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Ten New Insights in Climate Science 2023/2024

Abstract

Non-technical summary:

We identify a set of essential recent advances in climate change research with high policy relevance, across natural and social sciences: (1) looming inevitability and implications of overshooting the 1.5°C warming limit, (2) urgent need for a rapid and managed fossil fuel phase-out, (3) challenges for scaling carbon dioxide removal, (4) uncertainties regarding the future contribution of natural carbon sinks, (5) intertwinedness of the crises of biodiversity loss and climate change, (6) compound events, (7) mountain glacier loss, (8) human immobility in the face of climate risks, (9) adaptation justice, and (10) just transitions in food systems.

Technical summary

The IPCC Assessment Reports offer the scientific foundation for international climate negotiations and constitute an unmatched resource for climate change researchers. However, the assessment cycles take multiple years. As a contribution to cross- and interdisciplinary understanding across diverse climate change research communities, we have streamlined an annual process to identify and synthesise essential research advances. We collected input from experts on different fields using an online questionnaire and prioritised a set of ten key research insights with high policy relevance. This year we focus on: (1) looming overshoot of the 1.5°C warming limit, (2) urgency of phasing-out fossil fuels, (3) challenges for scaling carbon dioxide removal, (4) uncertainties regarding the future of natural carbon sinks, (5) need for join governance of biodiversity loss and climate change, (6) advances in the science of compound events, (7) mountain glacier loss, (8) human immobility in the face of climate risks, (9) adaptation justice, and (10) just transitions in food systems. We first present a succinct account of these Insights, reflect on their policy implications, and offer an integrated set of policy relevant messages. This science synthesis and science communication effort is also the basis for a report targeted to policymakers as a contribution to elevate climate science every year, in time for the UNFCCC COP.

Social media summary

We highlight recent and policy-relevant advances in climate change research - with input from more than 200 experts

Introduction

In 2023, the world takes a critical look at progress towards collectively delivering on the Paris Agreement, with the first Global Stocktake to be completed at COP28. At this key moment in international climate negotiations, the science is already clear that a course-correction from current greenhouse gas (GHG) emissions trends is needed. As we move deeper into this crucial decade for action on climate change, it is vital that the latest science on climate change and its impacts be readily available and in accessible formats for all those involved in international negotiations, national policymaking, private sector decision-making, and civil society mobilisation. At the heart of the United Nations Framework Convention on Climate Change (UNFCCC) process, the Intergovernmental Panel on Climate Change (IPCC) is responsible for assessing the science underpinning the levers and scale of climate action. Through periodic, extensive assessments of the scientific literature, the IPCC is the most authoritative voice on the state of knowledge on climate change. The latest cycle of the IPCC concluded this year with the Sixth Assessment Report (AR6) (IPCC, 2021; 2022a; 2022b; 2023). Through these reports, the IPCC informs stakeholders not only about the current scientific understanding on climate change, associated impacts, risks and solution space, but also the pace of climate actions under the international pledges and agreements.

Given the thematic breadth and procedural demands of the IPCC assessments, each cycle takes several years to complete. For example, more than eight years passed between the release of the AR5 Synthesis Report (SYR) and the AR6 SYR. One obvious limitation of this setup is that in the multi-year periods between the release of major IPCC reports, negotiators and decision-makers are in need of an authoritative source of scientific advances, which otherwise remain less visible and accessible to them. Furthermore, while the AR6 SYR was published this year (2023), the cut-off point for the scientific literature assessed by the three work groups was more than two years before that. The '10 New Insights in Climate Science' series (https://10insightsclimate.science/), a collaboration between Future Earth, The Earth League, and the World Climate Research Programme (WCRP), contributes to fill this gap each year. Starting in 2017, three years after the publication of the AR5 SYR, and every year since, the '10 New Insights' report has been published to highlight essential advances in climate change research from the prior year, from both natural and social sciences, and with high policy relevance. The aim of this international collaboration is to provide a timely and curated set of synthesised science-based 'Insights' for negotiators, decision-makers, and other stakeholders, to stay up-to-date and grounded in the latest peer-reviewed research. Since 2020, the report has been developed on the basis of a peer-reviewed academic paper (Martin et al., 2021, 2022; Pihl et al., 2021), providing a more solid foundation and strengthening the messages.

Every year, there is a plethora of relevant reports on different aspects of climate change and climate action, including the State of the Global Climate (WMO, 2023b), the Emissions Gap Report (UNEP, 2022a), Adaptation Gap Report (UNEP, 2022b), the Global Carbon Budget (Friedlingstein et al., 2022), and United in Science (2022). Generally, these well-recognised reports are focused on updating diagnostic indicators that are familiar to those involved in or following climate negotiation. The '10 New Insights' report links recent research advances to those categories, but also seeks to inform stakeholders about a wider range of topics across the full landscape of climate change research and their interactions, including many that are likely less familiar to the climate negotiations audience though not less relevant. The '10 New Insights' 2023 report is also intended as a resource for researchers interested in having a better understanding of developments in different areas of climate change research beyond their domain of expertise, and their policy implications.

We define a ‘New Insight’ as a recent development or advance in a particular area of climate change research. The Insight can be the result of discrete new evidence or analyses that significantly updated previous understanding with regards to processes or patterns of climate change, including impacts and the possible means for addressing the climate emergency. We also consider emerging developments (novel topics and research questions) gathering recognition in the field and important issues on the horizon of climate change research. In this latter case, the advance might be more conceptual in nature. To be considered recent, these developments or advances must be anchored in peer-reviewed literature published in 2022 and 2023.

This year we highlight the looming inevitability of overshooting the 1.5°C global warming limit target (Insight 1), a situation that will mean an increase in risks, but also significant uncertainty. In this context, we call attention to the fast-shrinking carbon budget and emphasise the inescapable necessity of a rapid and managed fossil fuel phase-out (Insight 2). Given the significance of carbon dioxide removal (CDR) to these two issues, we outline the challenges for up-scaling, accounting, and governance of CDR (Insight 3). We cast light on key uncertainties regarding the future of natural carbon sinks in land and oceans as warming levels rise (Insight 4). This adds to the urgency for decarbonising our economy and being clear-sighted about the realistic role of CDR methods.

We stress the intertwinedness of the crises of biodiversity loss and climate change, and the need to joint governance and synergistic approaches to confront them (Insight 5). Impacts and vulnerabilities continue to increase, and this year we feature science advances in regarding compound events (Insight 6) and the acceleration of mountain glacier loss (Insight 7). Much confusion persists regarding the complex relationship between climate change and human mobility; we covered several aspects of this relationship in 2022, and this year we devote one Insight to immobility in the face of climate risks (Insight 8). Insight 9 synthesises recent advances to conceptualise and evaluate justice in adaptation planning and the key role of locally-led adaptation (LLA) efforts. Finally, Insight 10 centres on the call from researchers to integrate just transitions in food systems transformations as a necessary condition for realising their mitigation potential while assuring food security and nature conservation.

Method[1]

The process for selecting the set of 10 Insights started with an open call for input distributed primarily across the partners’ institutional networks, reaching experts globally. Contributions were collected through an online questionnaire, in which the main question was: *What is a key recent advance in climate change research that you think should be highlighted for policymakers?* The respondents were also asked to provide the peer-reviewed publications, published in 2022 and 2023, that support the suggested ‘key recent advance’. The call for input was open from January 23 to February 20, and we received 167 *entries* from 131 individual respondents. The entries were screened based on

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[1] In the supplementary material we provide 1) a flow diagram of the process described above, 2) the questionnaire used for the open call, 3) brief characterisation of the respondents to the questionnaire, 4) inclusion criteria for entries, 5) complementary literature scan, and 6) the list of resulting themes, and a brief account of the relative contribution to the final set of 10 Insights obtained from the open call for input and from the complementary literature scan.

predefined inclusion criteria, with each individual entry screened by two team members, at least. Discrepancies were further discussed among the project team to reach a final decision. When necessary, project coordinators completed one additional round of screening and made a final decision. Seventy-one entries met the inclusion criteria. After merging closely related entries, the list was reduced to 43 *themes* and was coded using a thematic framework based on prior '10 New Insights' reports. This list was complemented with a literature scan of impactful papers in climate change research published in the same period (2022 and the first months of 2023, which yielded 23 additional themes. The final list of 66 themes was then evaluated in a three-stage process by a group of 24 very well-established international researchers on climate change from different disciplines, who constitute our Editorial Board. First, each Editorial Board member selected 4-20 themes considered most relevant (1-5 in each of four broad categories: the Earth system, impacts, action needed, and barriers). Second, building on the outcomes of the individual prioritisation of themes, in a virtual workshop the Editorial Board members collectively revised the priority themes, leading to a preliminary set of close to 10 *candidate Insights*. Finally, each of the candidate Insights was examined more deeply, providing the input for a second workshop of the Editorial Board, in which a final list of the 10 Insights was decided on, through deliberation. Once the 10 Insights were outlined, 10 international groups of 4-6 experts each were formed. Each group was tasked with synthesising key messages from recent academic literature and their policy implications.

