmook, L. Carte and S. Mardero, 2018: Toward a political ecology of migration: land, labor migration, and climate change in northwestern Nicaragua. *World Dev*, **108**, 263–273, doi:10.1016/j.worlddev.2017.04.023.

Rahman, A.T.M.S., et al., 2017: Drought analysis and its implication in sustainable water resource management in Barind area, Bangladesh. *J Geol Soc India*, **89**(1), 47–56, doi:10.1007/s12594-017-0557-3.

Rahman, S., M.S. Islam, M.N.H. Khan and M. Touhiduzzaman, 2019: Climate change adaptation and disaster risk reduction (DRR) through coastal afforestation in South-Central Coast of Bangladesh. *Manag. Environ. Qual. Int. J.*, **30**, 498–517, doi:10.1108/MEQ-01-2018-0021.

Cross-Chapter Box FEASIB (continued)

Rahut, D.B., J.P. Aryal and P. Marenya, 2021: *Understanding climate-risk coping strategies among farm households: Evidence from five countries in Eastern and Southern Africa*. **769**, 145236.
Ramalho, J., 2019: Worlding aspirations and resilient futures: Framings of risk and contemporary city-making in Metro Cebu, the Philippines. *Asia Pac Viewp*, **60**, 24–36, doi:10.1111/apv.12208.
Ranganathan, M. and E. Bratman, 2021: From urban resilience to abolitionist climate justice in Washington, DC. *Antipode*, **53**(1), 115–137, doi:10.1111/anti.12555.
Rao, N., et al., 2020: Managing risk, changing aspirations and household dynamics: Implications for wellbeing and adaptation in semi-arid Africa and India. *World Dev*, **125**, 104667, doi:10.1016/J.WORLDDEV.2019.104667.
Rasmussen, D., M. Oppenheimer, R.E. Kopp and R. Shwom, 2020: The political complexity of coastal flood risk reduction: lessons for climate adaptation public works in the U.S. *Earth Space Sci. Open Arch.*, doi:10.1002/essoar.10502705.3.
Ratter, B., A. Hennig and Zahid, 2019: Challenges for shared responsibility – Political and social framing of coastal protection transformation in the Maldives. *Die Erde – J. Geogr. Soc. Berl.*, **150**, doi:10.12854/erde-2019-426.
Raymond, C.M., et al., 2017: A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environ. Sci. Policy*, **77**, 15–24, doi:10.1016/j.envsci.2017.07.008.
Reddy, V.R., T. Chiranjeevi and G. Syme, 2020: Inclusive sustainable intensification of agriculture in West Bengal, India: policy and institutional approaches. *Int. J. Agric. Sustain.*, **18**, 70–83, doi:10.1080/14735903.2019.1698489.
Reguero, B.G., et al., 2018: Comparing the cost effectiveness of nature-based and coastal adaptation: a case study from the Gulf Coast of the United States. *PLoS ONE*, **13**(4), e192132, doi:10.1371/journal.pone.0192132.
Rigg, J. and K. Oven, 2015: Building liberal resilience? A critical review from developing rural Asia. *Glob. Environ. Chang.*, **32**, 175–186, doi:10.1016/j.gloenvcha.2015.03.007.
Rogelj, J., et al., 2018: Scenarios towards limiting global mean temperature increase below 1.5°C. *Nature Clim Change*, **8**, 325–332, doi:10.1038/s41558-018-0091-3.
Romañach, S.S., et al., 2018: Conservation and restoration of mangroves: Global status, perspectives, and prognosis. *Ocean. Coast. Manag.*, **154**, 72–82, doi:10.1016/j.ocecoaman.2018.01.009.
Rosendo, S., L. Celliers and M. Mechisso, 2018: Doing more with the same: a reality-check on the ability of local government to implement integrated coastal management for climate change adaptation. *Mar. Policy*, **87**, 29–39, doi:10.1016/j.marpol.2017.10.001.
Rosenzweig, C., et al., 2018: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. Cambridge University Press, 17–42.
Rosyida, I., W. Ullah, A. Helmi and M. Sasaoka, 2019: *Adapting livelihoods to the impacts of tin mining in Indonesia: options and constraints*. Vol. 6, 1302–1313.
Roy, J., et al., 2018: Sustainable development, poverty eradication and reducing inequalities. In: *Global warming of 1.5° C*.
Rudolph, L., N. Maizlish, S. North and K. Dervin, 2020: A public health learning collaborative on climate change for urban health departments, 2016-2018. *Public Health Rep*, **135**, 189–201, doi:10.1177/0033354920902468.
Runkle, J., et al., 2018: *Population Health Adaptation Approaches to the Increasing Severity and Frequency of Weather-Related Disasters Resulting From our Changing Climate: A Literature Review and Application to Charleston, South Carolina*. Springer, 439–452.
Ruszczyk, H.A., et al., 2020: Empowering women through participatory action research in community-based disaster risk reduction efforts. *Int. J. Disaster Risk Reduct.*, **51**, 101763, doi:10.1016/j.ijdrr.2020.101763.
Salam, S. and S. Bauer, 2020: Rural non-farm economy and livelihood diversification strategies: evidence from Bangladesh. *GeoJournal*, 1–13, doi:10.1007/s10708-020-10269-2.
Salmon, G., et al., 2018: Trade-offs in livestock development at farm level: Different actors with different objectives. *Glob Food Sec*, **17**, 103–112, doi:10.1016/j.gfs.2018.04.002.
Sampantamit, T., et al., 2020: Aquaculture production and its environmental sustainability in Thailand: challenges and potential solutions. *Sustainability*, **12**, doi:10.3390/su12052010.
Sani Ibrahim, S., H. Ozdeser and B. Cavusoglu, 2019: Financial inclusion as a pathway to welfare enhancement and income equality: Micro-level evidence from Nigeria. *Dev. South. Afr.*, **36**, 390–407, doi:10.1080/0376835X.2018.1498766.
Santoro, A., M. Venturi, R. Bertani and M. Agnoletti, 2020: A review of the role of forests and agroforestry systems in the FAO globally important agricultural heritage systems (GIAHS) programme. *Forests*, **11**, 860, doi:10.3390/F11080860.
Sarkar, D., et al., 2018: Can sustainability of maize-mustard cropping system be achieved through balanced nutrient management? *Field Crop. Res.*, **225**, 9–21, doi:10.1016/j.fcr.2018.05.018.
Scheres, B. and H. Schüttrumpf, 2019: *Enhancing the Ecological Value of Sea Dikes*.
Schoeneberger, M., et al., 2012: Branching out: Agroforestry as a climate change mitigation and adaptation tool for agriculture. *J. Soil Water Conserv.*, **67**, 128A–136A, doi:10.2489/jswc.67.5.128A.
Schoonees, T., et al., 2019: Hard structures for coastal protection, towards greener designs. *Estuaries Coasts*, **42**, 1709–1729, doi:10.1007/s12237-019-00551-z.
Schramm, P.J., et al., 2020: How indigenous communities are adapting to climate change: insights from the climate-ready tribes initiative. *Health Aff.*, **39**(12), 2153–2159, doi:10.1377/hlthaff.2020.00997.
Schuhbauer, A., et al., 2017: How subsidies affect the economic viability of small-scale fisheries. *Mar. Policy.*, **82**, 114–121, doi:10.1016/j.marpol.2017.05.013.
Schulte, L.A., et al., 2017: Prairie strips improve biodiversity and the delivery of multiple ecosystem services from corn–soybean croplands. *Proc. Natl. Acad. Sci. U.S.A.*, **114**, 11247–11252, doi:10.1073/pnas.1620229114.

Cross-Chapter Box FEASIB (continued)

Schwerdtle, P., K. Bowen and C. McMichael, 2018: The health impacts of climate-related migration. *BMC Med*, **16**(1), 1–7, doi:10.1186/S12916-017-0981-7.

Schwerdtle, P., C. McMichael and I. M.-E. and u., 2020: Health and migration in the context of a changing climate: a systematic literature assessment . doi:10.1088/1748-9326/ab9ece. iopscience.iop.org.

Seddon, N., et al., 2020a: *Understanding the value and limits of nature-based solutions to climate change and other global challenges*. Royal Society Publishing.

Seddon, N., et al., 2020b: Global recognition of the importance of nature-based solutions to the impacts of climate change. *Glob. Sustain.*, **3**, doi:10.1017/sus.2020.8.

Seddon, N., et al., 2019: *Grounding nature-based climate solutions in sound biodiversity science*. Nature Publishing Group, 84–87.

Sedova, B. and M. Kalkuhl, 2020: Who are the climate migrants and where do they go? Evidence from rural India. *World Dev.*, **129**, 104848, doi:10.1016/j.worlddev.2019.104848.

See, J. and B. Wilmsen, 2020: Just adaptation? Generating new vulnerabilities and shaping adaptive capacities through the politics of climate-related resettlement in a Philippine coastal city. *Glob. Environ. Chang.*, **65**, 102188, doi:10.1016/J.GLOENVCHA.2020.102188.

Seebauer, S., S. Ortner, P. Babcicky and T. Thaler, 2019: Bottom-up citizen initiatives as emergent actors in flood risk management: Mapping roles, relations and limitations. *J. Flood Risk Manag.*, **12**, doi:10.1111/jfr3.12468.

Seleka, M., B. Lough, E. Combaz and M.L. Seleka, 2017: *African Young Graduates and Scholars Conference Paper*.