Results

Insight 1. Overshooting 1.5°C is fast becoming inevitable, greatly increasing risks as mitigation action is delayed

The IPCC AR6 found that global warming is *likely* or *very likely* to exceed 1.5°C relative to the pre-Industrial era in the near term (before 2040) under all but the very low greenhouse gas (GHG) emissions scenarios (SSP1-1.9). Few pathways remain that avoid a 1.5°C overshoot; pathways with no or limited overshoot require emissions to peak before 2025 and be cut by 43% by 2030 relative to 2019 levels (IPCC, 2022b, Ch3 p. 329), representing a 6% decrease each year. Research since AR6 indicates overshooting 1.5°C is all but inevitable in the near term, based on assessments of:

a) The remaining carbon budget (Friedlingstein et al., 2022) and emission trends: Fossil CO_2 emissions in 2022 were 1% higher than in 2021. The remaining carbon budget for 1.5°C is currently estimated to be 250 Gt CO_2 (50% likelihood) (Forster et al., 2023), and will be used up in 6-7 years based on current annual emissions GHG emissions;

b) New evidence on the geophysical warming commitment inherent in the climate system: Global climate modelling indicates that there is a 42% probability that the world is committed to peak global warming of at least 1.5°C based on past emissions alone (Dvorak et al., 2022);

c) The most recent emissions reduction pledges put forward by countries: Modelling indicates the Paris Agreement target of 1.5°C will be exceeded shortly after 2030 even under the most ambitious emission pledge scenarios (Meinshausen et al., 2022);

d) The carbon lock-in and inertia of the global energy sector, responsible for about three-quarters of current emissions (IEA, 2023a): Proposed and existing large fossil-fuel projects would produce emissions of up to twice the carbon budget for 1.5°C (Kühne et al., 2022) (see Insight 2 on fossil fuel phase-out).

Box 1. Definition of 1.5°C overshoot. The IPCC (2021, Annex VII p. 2251) defines temperature overshoot as the exceedance of a specified level of global warming, followed by an eventual return. Global warming, which the Paris Agreement aims to limit his century to 1.5°C, refers to increases in global mean surface temperature with respect to the pre-industrial era (1850-1900), averaging over a period long enough to remove interannual variations (e.g., 20 or 30 years). Breaching 1.5°C in any given year is expected to become more frequent in the upcoming decades (WMO, 2023a).

If overshooting 1.5°C is all but inevitable, it is essential that policymakers and citizens are informed appropriately about the factors that determine the peak temperature and duration of the overshoot, and the risk implications during the time of overshoot. There is real risk that temperatures might not be brought down, mainly due to the scale of net negative emissions required, which may not be feasible, and/or their costs and impacts seen as unacceptable (see Insight 3). The risks of overshooting 1.5°C will inform the urgency and scale of near-term adaptation and mitigation efforts. In that regard, every fraction of a degree of warming greatly matters.

Warming is near-linearly related to cumulative CO_2 emissions (IPCC, 2021, TS p. 55 and Ch5 p. 742). Hence, the peak warming during overshoot is determined by the extent to which global carbon dioxide (CO_2) emissions accumulated over time exceed the carbon budget for 1.5°C and, therefore, the world's emissions trajectory until net zero CO_2 emissions are achieved. Scenarios assuming continuation of current policies project a warming of 2.6°C (1.9-3.7°C) (Meinshausen et al., 2022) and 2.1-2.4°C (van der Ven et al., 2023) by the end of the century. Assessments of emissions trajectories that assume all countries fulfil their short and long-term climate pledges, project 1.9-2.0°C (Meinshausen et al., 2022) and 1.7-1.8°C warming by 2100 (van der Ven et al., 2023). This shows that current pledges are insufficient to avoid overshooting 1.5°C, whilst current policy actions are insufficient for even keeping within 2°C.

Recent studies converge on the importance of implementing current pledges up to 2030 to limit peak warming closer to 1.5°C, as well as ratcheting ambition in the long-term (Meinshausen et al., 2022; van der Ven et al., 2023). Although early mitigation presents near-term challenges, it is less costly over the long term (see Insight 3 on CDR). Postponing mitigation until after 2030 comes with higher and persistent feasibility concerns, notably due to volatility and uncertainty caused by higher climate impacts (Brutschin et al., 2021), particularly in non-OECD countries (Bauer et al., 2023).

Reaching net zero CO_2 emissions is necessary for containing the peak warming level. The world's ability to bring temperature down to specific goals after overshoot depends on removing more CO_2 from the atmosphere than is emitted: achieving net-negative CO_2 emissions. If achieved (this is uncertain due to unresolved, fundamental questions regarding CDR; see Insight 3), there may still be a delay of several years before the climate cools, due to lags in the carbon cycle and thermal response (IPCC, 2021, Ch4 p. 624 and Ch5 p. 775).

Warming reversal may also be delayed if overshoot triggers the release of GHGs from natural carbon sinks in ways not yet modelled, or not yet anticipated. Such impacts are already being observed (IPCC 2022a: Ch2.4 and Ch2.5; see Insight 4) This uncertainty is represented by the red shaded area in Figure 1.

Breaching the 1.5°C target over decades would leave a long-lasting legacy on the Earth system, since some aspects of the climate and wider environment will not recover, within human-relevant timescales of decades to a century, to the same state as in a reference scenario without overshoot. This is mainly due to the slow response time of key Earth system components. Surface air temperature and precipitation changes appear largely reversible at the global scale following a decline in atmospheric CO_2, but they exhibit irreversibility at regional scale on a timescale of centuries, posing a greater risk to human and natural systems in regions of irreversibility (Kim et al., 2022; Oh et al., 2022). Further long-term, irreversible changes include sea level rise from ocean thermal expansion and melting of ice sheets and glaciers during overshoot, sea ice loss, changes in the deep sea environment (e.g., oxygen, acidity), and changes in structure and composition of terrestrial ecosystems that affect carbon uptake and losses, including permafrost carbon loss (Bauer et al., 2023; IPCC, 2021: Ch4.6.2.1; IPCC, 2022a: Ch2.5.2.10); Schwinger et al., 2022).

Spatially heterogeneous and potentially irreversible impacts, such as more frequent heatwave exposure with subsequent economic damages as well as mass mortality of species, worsen with higher peak and duration of overshoot (Bauer et al., 2023; Meyer et al., 2022). Irreversible impacts can be especially identified for marine biodiversity, with species facing the added pressure of prolonged ocean acidification after peak overshoot (Meyer et al., 2022).

Lastly, there is considerable risk that a long overshoot period above 2°C could trigger self-perpetuating feedbacks associated with climate tipping elements, such as instabilities of the Greenland or West Antarctic Ice Sheets or loss of mountain glaciers (Armstrong McKay et al., 2022; Wunderling et al., 2023), which would be largely irreversible on timescales of centuries to millennia. Impacts of tipping elements include several metres of sea level rise in the long-term, causing loss of land, livelihoods and cultural heritage in coastal communities and small island states, and irreversible degradation of mid-latitude coral reef species (Bauer et al., 2023; Meyer et al., 2022). All these risks increase severely with the extent of overshoot above 1.5°C. If the 1.5°C goal is missed, decision-makers should continue to strive to limit warming to as close to 1.5°C as possible and minimise the duration of overshoot. Further studies are urgently needed to investigate the direct and indirect impacts of overshoot to inform policy and action.