Semenza, J.C. and K.L. Ebi, 2019: Climate change impact on migration, travel, travel destinations and the tourism industry. *J. Travel Med.*, **26**, doi:10.1093/jtm/taz026.

Serre, D. and C. Heinzlef, 2018: Assessing and mapping urban resilience to floods with respect to cascading effects through critical infrastructure networks. *Int. J. Disaster Risk Reduct.*, **30**, 235–243, doi:10.1016/j.ijdrr.2018.02.018.

Shackleton, S., et al., 2015: Why is socially-just climate change adaptation in sub-Saharan Africa so challenging? A review of barriers identified from empirical cases. *Wiley Interdiscip. Rev. Clim. Chang.*, **6**, 321–344, doi:10.1002/wcc.335.

Shaffril, H.A.M., A. Abu Samah and J.L. D'Silva, 2017: Adapting towards climate change impacts: Strategies for small-scale fishermen in Malaysia. *Mar. Policy.*, **81**, 196–201, doi:10.1016/j.marpol.2017.03.032.

Shah, F. and W. Wu, 2019: Soil and crop management strategies to ensure higher crop productivity within sustainable environments. *Sustainability*, **11**, 1485, doi:10.3390/su11051485.

Shang, Z., et al., 2021: Can cropland management practices lower net greenhouse emissions without compromising yield? *Glob Change Biol*, doi:10.1111/gcb.15796.

Shannon, P.D., et al., 2019: *Adaptation strategies and approaches for forested watersheds*. Elsevier B.V., 51–64.

Shapiro, S., 2016: The realpolitik of building codes: overcoming practical limitations to climate resilience. *Build. Res. Inf.*, **44**, 490–506, doi:10.1080/09613218.2016.1156957.

Sharma, H., D. Kumar, L. and K.S. Pant, 2020: Agroforestry- A sustainable tool for climate change adaptation and mitigation. *Agric. Rev.*, doi:10.18805/ag.r-1924.

Sharma, R. and R. Sharma, 2021: Community based flood risk management: local knowledge and actor's involvement approach from lower Karnali river basin of Nepal. *J. Geosci. Environ. Prot.*, **9**(6), 35–65, doi:10.4236/GEP.2021.96003.

Sheehan, M.C. and M. A. Fox, 2020: Early warnings: the lessons of COVID-19 for public health climate preparedness. *Int J Health Serv*, **50**, 264–270, doi:10.1177/0020731420928971.

Shi, L., 2019: Promise and paradox of metropolitan regional climate adaptation. *Environ. Sci. Policy*, **92**, 262–274, doi:10.1016/j.envsci.2018.11.002.

Shi, L. and A.M. Varuzzo, 2020: Surging seas, rising fiscal stress: Exploring municipal fiscal vulnerability to climate change. *Cities*, **100**, doi:10.1016/j.cities.2020.102658.

Shokry, G., J.J. Connolly and I. Anguelovski, 2020: Understanding climate gentrification and shifting landscapes of protection and vulnerability in green resilient Philadelphia. *Urban Clim.*, **31**, 100539, doi:10.1016/j.uclim.2019.100539.

Siders, A.R., 2019: Social justice implications of US managed retreat buyout programs. *Clim Change*, **152**, 239–257, doi:10.1007/s10584-018-2272-5.

Siders, A.R. and J.M. Keenan, 2020: Variables shaping coastal adaptation decisions to armor, nourish, and retreat in North Carolina. *Ocean. Coast. Manag.*, **183**, 105023, doi:10.1016/j.ocecoaman.2019.105023.

Sietsma, A.J., J.D. Ford, M.W. Callaghan and J.C. Minx, 2021: Progress in climate change adaptation research. *Environ. Res. Lett.*, **16**, 54038, doi:10.1088/1748-9326/abf7 f3.

Sina, D., A.Y. Chang-Richards, S. Wilkinson and R. Potangaroa, 2019: What does the future hold for relocated communities post-disaster? Factors affecting livelihood resilience. *Int. J. Disaster Risk Reduct.*, **34**, 173–183, doi:10.1016/j.ijdrr.2018.11.015.

Singh, B.P., R. Setia, M. Wiesmeier and A. Kunhikrishnan, 2018a: *Agricultural management practices and soil organic carbon storage*. Elsevier, 207–244.

Singh, C. and R. Basu, 2020: Moving in and out of vulnerability: Interrogating migration as an adaptation strategy along a rural–urban continuum in India. *Geogr. J.*, **186**, 87–102, doi:10.1111/geoj.12328.

Singh, C., et al., 2020a: Assessing the feasibility of climate change adaptation options in the water sector: Examples from rural and urban landscapes. *Water Secur.*, **11**, 100071, doi:10.1016/j.wasec.2020.100071.