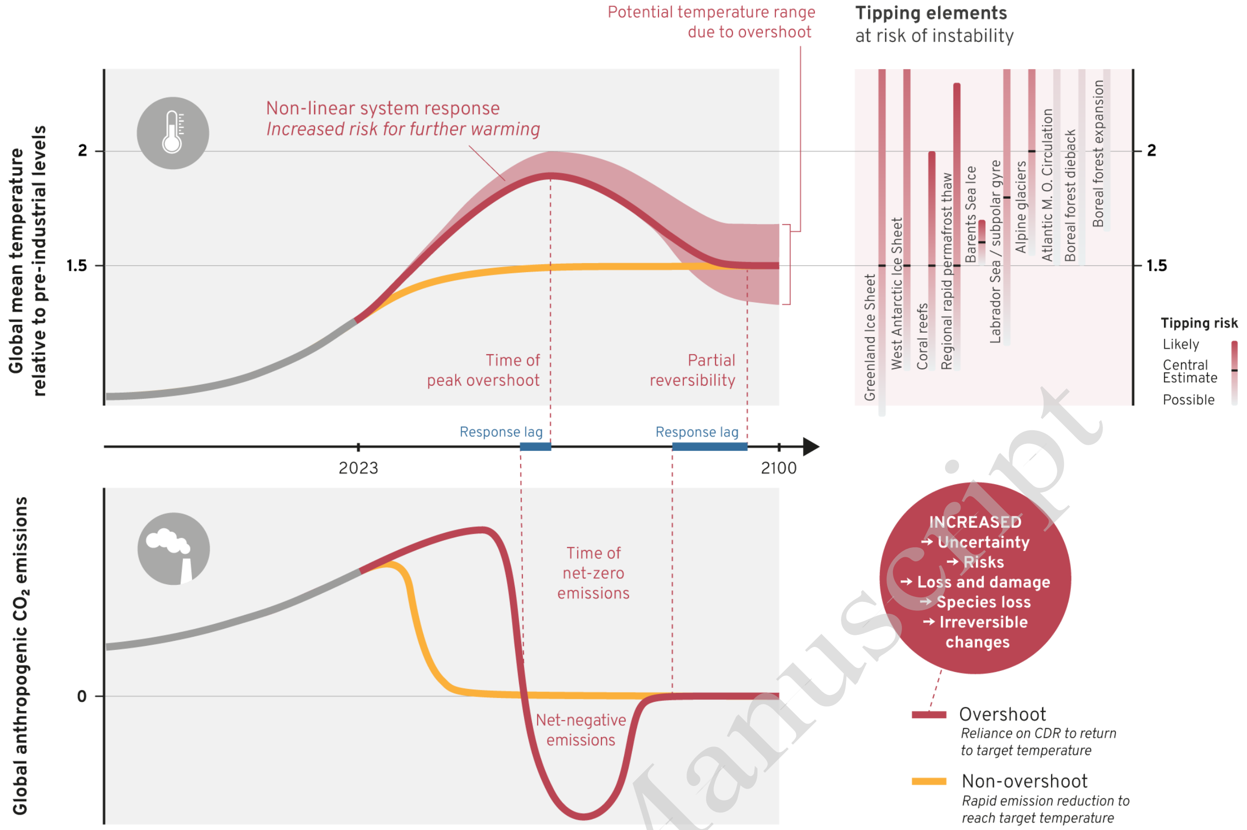


Figure 1: Overshoot and non-overshoot scenarios. Stylised representation of a temperature overshoot scenario (red line) and its risks after reaching net zero CO_2 emissions in comparison to a non-overshoot scenario (yellow line) stabilising at the target temperature of 1.5°C by 2100. The temperature of the overshoot pathway may not return to 1.5°C on reaching the same cumulative emissions as the non-overshoot scenario due to feedbacks and response lags in the Earth system components. The associated uncertainty of global mean temperature reversibility after the overshoot, together with simultaneous regional climate irreversibility, may only lead to 'partial reversibility'. Note that the tipping elements at risk of instability in the upper panel only correspond to the global warming levels, not to the time axis. Data for the tipping element risk assessment is taken from Armstrong McKay et al. (2022).

Insight 2. Fast-shrinking carbon budget calls for a managed and equitable fossil fuel phase-out

Fossil fuels are the largest cause of climate change, accounting for close to 90% of global CO_2 emissions (Friedlingstein et al., 2022). The "committed emissions" that would occur over the lifetime of already-existing infrastructure used in extraction and consumption of fossil fuels is estimated to exceed the remaining carbon budget for a 50% chance of limiting warming to 1.5°C (Tong et al., 2019; Trout et al., 2022; see Figure 2). Investments in new fields, mines, power plants, heating systems, and other long-lived fossil-fuel infrastructure are thus inconsistent with pathways to keep the 1.5°C goal within reach (IEA, 2023c; IISD, 2022) and risk creating trillions of dollars of stranded assets (see Box 2). Furthermore, they create “carbon lock-in”: it is harder to stop fossil fuel projects from operating once they are built, since companies tend to pursue full-lifetime use of assets to recover sunk investment. However, governments and companies still plan on extracting vastly more fossil fuels than consistent with the 1.5°C target, creating a so-called “production gap”(Rekker et al., 2023; SEI et al., 2023). Government subsidies for fossil fuel production and use also reached an all-time high of one trillion USD in 2022 (IEA, 2023b).

Fossil fuel expansion is also perpetuated by financial actors through their investments and company ownership. Potential economic losses from stranded assets in upstream oil and gas are estimated upwards of one trillion USD, held predominantly in the Global North through cross-border financial stakes in oil and gas fields elsewhere (Semieniuk et al., 2022). Stranded assets can have macroeconomic consequences by affecting the valuation of other assets, i.e. contagion and triggering spillovers from the financial to the real economy (Campiglio & van der Ploeg, 2022). Governments are directly exposed through state-owned companies and reduced taxes and royalties, and indirectly through commitments to bailing out private fossil-fuel investors or stabilising the financial system. New government policies and explicit planning are thus needed to facilitate a rapid and managed phase-out of fossil-fuel production and use in line with achieving net-zero CO_2 emissions by 2050 (IEA, 2023c; Grubert & Hastings-Simon, 2022).

A managed approach is needed, which entails preventing new facilities being built (IEA, 2023c), establishing timelines for phasing out existing facilities (Trencher et al., 2022), creating financial mechanisms for an orderly wind-down (GFANZ, 2022), coordinating actions on fossil fuel supply and demand to avoid price volatility (Diluiso et al., 2021), ensuring a just transition for workers and communities, and fairly allocating efforts between countries (Muttitt and Karth, 2020).

A global phase-out of fossil fuels faces several barriers. First, fossil fuels are intertwined with geopolitics and concerns over energy security (Espagne et al., 2023). Europe’s dramatic reduction of Russian gas imports following the invasion of Ukraine sparked a new dash for gas supplies and, in some cases, heightened reliance on coal power. Second, pressing energy and economic needs in developing countries are driving increased fossil-fuel consumption and production (Saha & Carter, 2022). The need to leapfrog to clean energy systems is hampered by insufficient international finance (Pachauri et al., 2022). Additionally, exporter countries continue to depend on fossil-fuel revenues, making it hard to transform their economies (Muttitt and Kartha, 2020). Third, long-standing political opposition from fossil-fuel interests and incumbents continues to undermine and delay mitigation efforts across all sectors (Stoddard et al., 2021, Steckel & Jakob, 2022).

Fourth, investors in fossil-fuel assets covered by international investment treaties are increasingly using investor-state dispute settlement to protect expected profits, with governments potentially exposed to up to USD 340 billion in liabilities from potential legal claims in the oil and gas sector alone (Tienhaara et al., 2022). Finally, while diverse policy options exist for implementing a managed and equitable wind-down of fossil fuels (Diluiso et al., 2021), sociopolitical contexts can affect their feasibility and effectiveness (Steckel & Jakob, 2022) (see Insight 9 on adaptation justice).

Nevertheless, in recent years, climate policies and actions are increasingly targeting fossil fuel phase-out. Notable inter-governmental efforts include the Powering Past Coal Alliance, aimed at phasing out coal-fired power by 2030-2040, and the Beyond Oil and Gas Alliance, focused on phasing out oil and gas production. Many governments are also exploring legal and diplomatic means of limiting exposure to potential investor-state disputes of fossil fuel infrastructure, such as by leaving the Energy Charter Treaty. Many national-level efforts are addressing gasoline vehicles and fossil-gas heating systems in buildings (Kerr & Winskel, 2022). In areas lacking viable alternatives (steel, cement, aviation, shipping), there is less phase-out research and policy (Trencher et al., 2022). Efforts to reduce fossil fuel consumption in military operations, which are a major source of publicly financed emissions globally, also lag (Stoddard et al., 2021).

Research is increasingly investigating how fast phase-outs can and should be achieved in different countries, taking into account differentiated capacities and circumstances (Calverley & Anderson, 2022; Fyson et al., 2022). The relative phase-out pace of the three fossil fuels matters too: while cost-optimised models vary in their pace of phaseout (Achakulwisut et al., 2023) a common feature is that they generally phase -out coal much more rapidly. However, this can put an unrealistic burden on coal-dependent developing countries, suggesting more attention is needed on oil and gas phase-out (Muttitt et al., 2023). There is also a growing literature on what a multilateral response to phasing out fossil fuels globally could look like, including models for international cooperation and the role of climate litigation and social movements (van Asselt & Newell, 2022). On the financial side, studies have mapped out the influence of specific actors in perpetuating fossil fuel lock-in, including asset managers and governments (Baines & Hanger, 2023; Dordi et al., 2022), top wealth owners (Semieniuk et al., 2023), banks (Rainforest Action Network et al., 2023)

In sum, building new fossil fuel infrastructure carries significant economic, financial, legal, and climate risks. Delaying action would not only necessitate a faster and costlier decarbonisation later on, but also heighten socioeconomic disruptions (Skjølsvold & Coenen, 2021). Strategies to phase out fossil fuels should also be paired with actions to accelerate the uptake of clean alternatives to avoid energy shortages, price spikes and inflation, and to create employment opportunities for workers transitioning from fossil fuel industries (Heffron & McCauley, 2022; Grubert & Hastings-Simon, 2022). Phase-out and phase-in are synergistic: evidence from past experiences shows that phase-out policies can drive innovation and the scale-up of alternatives (Diluiso et al., 2021; Trencher et al., 2023).Governments and financial institutions should plan a managed and internationally coordinated, and equitable phase-out, beginning now.

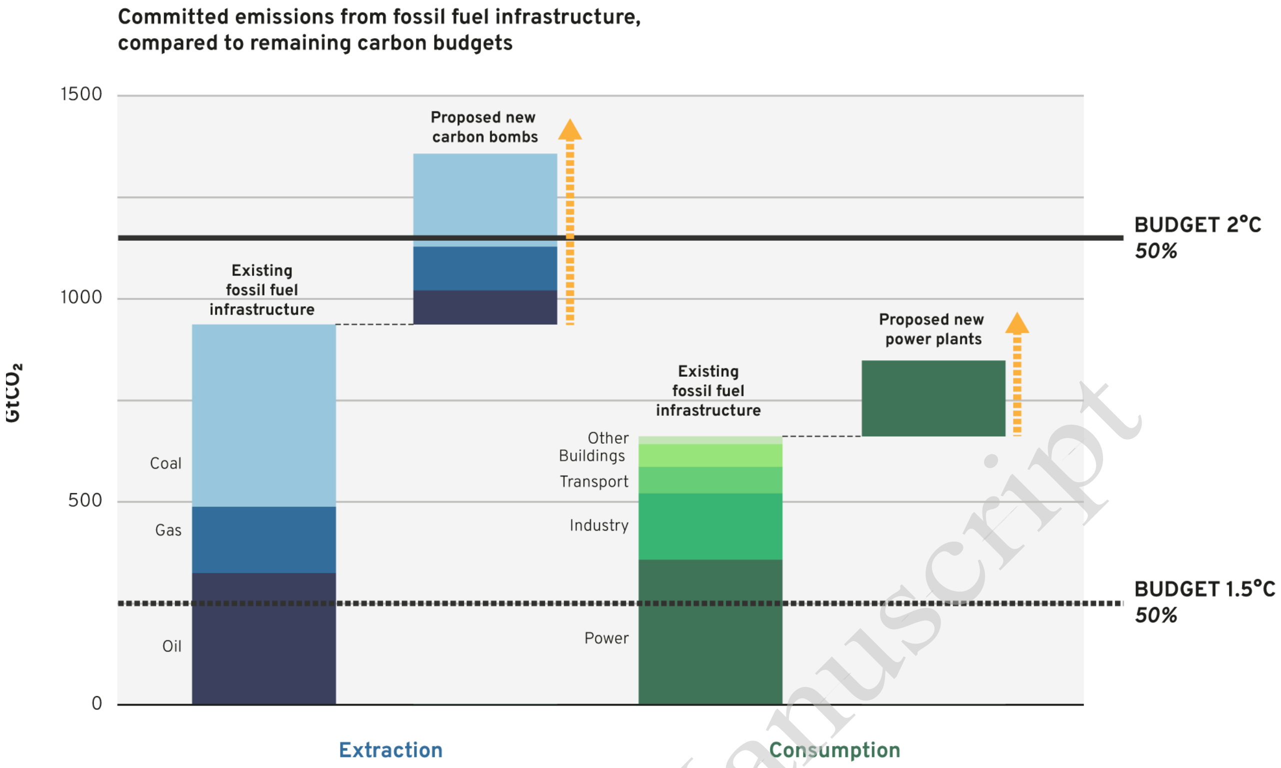


Figure 2. Committed CO_2 emissions from fossil fuel infrastructure compared to carbon budgets reflecting the Paris goals. Bars show future emissions arising from full-lifetime operation of fossil fuel-consuming infrastructure (Tong et al., 2019) and of fossil-fuel extracting infrastructure (Trout et al, 2022), also showing proposed "carbon bombs", defined as fossil fuel extraction projects whose lifetime emissions exceed 1 $GtCO_2$ (Kühne et al, 2022). These are compared with the remaining carbon budget (Friedlingstein et al., 2022) updated remaining for early 2023 (Forster et al., 2023). Whilst the estimates for existing infrastructure are comprehensive, those for proposed infrastructure are partial due to lack of available data on consuming infrastructure in industry, transport, buildings or other, or on smaller future extraction infrastructure projects. "Existing" generally means that capital has been invested or committed, as at the start of 2018 (see original papers for further details on methods). New infrastructure built since then will likely exceed retirements and reductions in remaining life, hence an updated estimate would likely be larger. Since the infrastructure estimates for extraction and consumption relate to different ends of the supply chain, they are non-additive: each carbon atom passes through both extraction and combustion stages. Whilst amounts of extraction and consumption are equal in any given year (apart from minor changes in storage), the committed emissions differ due to different amounts and lifetimes of capital stock of the types of infrastructure.

Box 2: Early retirement, asset stranding, and lock-in

A key problem for a fast fossil-fuel phase-out is the long operational lifetimes of many fossil-fuel assets, ranging from less than 20 years for vehicles to 60 years for infrastructure. Limiting global warming to 1.5°C will require a substantial amount of existing fossil fuel infrastructure to be retired early, shortening these lifetimes, and/or running assets below their normal capacity (Figure 2). Asset stranding occurs when such early retirement, or devaluation of the asset's product (e.g., a structurally lower oil price), is unanticipated at the time a firm invests building the asset, thus missing the firm's expected rate of return, and leading to income losses. Financial assets that derive their value from physical fossil-fuel assets, such as shares in a fossil-fuel company, can also strand (Semieniuk et al. 2022). This can happen earlier than physical asset stranding and might happen abruptly if enough investors adjust their expectations of future returns downward at the same time. Such a "green swan" event substantially devalues stocks, which in turn could affect macro-financial stability (Campiglio & van der Ploeg 2022). Carbon lock-in where an incumbent set of infrastructure, institutions and behaviours creates inertia that make it harder for clean energy to compete and replace fossil fuels (Kemfert et al., 2022). For example, income and wealth losses of fossil fuel companies and financial beneficiaries due to asset stranding may lead to their opposition to mitigation policies.

Insight 3. Carbon Dioxide Removal is necessary but faces challenges in up-scaling, accounting, and governance

Meeting the Paris Agreement will require rapidly reducing emissions while also scaling up carbon dioxide removals (CDR) (IPCC 2022b: Ch12.3). CDR involves capturing atmospheric CO_2 and durably storing it. Scenarios that keep warming well below 2°C include removing hundreds of billions of tons of CO_2 from the atmosphere over the course of the century to compensate both for residual emissions and potential overshoot (IPCC 2022b: Ch12.3). At present, nearly all CDR consists of CDR via afforestation/reforestation and forestry). By contrast, only 0.1% of current removals come from more "novel CDR" methods which partly go beyond the land use, land-use change and forestry (LULUCF) sector. These more novel methods comprise in particular bioenergy with carbon capture and storage (BECCS) and biochar, with an even smaller contribution from other novel methods (e.g., direct air carbon capture and storage (DACCS), enhanced weathering (EW), and ocean CDR approaches such as alkalinity enhancement or macroalgae sinking) (Powis et al., 2023). However, novel CDR methods have large technical removal potential (S. M. Smith et al., 2023) and are scaled up in virtually all scenarios that limit warming to 1.5°C or 2°C (Fuss et al., 2018; IPCC 2022b: Ch12.3.

A "CDR gap" exists between the extent of CDR deployment in countries' plans and what mitigation scenarios indicate would be needed to meet the Paris Agreement temperature limit. The median yearly gap for 2050 across scenarios is >1GtCO_2 at a minimum and >7GtCO_2 with less ambitious emissions reductions (for comparison, the total current CDR capacity is 2Gt/year) (S. M. Smith et al., 2023). Closing the CDR gap requires lengthy times (1-3 decades) for developing technology, designing effective monitoring, reporting, and verification (MRV), ensuring ecosystem safety, building supporting infrastructure, and scaling up deployment. Therefore, the extent of early deployment of novel CDR over the next decade is likely to be consequential in determining whether CDR will be available at scale and in time to reach net zero CO_2 emissions by the early 2050s, as well as whether it will be available for net-negative CO_2 emissions afterwards.

CDR options include a wide variety of approaches, levels of technological readiness, and durability of sequestration (Figure 3) (Fuhrman et al., 2023). All CDR options have remaining scientific uncertainties around MRV and life-cycle assessment (LCA) boundaries that need to be addressed (Mercer & Burke, 2023) (see Box 3). For example, while measuring the capture and sequestration from DACCS is straightforward, its high energy intensity risks diverting clean energy that could otherwise be used for grid decarbonization (Sovacool et al., 2023). Estimates of CO_2 fluxes in the LULUCF sector suffer from high levels of uncertainty in general and are hampered by confounding effects from environmental changes and inconsistent definitions (Pongratz et al., 2021).

Similarly, there are large uncertainties (as well as practical limitations to measurement) in the weathering rates of silicate rocks when applied to fields (Buckingham et al., 2022) and air-sea gas exchange dynamics for direct ocean removal or ocean alkalinity enhancement (Bach et al., 2023). There are also unclear risks of runaway secondary precipitation associated with ocean alkalinity enhancement (Hartmann et al., 2023), and counterfactual carbon storage uncertainties associated with biomass-based CDR (Hausfather et al., 2022). When CDR is used to claim that a ton of fossil CO_2 emissions is effectively undone, a mismatch in timeframes may still result in long-term climate effects (Allen et al., 2022). All these can undermine our ability to meet the Paris temperature goal, which is a function of cumulative CO_2 emissions and can only be achieved if CO_2 emissions reach net zero.