Singh, C., et al., 2018b: The utility of weather and climate information for adaptation decision-making: current uses and future prospects in Africa and India. *Clim. Dev.*, **10**, 389–405, doi:10.1080/17565529.2017.1318744.

Singh, C., et al., 2020b: Assessing the feasibility of adaptation options: methodological advancements and directions for climate adaptation research and practice. *Clim Change*, doi:10.1007/s10584-020-02762-x.

Cross-Chapter Box FEASIB (continued)

Singh, C., G. Jain, V. Sukhwani and R. Shaw, 2021a: Losses and damages associated with slow-onset events: urban drought and water insecurity in Asia. *Curr. Opin. Environ. Sustain.*, **50**, 72–86, doi:10.1016/j.cosust.2021.02.006.

Singh, C., M. Madhavan, J. Arvind and A. Bazaz, 2021b: Climate change adaptation in Indian cities: A review of existing actions and spaces for triple wins. *Urban Clim.*, **36**, 100783, doi:10.1016/j.uclim.2021.100783.

Singh, C., A. Rahman, A. Srinivas and A. Bazaz, 2018c: Risks and responses in rural India: Implications for local climate change adaptation action. *Clim. Risk Manag.*, **21**, 52–68, doi:10.1016/j.crm.2018.06.001.

Singh, D., et al., 2020c: *A review on feedstocks, production processes, and yield for different generations of biodiesel*. Elsevier Ltd.

Siriwardane-de Zoysa, R., 2020: Beyond the wall: Dyking as an object of everyday governance in the Bay of Manila, Philippines. *Mar. Policy.*, **112**, 103661, doi:10.1016/j.marpol.2019.103661.

Sletto, B., S. Tabory and K. Strickler, 2019: Sustainable urban water management and integrated development in informal settlements: The contested politics of co-production in Santo Domingo, Dominican Republic. *Glob. Environ. Chang.*, **54**, 195–202, doi:10.1016/J.GLOENVCHA.2018.12.004.

Smith, J., B.D. Pearce and M.S. Wolfe, 2013: Reconciling productivity with protection of the environment: Is temperate agroforestry the answer? *Renew. Agric. Food Syst.*, **28**(1), 80–92, doi:10.1017/S1742170511000585.

Smucker, T.A., M. Oulu and R. Nijbroek, 2020: Foundations for convergence: sub-national collaboration at the nexus of climate change adaptation, disaster risk reduction, and land restoration under multi-level governance in Kenya. *Int. J. Disaster Risk Reduct.*, **51**, 101834, doi:10.1016/j.ijdrr.2020.101834.

Sojka, M., et al., 2019: Sustainable water management in agriculture—the impact of drainage water management on groundwater table dynamics and subsurface outflow. *Sustainability*, **11**(15), doi:10.3390/su11154201.

Sollen-Norrlin, M., B.B. Ghaley and N.L. Rintoul, 2020: Agroforestry Benefits and Challenges for Adoption in Europe and Beyond. *Sustainability*, **12**(17), doi:10.3390/su12177001.

Somasundaram, J., et al., 2020: No-till farming and conservation agriculture in south asia–issues, challenges, prospects and benefits. *CRC Crit Rev Plant Sci*, **39**, 236–279, doi:10.1080/07352689.2020.1782069.

Sommer, R., B.K. Paul, J. Mukalama and J. Kihara, 2018: Reducing losses but failing to sequester carbon in soils – the case of conservation agriculture and integrated soil fertility management in the humid tropical agro-ecosystem of western Kenya. *Agric. Ecosyst. Environ.*, **254**, 82–91, doi:10.1016/j.agee.2017.11.004.

Son, H.N., A. Kingsbury and H.T. Hoa, 2021: Indigenous knowledge and the enhancement of community resilience to climate change in the northern mountainous region of Vietnam. *Agroecol. Sustain. Food Syst.*, **45**(4), 499–522, doi:10.1080/21683565.2020.1829777.

Sova, C.A., et al., 2018: *Bringing the Concept of Climate-Smart Agriculture to Life*. doi:10.1596/31064. Bringing the Concept of Climate-Smart Agriculture to Life.

Spaans, M. and B. Waterhout, 2017: Building up resilience in cities worldwide–Rotterdam as participant in the 100 resilient cities programme. *Cities*, **61**, 109–116.

Spilker, G., Q. Nguyen, V. Koubi and T. Böhmelt, 2020: Attitudes of urban residents towards environmental migration in Kenya and Vietnam. *Nature Clim Change*, **10**, 622–627, doi:10.1038/s41558-020-0805-1.

Stefanakis, A.I., 2019: The role of constructed wetlands as green infrastructure for sustainable urban water management. *Sustainability*, **11**(24), doi:10.3390/su11246981.

Stentiford, G.D., et al., 2020: Sustainable aquaculture through the one health lens. *Nat. Food*, **1**, 468–474, doi:10.1038/s43016-020-0127-5.