The durability of using afforestation/reforestation (A/R) or soil carbon is at risk in a warming world because of the increased prevalence of wildfires, droughts, and pests (Anderegg et al., 2022); analogous to effects in natural carbon sinks (see Insight 4). Vegetation regrowth in the absence of anthropogenic A/R interventions is also largely unaccounted for at present (Jayakrishnan et al., 2022). For this reason both the scientific community (Allen et al., 2022) and standard-setting bodies (e.g., SBTi, 2020) are increasingly emphasising a “like-for-like” approach to CDR neutralisation claims, where fossil CO_2 emissions should be neutralised through CDR that durably sequesters CO_2, while LULUCF CDR can only be used to neutralise land-use related CO_2 emissions (Allen et al., 2022). Propositions for how to account for non-permanence have emerged in frameworks for quantifying the climate benefit (Prado & Mac Dowell, 2023) and the design of policy architectures (Edenhofer et al., 2023). One practical example is a European Commission proposal for temporary CDR credits for less permanent options (European Commission, 2022c).

With the widespread adoption of net-zero emissions targets, countries have begun to integrate CDR into modelled national mitigation pathways, increase research, development, and demonstration (RD&D) efforts on CDR methods, and consider CDR-specific incentives and policies (Babiker et al. 2022; Smith et al. 2023). CDR policymaking is faced with the need to consider the method-specific timescales of CO_2 storage, and challenges in MRV and accounting described above, as well as potential co-benefits, adverse side effects, interactions with adaptation and trade-offs with the Sustainable Development Goals (SDGs) (IPCC 2022b: Ch3.7 and Ch12.3). Therefore, CDR governance and policymaking are expected to focus on responsibly incentivizing RD&D and targeted deployment, building on the technical and governance experience gained from already widely practised CDR methods like A/R, as well as learning from two decades of the slow-moving carbon capture and storage (CCS) deployment. For novel CDR, such as ocean alkalinisation or enhanced weathering, investment in RD&D would help in understanding the risks, rewards, and uncertainties of deployment (S. M. Smith et al., 2023).

Some aspects of CDR governance and policy instruments will be similar to those around emissions reduction measures, while others will require governance innovation. Effectively integrating CDR into governments' mitigation portfolios, to close the "CDR gap", can build on already existing rules, procedures and instruments for emissions abatement (Edenhofer et al., 2023; Michaelowa et al., 2023). A political commitment to formal integration into existing climate policy frameworks is required (Sovacool et al., 2023), as are robust MRV systems (Mercer & Burke, 2023). To avoid CDR being misperceived as a substitute for deep emissions reductions (Buck et al., 2023), the prioritisation of emissions cuts can be signalled and achieved by explicitly setting separate targets for reductions and removals (Carton et al., 2023), for example. Similarly, sub-targets are conceivable for different types of CDR, to prioritise preferred methods according to characteristics such as removal processes or timescales of storage (Allen et al., 2022).

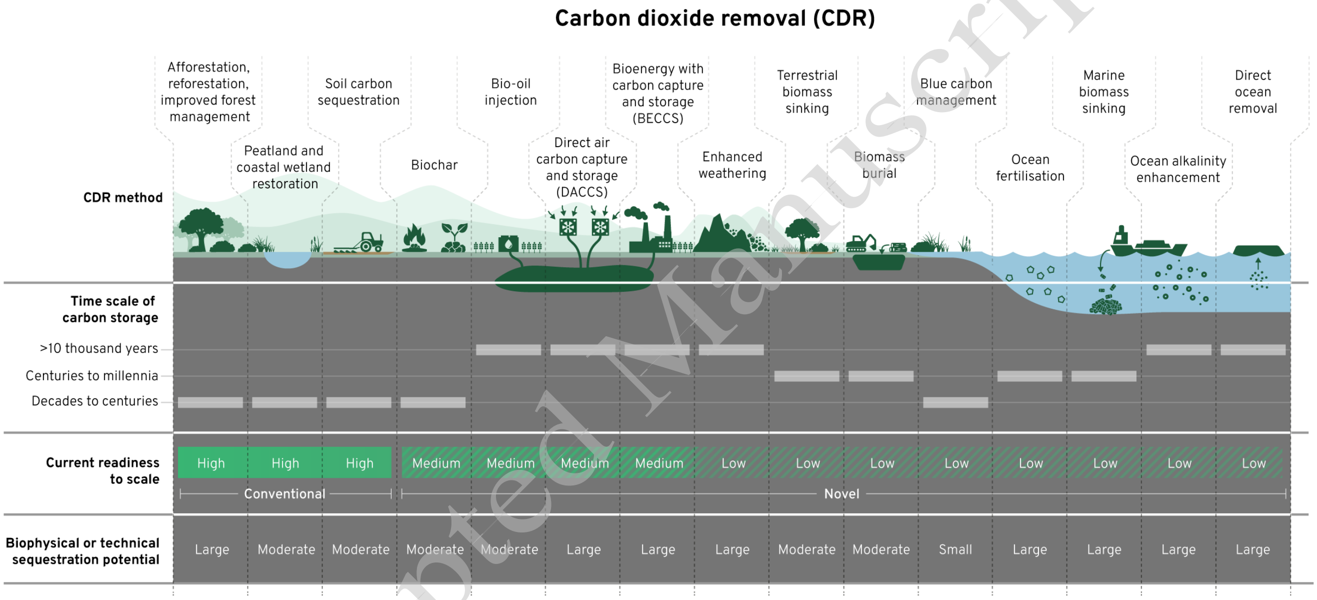


Figure 3. Taxonomy of carbon dioxide removal options. The 'CDR method' (first row of the figure) most widely discussed in the recent literature, 'Time scale of carbon storage' (second row) refers to the expected durability of the carbon storage, 'Current readiness to scale' (third row) refers to the maturity level for deployment at scale, and 'Biophysical or technical sequestration potential' (fourth row) reflects current understanding (based largely on IPCC 2022b: Ch12.3), additional references in Supplementary material, SM7). Modified from IPCC (2022b: Ch12.3).

Box 3: The mix of CDR options deployed and included in scenarios will evolve.
Currently, the vast majority of CDR happens through methods that fall in the LULUCF sector (such as afforestation/reforestation; improved forest management and long-lived product usage; agroforestry; soil carbon in croplands and grasslands). All methods imply trade-offs but may offer co-benefits e.g., local climate or biodiversity, if implemented carefully. But the impermanence of the carbon storage in LULUCF options is of particular concern, as forests in many regions are increasingly threatened by climate driven disturbances (droughts, heatwaves, fires, storms, pests). “Novel” CDR options, like bioenergy with carbon capture and storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), biochar and ocean alkalinization currently play only a minor role and come with their own challenges e.g., cost, energy demand, and unintended ecological side-effects. Scenarios evaluated by the IPCC that stay below a 2°C warming (2022b: Ch3) typically assign a large relevance to LULUCF CDR and to BECCS. Many of these scenarios assume BECCS scales up substantially by the end of the century, some also assume a large scale-up of DACCS in the second half of the century. The importance of these three CDR options reflects the current capabilities of the underlying socioeconomic models rather than a judgement of the feasibility of CDR options. Many research and demonstration programs, as well as policy strategies, consider a broader range of CDR options, and given the limited potential of each method and associated risks at scale, it may be preferable to complement emission reduction efforts with a portfolio of CDR options, which adjusts over time to account for technological progress and changing environmental, societal, economic and political requirements.

Insight 4. New reasons for concern: the uncertain future contribution of land and ocean carbon sinks

The remaining carbon budget, constructed to ensure staying within temperature limits, shrinks with every ton of emitted $CO_{2,}$ and will be exhausted soon when aiming at staying below 1.5°C of global warming with a chance of 50% (see Insight 1 on overshoot). The magnitude of the remaining carbon budget substantially depends on assumptions about the future contribution of the natural carbon sinks on land and in the ocean. In IPCC’s carbon budgets for the 21st century (2021: Chp5.5), the sinks are assumed to respond in a relatively linear manner to changes in temperature, CO_2, and other forcings, yet recent scientific insights cast doubts on our understanding and knowledge of their future trajectory (Figure 4).

In spite of rising emissions, a relatively constant *fraction* of only about 44% has remained in the atmosphere over the past 50 years (IPCC, 2021: Ch5), because the sinks on land and in the ocean have become stronger in line with increases in atmospheric CO_2. However, recent data suggests that the *rate of increase* in the strength of the land sink may have slowed down (Chandra et al., 2022; Friedlingstein et al., 2022). This could be the result of natural variability of the land sink, or potentially an indication of reduced capacity of terrestrial ecosystems to take up and store CO_2. The latter would be related to negative effects of climate change including the associated increase in temperature (Fernández- Martínez et al., 2023), changes in rainfall patterns and weather extremes like concurrent hot-dry conditions (Tschumi et al., 2023), and a general risk of destabilisation of the sinks owing to multiple human disturbances (Fernández- Martínez et al., 2023). Even though additional human factors like land-use change and landscape fragmentation and model limitations make these interpretations highly uncertain (Rosan et al., 2022, 2023), there is sparse but strong evidence that the land sinks are changing more rapidly than expected: For the tropics, a region for which already in 2020 have raised the concern that observed carbon uptake may have peaked (Hubau et al., 2020) or even shifted to a carbon source (Gatti et al. 2021), show that most models do not reproduce the observed strengthening in the coupling between water availability and the terrestrial carbon cycle (L. Liu et al., 2023). Also forest degradation, triggered mainly by drought and increased vapour pressure deficit, is usually not well represented in ecosystem models but may account for as much carbon emissions as deforestation (Lapola et al. 2023). But also boreal forests are under stress: Liu et al. (2023) report a drought-induced increase in tree-mortality and a corresponding decrease in the carbon sink capacity of Canadian boreal forests (which represent a third of all boreal forests worldwide) over the past 50 years. Unexpected events of elevated tree mortality are observed across the world, but due to lacking data and understanding it is not yet clear whether this represents a global trend toward increasing tree mortality (Hartmann et al., 2022).

The ocean sink strength stalled in the 1990s, primarily driven by wind-changes in the Southern Ocean, and has recovered since (Gruber et al., 2023; DeVries et al., 2023). While the main contribution for this increase is the uptake of more anthropogenic CO_2 from the atmosphere due to rising atmospheric CO_2 concentrations (Müller et al., 2023), climate change acting on the large natural carbon reservoir in the ocean seems to be involved as well (Crisp et al. 2023; Gruber et al., 2023). For example, ocean warming may reduce CO_2 uptake (Mignot et al., 2022) and lead to a substantial shift of natural carbon flux from the surface ocean to deeper ocean layers, likely via a feedback between biology and circulation (Keppler et al., 2023). The imprints of climate change are strongest in the polar regions. In the Southern Ocean, wind changes continue to expose more carbon-rich deep waters to the air-sea interface and thus to a loss of natural carbon (Hauck et al., 2023). The Arctic Ocean stands out as the only region where climate change increases the carbon sink strength with sea-ice retreat leading to larger ocean surface areas where CO_2 uptake happens (Yasunaka et al., 2023).

Still, large uncertainties remain about the trends in the ocean carbon sink and on the confounding effects of land-use change and management and the impact of extreme events and disturbances. Observational records span only a few decades, so observed trends are influenced by slow modes of natural climate variability (N. Li et al., 2022), superimposed on longer-term effects such as climate change, elevated CO_2 and others. Also, effects of climate change and internal ecological processes, which are currently poorly constrained and represented in models, may in the future play much bigger roles than today. This is expected to become especially important after peak emissions and under CO_2 removal scenarios, when sinks will no longer be influenced by the current near-exponential increase in atmospheric CO_2 and rather start outgassing some of the accumulated carbon (Keller et al. 2018; Zickfield et al. 2021). Therefore, disentangling the impacts of anthropogenic activity from natural climate variability on the carbon cycle is crucial (Bastos et al., 2022; Friedlingstein et al., 2022; Gruber et al., 2023).

Overall, these remaining, including recently discovered, uncertainties give rise to new reasons for concern about the future of the global natural carbon sink, with implications for the reliability of nature-based solutions (NbS) (Box 4), and nature-based CDR (see Insight 3).

Given these concerns, scientists and policymakers need to be alert to a potential problem: Assessments of mitigation requirements for the Paris Agreement rely on current model projections of the sink capacity (IPCC, 2021: Ch5.5). If these were to overestimate the potential future sink size (which is likely because model evaluation over the historical period fails to grasp, among other things, the need to adjust assumptions to new climatic conditions and to include certain additional processes) the remaining carbon budget might be smaller than it has been estimated (see Figure 4). This has significant implications for policymaking towards zero emission goals. In order to reduce the uncertainties and avoid possible over- reliance on the benefits of natural carbon sinks, reliable quantifications of the sinks with reduced, but known, uncertainty are needed, particularly in forecasting. Thus, a fit-for-purpose and sustainably funded and managed ocean and land carbon observation system is crucially needed (Crisp et al., 2022; Hartmann et al., 2022).

We acknowledge the importance of NbS as negative emissions strategies, albeit a clear vulnerability assessment is required to make them effective and a permanent solution. It is essential that plans of carbon sequestration with NbS (of shorter storage durability, see Insight 3) are not used to justify further delays on urgently needed emission reductions.

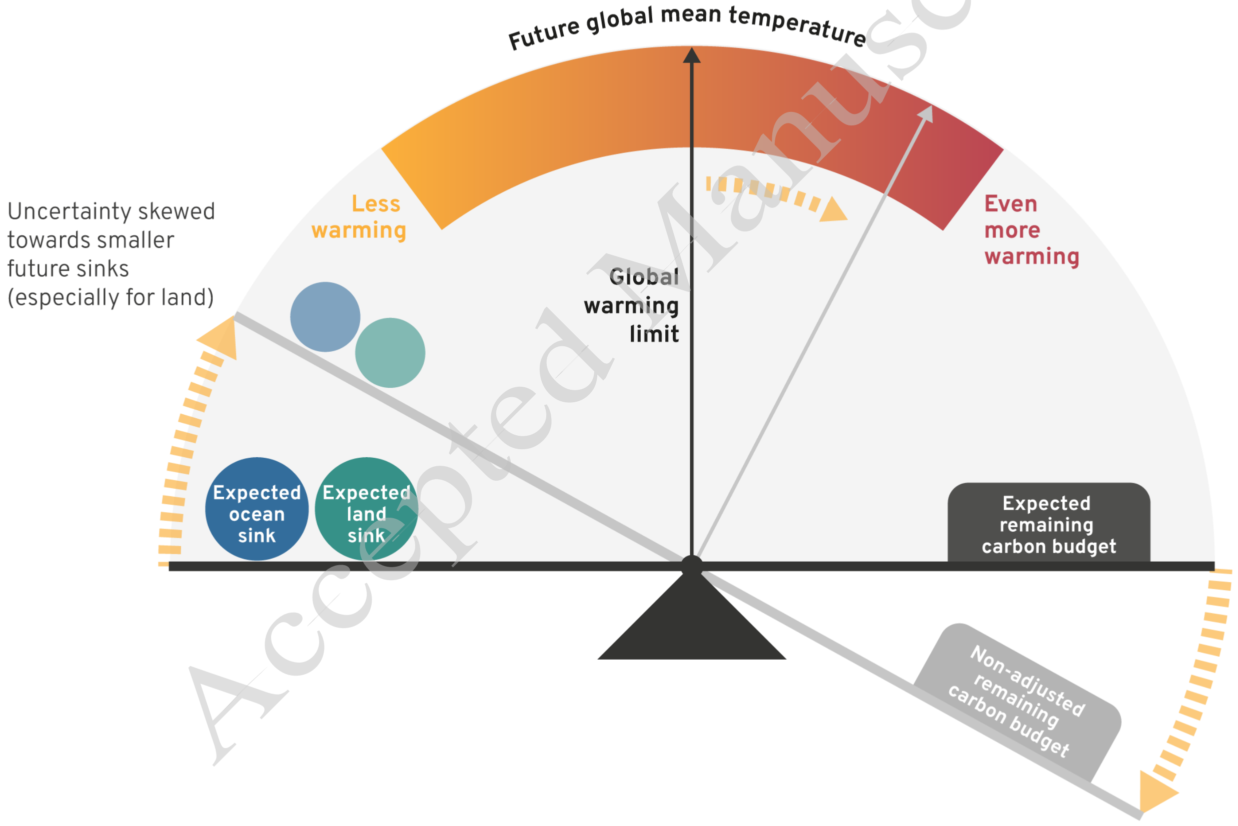


Figure 4: Future carbon sinks and the remaining carbon budget: For any given temperature limit, the remaining carbon budget (cumulative net global anthropogenic for a given global warming limit. CO_2 emissions, expressed from a recent specified date) is constructed to balance expectations on the future capacities of natural carbon sinks (among other variables). If sinks are smaller than expected (according to skewed uncertainties pointing in that direction, especially for land), there will be even more warming than expected, unless the remaining carbon budget is adjusted – and action taken accordingly to stay within the adjusted budget.

Box 4. “Reality check” on nature-based solutions

The future of the natural sinks, discussed in this insight, is decisive for the realistic potential of nature-based solutions (NbS) in the coming decades, as natural sinks are the basis for most anthropogenic activities directed at carbon dioxide removal (see Insight 3 on CDR). Therefore, by building on NbS, scenarios for climate mitigation policies rely heavily on current expectations for natural carbon sinks. If those expectations were too high, this would endanger the efficiency of NbS. In this box, we highlight some examples:

An increase in extreme events would change established disturbance regimes both on land and in the ocean (see Insight 6 on compound events), with the risk of reducing the carbon storage potential. On land, a good example is fire, as it is a key driver of change among all types of disturbances that will increase in the future (Canadell et al., 2021; M. W. Jones et al., 2022; B. Zheng et al., 2023). In the ocean, there are large uncertainties in carbon accounting due to the flows between coastal ecosystems, the shelves and beyond. Additionally, the rapid increase of recent past and future marine heatwaves and extremes in ocean oxygen loss and acidification makes these ecosystems particularly vulnerable to climate change (Gattuso et al., 2021; Williamson & Gattuso, 2022) and increases uncertainties even further. This casts doubt on the potential of coastal ecosystems restoration (blue carbon) and other marine-based CDR methodologies.