Suckall, N., E. Fraser and P. F.-C. a. Development and u, 2017: 2016: reduced migration under climate change: evidence from Malawi using an aspirations and capabilities framework. *Taylor Francis*, **9**, 298–312, doi:10.1080/17565529.2016.1149441.

Surminski, S., L.M. Bouwer and J. Linnerooth-Bayer, 2016: How insurance can support climate resilience. *Nature Clim Change*, **6**, 333–334, doi:10.1038/nclimate2979.

Szewrański, S., et al., 2018: *Socio-Environmental Vulnerability Mapping for Environmental and Flood Resilience Assessment: The Case of Ageing and Poverty in the City of Wrocław, Poland*. Wiley-Blackwell, 592–597.

Tabe, T., 2019: Climate change migration and displacement: learning from past relocations in the pacific. *Soc Sci*, **8**(7), doi:10.3390/socsci8070218.

Tagliari, M.M., et al., 2021: *Collaborative management as a way to enhance Araucaria Forest resilience*. Associacao Brasileira de Ciencia Ecologica e Conservacao, 131–142.

Tall, A., J.Y. Coulibaly and M. Diop, 2018: Do climate services make a difference? A review of evaluation methodologies and practices to assess the value of climate information services for farmers: Implications for Africa. *Clim. Serv.*, **11**, 1–12, doi:10.1016/j.cliser.2018.06.001.

Tanaya, T., et al., 2021: Improvement of the coral growth and cost-effectiveness of hybrid infrastructure by an innovative breakwater design in Naha Port, Okinawa, Japan. *Coast. Eng. J.*, doi:10.1080/21664250.2021.1889823.

Tanner, T., et al., 2015: *Livelihood resilience in the face of climate change*. Nature Publishing Group, 23–26.

Tavenner, K. and T.A. Crane, 2018: Gender power in Kenyan dairy: cows, commodities, and commercialization. *Agric Hum Values*, **35**(3), 701–715, doi:10.1007/s10460-018-9867-3.

Telave, A.B. and S.R. Chandankar, 2021: Integrated coastal zone management: An Indian perspective-A Review. *Ecol. Environ. Conserv.*, 162–167.

Telford, A., 2018: A threat to climate-secure European futures? Exploring racial logics and climate-induced migration in US and EU climate security discourses. *Geoforum*, **96**, 268–277, doi:10.1016/j.geoforum.2018.08.021.

TerAvest, D., P.R. Wandschneider, C. Thierfelder and J.P. Reganold, 2019: Diversifying conservation agriculture and conventional tillage cropping systems to improve the wellbeing of smallholder farmers in Malawi. *Agric Syst*, **171**, 23–35, doi:10.1016/j.agsy.2019.01.004.

Terêncio, D.P.S., et al., 2018: Rainwater harvesting in catchments for agro-forestry uses: A study focused on the balance between sustainability values and storage capacity. *Sci. Total. Environ.*, **613-614**, 1079–1092, doi:10.1016/j.scitotenv.2017.09.198.

Cross-Chapter Box FEASIB (continued)

Tesselaar, M., W.J.W. Botzen and J.C.J.H. Aerts, 2020: Impacts of climate change and remote natural catastrophes on EU flood insurance markets: an analysis of soft and hard reinsurance markets for flood coverage. *Atmosphere*, **11**, doi:10.3390/atmos11020146.

Thierfelder, C., et al., 2017: How climate-smart is conservation agriculture (CA)? – its potential to deliver on adaptation, mitigation and productivity on smallholder farms in southern Africa. *Food Sec.*, **9**, 537–560, doi:10.1007/s12571-017-0665-3.

Thober, J., N. Schwarz and K. Hermans, 2018: Agent-based modeling of environment-migration linkages: A review. *Ecol. Soc.*, **23**, doi:10.5751/ES-10200-230241.

Thomas, A. and L. Benjamin, 2018: Policies and mechanisms to address climate-induced migration and displacement in Pacific and Caribbean small island developing states. *Int. J. Clim. Chang. Strateg. Manag.*, **10**, 86–104, doi:10.1108/IJCCSM-03-2017-0055.

Thomas, M., et al., 2021: When more is more: taking advantage of species diversity to move towards sustainable aquaculture. *Biol Rev*, **96**, 767–784, doi:10.1111/brv.12677.

Thompson, P.L., B. Rayfield and A. Gonzalez, 2017: Loss of habitat and connectivity erodes species diversity, ecosystem functioning, and stability in metacommunity networks. *Ecography*, **40**, 98–108, doi:10.1111/ecog.02558.

Thorne, C.R., et al., 2018: Overcoming uncertainty and barriers to adoption of blue-green infrastructure for urban flood risk management. *J. Flood Risk Manag.*, **11**(S2), 960–972, doi:10.1111/jfr3.12218.