Forests play a key role in the Nationally Determined Contributions (NDCs) by many countries (European Commission, 2022b, 2022a). 54% of parties refer to forest conservation, reforestation, or afforestation as a domestic opportunity (UNFCCC, 2022). Even though there is certainly a role for this type of mitigation, limits to the natural basis exist that were not always accounted for in earlier estimates. For example, a recent study by (Roebroek et al., 2023) has shown that when accounting for natural disturbances at present day levels, stopping all types of forest management would result in only low mitigation. (Rohatyn et al., 2022) find that carbon-benefits of forestation of the vast global drylands would be largely compensated by counteracting albedo effects.

Insight 5. The climate and biodiversity emergencies and their solutions are intimately linked

There is now ample scientific evidence that the climate and biodiversity crises are closely intertwined, yet are addressed by separate political, economic, social and legal institutions, and different actors. In 2019-2021, for the first time, IPBES and IPCC together gathered international experts in a joint report on the co-benefits and trade-offs of climate and biodiversity actions (Pörtner et al., 2021). ‘Nexus interactions’ are increasingly being studied (Estoque, 2023), and reflected under the policy umbrella of the Sustainable Development Goals (SDG) (Martín et al. 2020), which are key instruments to support decision-making and trigger synergistic and effective actions.

The major global crises of biodiversity loss and climate change both result from the dominant economic development and sociopolitical systems in modern societies (Dasgupta, 2021). These drivers manifest in a range of proximate pressures, some of which impact both climate and biodiversity, such as deforestation and intensive agriculture. Their expression locally varies with myriad contextual factors, and interactions with other pressures acting at varied scales. Both drivers and pressures are governed and entrenched through institutional factors such as economic regulations, legislation and financial and tax systems, that have promoted and incentivized environmentally-damaging production and consumption models (Pörtner et al., 2021), and that need reform to alleviate both crises.

Climate change has far-reaching impacts, affecting biological processes from the smallest intracellular level to entire ecosystems. These effects across multiple levels may amplify predicted impacts at a single level, triggering rapid and unexpected ecosystem and species shifts across equatorial to polar, and terrestrial and aquatic realms (Arneth et al., 2020). When modelling climate impacts on species, large-scale analyses tend to show smoothed aggregate responses, while models developed for individual species can exhibit abrupt responses to changing climate conditions, often experiencing half of their impact within just a decade (Pigot et al., 2023). Addressing multiple processes and interactions is as important as addressing multiple scales. To gain a more accurate understanding of the biodiversity losses resulting from climate change, incorporating species interactions and potential co-extinction cascades in climate-biodiversity models is also needed (Moullec et al., 2022). Furthermore, feedbacks caused by climate-induced changes in species' physiology and shifts in functional diversity can trigger changes in marine and terrestrial carbon uptake and losses, potentially amplifying the initial CO_2 forcing in many climate change scenarios (Arneth et al., 2020). In coastal marine ecosystems, climate migration and complex ecosystem transitions compounded by local pressures (overfishing, increasing turbidity of coastal waters, increasing toxicity of metal pollution) are anticipated to strongly impact coastal marine ecosystems, particularly in tropical regions (Herbert-Read et al., 2022) where social and political vulnerability is already high.

Climate impacts on society mediated by biodiversity occur through shifts in nature's contributions to people (NCP). For example, pollinator diversity that is strongly affected by fluctuations in winter weather, changes in the length of the vegetational season and increased frequency of extreme weather events (Vasiliev & Greenwood, 2021) influences food production and hence human health (M. R. Smith et al., 2022). Complex climate-biodiversity-NCP feedback loops are increasingly being shown (Pörtner et al., 2021). For example, coastal ecosystems such as marshes and mangroves mitigate climate change by sequestering carbon while also reducing the impact of coastal storms on people but they are at the same time vulnerable to sea level rise, flooding from inland rainfall, and warming, thus compromising the benefits they provide (Temmerman et al., 2023).

Nature-based solutions (NbS) and 'multifunctional scape' approaches can provide not only precautionary but also regenerative options for protecting biodiversity, mitigating climate change and reinforcing the adaptation of nature and society to a wide spectrum of impacts if they are implemented appropriately (Pörtner et al., 2021). The need for caution, however, is demonstrated by the hasty implementation of large-scale tree planting to maximise carbon sequestration, resulting in missed synergistic opportunities and harm to other aspects of nature, the provisioning of benefits to people as well as to broader human rights (Seddon et al., 2021). Safeguards and guidance for well-designed NbS that deliver multiple benefits for people and nature are required (Seddon et al., 2021; Shin et al., 2022) in the terminology of the CBD, using 'ecosystem-based approaches'. For example, synergies and trade-offs between biodiversity protection, climate mitigation and food production show that moderate ambition across all targets may achieve balance, but high ambition for just one results in lower achievement of others (Arneth et al., 2023).

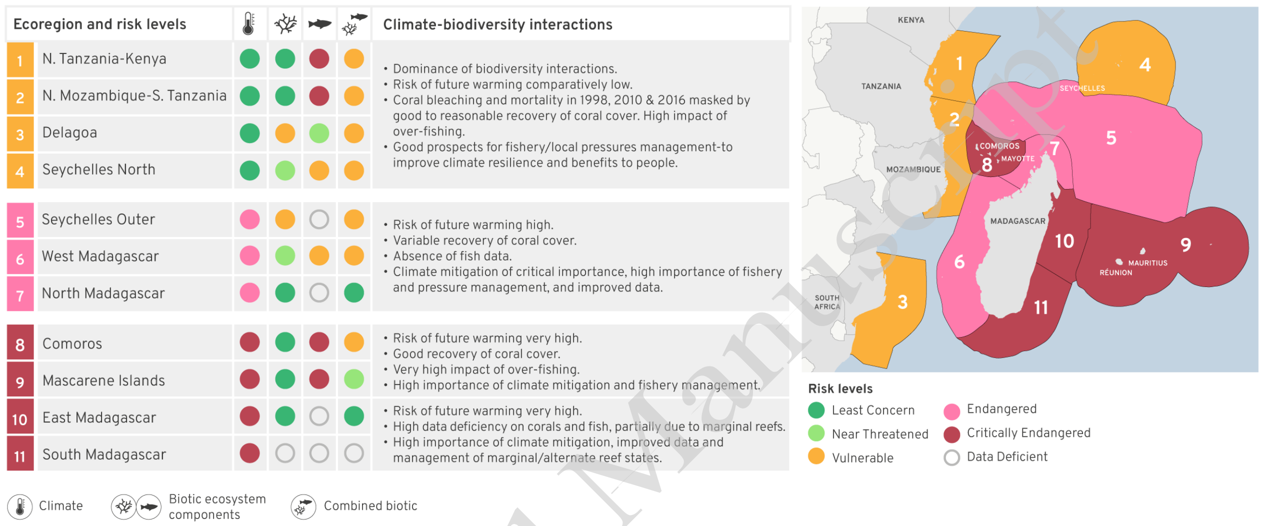
Understanding and managing the interlinked impacts of climate and biodiversity change on society remains extremely challenging. Available data and dominant approaches for biodiversity conservation are still strongly biased to the Global North (Isbell et al., 2023), as are capacities for producing and using climate information. While there is significant progress in scientific understanding of Global South ecosystems (e.g., grassland ecosystems, Stevens et al., 2022), much evidence coming from Global South researchers still does not find its way to global decision-making (e.g., Armani et al., 2022). Even so, our ability to model and anticipate risks and shifts induced by biodiversity-climate changes is insufficient to incorporate them into policy responses (Marske et al., 2023) and their complexity challenges implementation. The disproportionate impacts of climate-biodiversity interactions in tropical regions in both terrestrial and coastal marine zones (Arneth et al., 2020; Herbert-Read et al., 2022) carry strong climate equity implications (see Insight 9 on adaptation justice). Countries in these regions have contributed least to climate forcing yet face high potential for cascades and tipping dynamics, making a strong case for precautionary and transformative policies.

The intimate interlinkages between climate change mitigation and adaptation, biodiversity conservation actions and broader societal needs will require transformative change in the governance of social-ecological systems at all scales (Pörtner et al., 2021). The most immediate and tangible implications for immediate application include:

1. Avoid each extra tenth of a degree of climate warming, minimise decline and reverse biodiversity trends, and align other policy areas, such as on release of hazardous chemicals and pollution, production sectors driving land use change and exploitation, just development, and financial incentives etc.
2. Actions must address the interactions between biodiversity loss and climate change mitigation and adaptation to trigger synergies, minimise trade-offs with other benefits (e.g., food production or soil regulation) and plan for performance under potential emission scenarios. NbS proposed for carbon sequestration, and their financing, must meet ecosystem-based and social justice criteria (see Insight 9 on adaptation justice). Planning of conservation and climate actions must also consider the influence of harmful financial incentives, risks posed by complex interactions, and positive economic and social effects (Kedward et al., 2022).
3. This alignment of actions may only be feasible through integrating work programmes and decisions of the climate and biodiversity conventions, and their instruments (two thirds of the post-2020 biodiversity actions of the CBD directly support climate goals (Shin et al., 2022) and other conventions under the framework of the SDGs (three quarter of SDG targets are positively related to at least one NbS in a given ecosystem (Mariani et al., in revision). This is needed to inform consultations on the post-2030 agenda.
4. Reform dominant economic and sociopolitical systems that drive climate change and biodiversity loss (Dasgupta, 2021); for example, through re-appraising indicators of economic and social development (European Parliament, 2023) and better addressing systemic biodiversity and climate-related risks (Kedward et al., 2022).