Tian, Q. and M.C. Lemos, 2018: Household livelihood differentiation and vulnerability to climate hazards in rural China. *World Dev*, **108**, 321–331, doi:10.1016/j.worlddev.2017.10.019.

Tiggeloven, T., et al., 2020: Global-scale benefit–cost analysis of coastal flood adaptation to different flood risk drivers using structural measures. *Nat. Hazards Earth Syst. Sci.*, **20**, 1025–1044, doi:10.5194/nhess-20-1025-2020.

Torell, E., C. McNally, B. Crawford and G. Majubwa, 2017: Coastal livelihood diversification as a pathway out of poverty and vulnerability: experiences from Tanzania. *Coast. Manag.*, **45**(3), 199–218, doi:10.1080/08920753.2017.1303718.

Tschora, H. and F. Cherubini, 2020: Co-benefits and trade-offs of agroforestry for climate change mitigation and other sustainability goals in West Africa. *Glob. Ecol. Conserv.*, **22**, doi:10.1016/J.GECCO.2020.E00919.

Turolla, E., G. Castaldelli, E.A. Fano and E. Tamburini, 2020: *Life Cycle Assessment (LCA) Proves that Manila Clam Farming (Ruditapes Philippinarum) is a Fully Sustainable Aquaculture Practice and a Carbon Sink*.

Uddin, M.S., C.E. Haque and M.N. Khan, 2020: Good governance and local level policy implementation for disaster-risk-reduction: actual, perceptual and contested perspectives in coastal communities in Bangladesh. *Disaster Prev. Manag. Int. J.*, **30**, 94–111, doi:10.1108/DPM-03-2020-0069.

Ulrichs, M., R. Slater and C. Costella, 2019: Building resilience to climate risks through social protection: from individualised models to systemic transformation. *Disasters*, **43**, 368–387, doi:10.1111/disa.12339.

Valenti, W.C., J.M. Kimpara, B.L. Preto and P. Moraes-Valenti, 2018: Indicators of sustainability to assess aquaculture systems. *Ecol Indic*, **88**, 402–413, doi:10.1016/j.ecolind.2017.12.068.

van den Brandeler, F., J. Gupta and M. Hordijk, 2019: Megacities and rivers: scalar mismatches between urban water management and river basin management. *J. Hydrol.*, **573**, 1067–1074, doi:10.1016/j.jhydrol.2018.01.001.

Van Hulst, F.J. and H. Posthumus, 2016: Understanding (non-) adoption of conservation agriculture in Kenya using the reasoned action approach. *Land Use Policy*, **56**, 303–314, doi:10.1016/j.landusepol.2016.03.002.

Van Langevelde, F., et al. (ed.), *The link between biodiversity loss and the increasing spread of zoonotic diseases Policy Department for Economic, Scientific and Quality of Life Policies Directorate-General for Internal Policies*.

Van Loon-Steensma, J.M. and P. Vellinga, 2019: How "wide green dikes" were reintroduced in The Netherlands: a case study of the uptake of an innovative measure in long-term strategic delta planning. *J. Environ. Plan. Manag.*, **62**, 1525–1544, doi:10.1080/09640568.2018.1557039.

Van Oijstaeijen, W., S. Van Passel and J. Cools, 2020: Urban green infrastructure: A review on valuation toolkits from an urban planning perspective. *J. Environ. Manag.*, **267**, 110603, doi:10.1016/j.jenvman.2020.110603.

van Valkengoed, A.M. and L. Steg, 2019: Meta-analyses of factors motivating climate change adaptation behaviour. *Nature Clim Change*, **9**, 158–163, doi:10.1038/s41558-018-0371-y.

Vanden Bygaart, A.J., 2016: *The myth that no-till can mitigate global climate change*. Elsevier B.V., 98–99.

Vargas-Hernández, J.G. and J. Zdunek-Wielgołaska, 2021: Urban green infrastructure as a tool for controlling the resilience of urban sprawl. *Environ. Dev. Sustain.*, **23**(2), 1335–1354, doi:10.1007/s10668-020-00623-2.

Vaughan, C., L. Buja, A. Kruczkiewicz and L. Goddard, 2016: Identifying research priorities to advance climate services. *Clim. Serv.*, **4**, 65–74, doi:10.1016/j.cliser.2016.11.004.

Vaughan, C., S. Dessai and C. Hewitt, 2018: Surveying climate services: what can we learn from a bird's-eye view? *Weather. Clim. Soc.*, **10**, 373–395, doi:10.1175/WCAS-D-17-0030.1.

Vaughan, C., et al., 2019: Evaluating agricultural weather and climate services in Africa: evidence, methods, and a learning agenda. *WIREs Clim. Change*, **10**(4), e586, doi:10.1002/wcc.586.

Velasco-Muñoz, J.F., J.A. Aznar-Sánchez, L.J. Belmonte-Ureña and M.J. López-Serrano, 2018: Advances in water use efficiency in agriculture: a bibliometric analysis. *Water*, **10**(4), doi:10.3390/w10040377.

Venter, Z.S., et al., 2020: Green Apartheid: Urban green infrastructure remains unequally distributed across income and race geographies in South Africa. *Landsc Urban Plan*, **203**, 103889, doi:10.1016/j.landurbplan.2020.103889.

Viani, F., M. Bertolli, M. Salucci and A. Polo, 2017: Low-cost wireless monitoring and decision support for water saving in agriculture. *IEEE Sensors J.*, **17**(13), 4299–4309, doi:10.1109/JSEN.2017.2705043.

Cross-Chapter Box FEASIB (continued)

Villamizar, A., et al., 2017: Climate adaptation in South America with emphasis in coastal areas: the state-of-the-art and case studies from Venezuela and Uruguay. *Clim. Dev.*, **9**, 364–382, doi:10.1080/17565529.2016.1146120.

Villeneuve, M., 2021: Building a roadmap for inclusive disaster risk reduction in Australian communities. *Prog. Disaster Sci.*, **10**, 100166, doi:10.1016/j.pdisas.2021.100166.

Vincent, K., et al., 2017: Identifying climate services needs for national planning: insights from Malawi. *Clim. Policy*, **17**(2), 189–202, doi:10.1080/14693062.2015.1075374.

von Holle, B., S. Yelenik and E.S. Gornish, 2020: Restoration at the landscape scale as a means of mitigation and adaptation to climate change. *Curr. Landsc. Ecol. Reports*, **5**, 85–97, doi:10.1007/s40823-020-00056-7.

Vousdoukas, M.I., et al., 2020: Economic motivation for raising coastal flood defenses in Europe. *Nat Commun*, **11**, 2119, doi:10.1038/s41467-020-15665-3.

Walsh, C., 2019: Integration of expertise or collaborative practice?: Coastal management and climate adaptation at the Wadden Sea. *Ocean. Coast. Manag.*, **167**, 78–86, doi:10.1016/j.ocecoaman.2018.10.004.

Wang, X., et al., 2020: Cutting carbon footprints of vegetable production with integrated soil - crop system management: A case study of greenhouse pepper production. *J Clean Prod*, **254**, 120158, doi:10.1016/j.jclepro.2020.120158.

Warner, K., 2018: Coordinated approaches to large-scale movements of people: contributions of the Paris Agreement and the global compacts for migration and on refugees. *Popul Environ*, **39**, 384–401, doi:10.1007/S11111-018-0299-1.

Warnken, J. and R. Mosadeghi, 2018: Challenges of implementing integrated coastal zone management into local planning policies, a case study of Queensland, Australia. *Mar. Policy*, **91**, 75–84, doi:10.1016/j.marpol.2018.01.031.

Waryszak, P., et al., 2021: Combining gray and green infrastructure to improve coastal resilience: lessons learnt from hybrid flood defenses. *Coast. Eng. J.*, 1–16, doi:10.1080/21664250.2021.1920278.

Watts, N., et al., 2021: The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises. *Lancet*, **397**(10269), 129–170, doi:10.1016/s0140-6736(20)32290-x.

Webb, J., 2020: What difference does disaster risk reduction make? Insights from Vanuatu and tropical cyclone Pam. *Reg. Environ. Change*, **20**, doi:10.1007/s10113-020-01584-y.

Webber, J.L., et al., 2020: Is green infrastructure a viable strategy for managing urban surface water flooding? *Urban Water Journal*, **17**(7), 598–608, doi:10.1080/1573062X.2019.1700286.

Webber, S. and S.D. Donner, 2017: Climate service warnings: cautions about commercializing climate science for adaptation in the developing world. *Wiley Interdiscip. Rev. Clim. Chang.*, **8**, e424, doi:10.1002/wcc.424.

Weng, W., L. Costa, M.K.B. Lüdeke and D.C. Zemp, 2019: Aerial river management by smart cross-border reforestation. *Land Use Policy*, **84**, 105–113, doi:10.1016/j.landusepol.2019.03.010.

WHO, 2015: *Operational framework for building climate resilient health systems*. World Health Organisation, 56.

WHO, 2019: *2018 WHO health and climate change survey report: Tracking global progress*.

Wiegel, H., I. Boas and J. Warner, 2019: A mobilities perspective on migration in the context of environmental change. *Wiley Online Libr.*, **10**, doi:10.1002/wcc.610.

Willems, J.J., A.V. Kenyon, L. Sharp and A. Molenveld, 2021: How actors are (dis)integrating policy agendas for multi-functional blue and green infrastructure projects on the ground. *J. Environ. Policy Plan.*, **23**(1), 84–96, doi:10.1080/1523908X.2020.1798750.

Williams, D.S., M.M. Costa, L. Celliers and C. Sutherland, 2018: Informal settlements and flooding: Identifying strengths and weaknesses in local governance for water management. *Water (Switzerland)*, **10**, doi:10.3390/W10070871.

Williams, D.S., et al., 2020: A method of assessing user capacities for effective climate services. *Clim. Serv.*, **19**, 100180, doi:10.1016/j.cliser.2020.100180.

Williams, P.A., et al., 2021: Feasibility assessment of climate change adaptation options across Africa: An evidence-based review. *Environ. Res. Lett.*, **16**, 73004, doi:10.1088/1748-9326/ac092d.

Wilmsen, B. and M. Webber, 2015: What can we learn from the practice of development-forced displacement and resettlement for organised resettlements in response to climate change? *Geoforum*, **58**, 76–85, doi:10.1016/j.geoforum.2014.10.016.

Wilson, N.J., 2014: The politics of adaptation: subsistence livelihoods and vulnerability to climate change in the Koyukon Athabascan village of Ruby, Alaska. *Hum Ecol*, **42**, 87–101, doi:10.1007/s10745-013-9619-3.

Winters, M.A., B. Leslie, E.B. Sloane and T.W. Gallien, 2020: *Observations and Preliminary Vulnerability Assessment of a Hybrid Dune-Based Living Shoreline*.

Wolfrom, L. and M. Yokoi-Arai, 2015: Financial instruments for managing disaster risks related to climate change. *OECD Journal: Financial Mark. Trends*, 25–47, doi:10.1787/fmt-2015-5jrqdkpxk5d5.

Woodhouse, E. and J.T. McCabe, 2018: Well-being and conservation: diversity and change in visions of a good life among the Maasai of northern Tanzania. *Ecol. Soc.*, **23**, 9986–230143, doi:10.5751/ES-09986-230143. Published online: Mar 26, 2018.

Woodruff, S., T.K. BenDor and A.L. Strong, 2018: Fighting the inevitable: infrastructure investment and coastal community adaptation to sea level rise. *Syst. Dyn. Rev.*, **34**, 48–77, doi:10.1002/sdr.1597.

Worboys, G.L., et al. (ed.), *Connectivity conservation area guidelines [definition, types, selection criteria and governance]*. advanced draft, may 2016.

Woroniecki, S., C. Wamsler and E. Boyd, 2019: The promises and pitfalls of ecosystem-based adaptation to climate change as a vehicle for social empowerment. *Ecol. Soc.*, **24**(2), doi:10.5751/ES-10854-240204.

Wrathall, D.J., et al., 2019: Meeting the looming policy challenge of sea-level change and human migration. *Nat. Clim. Chang.*, **9**(12), 898–901, doi:10.1038/s41558-019-0640-4.

Cross-Chapter Box FEASIB (continued)

Xuan, B.B., E.D. Sandorf and Q.T.K. Ngoc, 2021: Stakeholder perceptions towards sustainable shrimp aquaculture in Vietnam. *J. Environ. Manag.*, **290**, 112585, doi:10.1016/j.jenvman.2021.112585.

Yumagulova, L., et al., 2021: The role of disaster volunteering in Indigenous communities. *Environ. Hazards*, **20**(1), 45–62, doi:10.1080/17477891.2019.1657791.

Zen, I.S., A.Q. Al-Amin and B. Doberstein, 2019: *Mainstreaming Climate adaptation and Mitigation Policy: Towards Multi-Level Climate Governance in Melaka, Malaysia*. Elsevier B.V.

Zhang, C., L. Zhong and J. Wang, 2018: Decoupling between water use and thermoelectric power generation growth in China. *Nat. Energy*, **3**, 792–799, doi:10.1038/s41560-018-0236-7.

Zhang, Z., S. Meerow, J.P. Newell and M. Lindquist, 2019: Enhancing landscape connectivity through multifunctional green infrastructure corridor modeling and design. *Urban For. Urban Green.*, **38**, 305–317, doi:10.1016/j.ufug.2018.10.014.

Zobeidi, T., et al., 2021: Factors affecting smallholder farmers' technical and non-technical adaptation responses to drought in Iran. *J. Environ. Manag.*, **298**, 113552, doi:10.1016/j.jenvman.2021.113552.

Zomer, R.J., D.A. Bossio, R. Sommer and L.V. Verchot, 2017: Global sequestration potential of increased organic carbon in cropland soils. *Sci. Rep.*, **7**, 1–8, doi:10.1038/s41598-017-15794-8.

Zwierzchowska, I., et al., 2019: Introducing nature-based solutions into urban policy – facts and gaps. Case study of Poznań. *Land Use Policy*, **85**, 161–175, doi:10.1016/j.landusepol.2019.03.025.