Box 5. Example: Coral reefs threatened by climate and biodiversity threats

Coral reefs are among the first ecosystems being driven to collapse globally, by multiple interacting drivers. Of the 11 Western Indian Ocean ecoregions, four are Critically Endangered, three are Endangered and four are Vulnerable to collapse over a 50 year period (Figure 5; Obura et al., 2021). Biodiversity-climate interactions underpin their risk of future collapse. Broadly, island reefs are at higher risk from increasing temperatures in the next 3-4 decades, while continental reefs have better climate futures, but higher impact from fishing and other local threats. The differential vulnerability of the ecoregions highlights the narrow gradient in vulnerability among reefs and that very small increments in global temperatures may make a difference between just some or all reef ecoregions crossing their point of collapse (Point 1, list above). The importance of coral reefs to coastal economies and livelihoods is illustrated in the differential vulnerability of ecoregions to fishing and temperature and the importance of maximising synergies among management actions to minimise both (Point 2, list above).



Ecoregion and risk levels	🌡	🪸	🐟	🪸🐟	Climate-biodiversity interactions
1 N. Tanzania-Kenya	🟢	🟢	🔴	🟠	• Dominance of biodiversity interactions. • Risk of future warming comparatively low. • Coral bleaching and mortality in 1998, 2010 & 2016 masked by good to reasonable recovery of coral cover. High impact of over-fishing. • Good prospects for fishery/local pressures management-to improve climate resilience and benefits to people.
2 N. Mozambique-S. Tanzania	🟢	🟢	🔴	🟠	
3 Delagoa	🟢	🟠	🟩	🟠	
4 Seychelles North	🟢	🟩	🟠	🟠	
5 Seychelles Outer	🩷	🟠	○	🟠	• Risk of future warming high. • Variable recovery of coral cover. • Absence of fish data. • Climate mitigation of critical importance, high importance of fishery and pressure management, and improved data.
6 West Madagascar	🩷	🟩	🟠	🟠	
7 North Madagascar	🩷	🟢	○	🟢	
8 Comoros	🔴	🟢	🔴	🟠	• Risk of future warming very high. • Good recovery of coral cover. • Very high impact of over-fishing. • High importance of climate mitigation and fishery management.
9 Mascarene Islands	🔴	🟢	🔴	🟩	
10 East Madagascar	🔴	🟢	○	🟢	• Risk of future warming very high. • High data deficiency on corals and fish, partially due to marginal reefs. • High importance of climate mitigation, improved data and management of marginal/alternate reef states.
11 South Madagascar	🔴	○	○	○	

🌡 Climate
🪸🐟 Biotic ecosystem components
🪸🐟 Combined biotic

Risk levels
🟢 Least Concern
🟩 Near Threatened
🟠 Vulnerable
🩷 Endangered
🔴 Critically Endangered
○ Data Deficient

Figure 5. Ecoregions of the Western Indian Ocean showing their risk of collapse in the IUCN Red List of Ecosystems (see also inset map). Colours in ecoregions and circles show: Least Concern-dark green; Near Threatened-light green; Vulnerable-yellow; Endangered-orange; Critically Endangered-red; Data Deficient-grey. Risk levels for climate (thermometer icon) and biotic (coral and fish icons) ecosystem components are shown and their individual levels of risk. The combined biotic risk level is shown in the ring around the coral/fish icons, and for each ecoregion by background shading and the map. The text highlights biodiversity-climate interactions and prospects for management and benefits for people.

Insight 6. Compound events heighten climate risks in unexpected ways

Compound events are defined as events that occur when a combination of drivers and/or hazards contribute to environmental or societal risks (Zscheischler et al., 2018) (Figure 6). These phenomena span a wide range of spatiotemporal scales and interaction types, including preconditioning, multiple variables, temporal compounding, and spatial compounding (Zscheischler et al., 2020). In the physical science domain, research on compound events was initially largely focused on the atmosphere and on bivariate events, such as drought-heat wave interactions.

Recently, substantial progress has been made in adapting the ‘compound event’ concept to a wider range of domains, including terrestrial ecosystems (Coughlan de Perez et al., 2023; Lesk et al., 2022; Vautard et al., 2023), the ocean (Burger et al., 2022; Gruber et al., 2021; Le Grix et al., 2022), and inter-domain linkages (Pathmeswaran et al., 2022). New methodological approaches, such as the use of large ensembles (Burger et al., 2022; Le Grix et al., 2022; Raymond et al., 2022) and extreme event attribution (Zscheischler & Lehner, 2022), have been developed and applied, demonstrating the relevance of compound events for a range of impacted domains. Recent literature shows how compound events pose critical risks for food security and ecosystem services over both land and ocean (Gruber et al., 2021; Yin et al., 2023), make disaster risk management more challenging (Schlumberger et al., 2022; van den Hurk et al., 2023), interfere with adaptation strategies (Simpson et al., 2023), and affect human migration patterns (Thalheimer et al., 2022). Parallel multi-hazard work has been making strides in developing analysis and adaptation tools to better prepare societies for these systemic complexities (De Angeli et al. 2022).

For agriculture and ecosystems, compound events may be viewed as causing physiological stress directly, or as a combination of stressors that leads to an impact. Crops are particularly sensitive to the co-occurrence of extremely hot and dry conditions (Lesk et al., 2022; Yin et al., 2023). In a warming climate, impacts are expected to intensify in many regions of the world. Some compound crop impacts are more closely linked to variability, such as an early spring followed by a late frost, an event type anticipated to increase in frequency (Vautard et al., 2023). Given that a large proportion of crops are grown in just a few breadbasket regions, if yields are impacted within the same harvest year in more than one region (i.e. spatially compounding events) there could be repercussions for global food security (Coughlan de Perez et al., 2023; Gaupp et al., 2020; Raymond et al., 2022). Ecosystems to can be highly sensitive to compounding impact drivers. After severe compound hot-dry events, plant recovery usually lags due to reduced growth, irreversible losses in hydraulic conductance or depletion of carbon reserves. Lagged growth may in turn increase vulnerability to another compound event if it occurs before complete recovery, potentially limiting vegetation's capacity to act as a carbon sink (Yin et al., 2023). Nonlinear effects of separate events, such as cyclones and fires, can lead to a permanently altered equilibrium ecological state (Ibanez et al., 2022).

Compound ocean events, such as marine heatwaves alongside changes in oxygen availability, ocean acidity and/or net primary production, can impact marine ecosystems at the individual, population and community levels (Burger et al., 2022; Gruber et al., 2021; Le Grix et al., 2022). For example, some of the devastating impacts of the Northeast Pacific 2013-2015 marine heatwave, including extreme mortality and reproductive failure of sea birds, mass stranding of whales and sea lions, and shifts in species composition towards warm-water species, were amplified by co-occurring extreme ocean acidity, low oxygen, and low net primary production conditions (Gruber et al. 2021). Compound ocean events, such as concurrent marine heatwaves and low oxygen events, can impact food security and cause considerable societal impacts. Increasingly these events are co-occurring with land events, multiplying the impact (Pathmeswaran et al., 2022).

Considering compounding drivers is in the early stages of development but, following on the multi-hazard model, can improve disaster risk assessment. More specifically, “compound event thinking” improves early warning, emergency response, infrastructure management, long-term planning, and capacity building (van den Hurk et al., 2023). Adaptation pathways, typically designed for univariate hazards, could also be extended to compounding hazards in many cases (Schlumberger et al., 2022). Niggli et al (2022) assessed cascading impacts of hot-dry compound events, showing interlinking effects throughout socioeconomic systems - health, energy, and agricultural impacts cascading on to public services, society, and culture. So far, however, there is limited evidence that adaptation efforts take into account compound events, and maladaptive characteristics are particularly prominent in this context (Simpson et al., 2023). Such shortcomings are partly due to a lack of knowledge about the physical system, and partly to the difficulty in translating knowledge into action.

The last few years have seen the occurrence of exceptional events far outside the previous local historical range, with severe socioecological impacts. Events are being connected to combinations of antecedent and/or simultaneous drivers that only together were able to achieve the observed conditions. This most prominently includes heatwaves, for example western North America in June 2021, as the integrated outcome of processes acting across scales, including atmospheric ridging, low soil moisture, and latent heating from upwind precipitation (Bartusek et al., 2022). Even when occurring in a single region, these exceptional events can be compound by heightening multiple types of impacts simultaneously: e.g., simultaneous heat stress, wildfire risk, and air pollution (Rosenthal et al. 2022), or heat-drought and heat-flood linkages (Gu et al., 2022).

Efforts to quantify how extreme weather in land and oceans will respond to climate change benefit from consideration of how discrete climate hazards can interact with and intensify each other. Using improved modelling tools and new statistical methods, an emerging body of evidence is also revealing that, relative to singular hazards, the impacts from compound events are more likely to exacerbate each other, in part because of longer recovery timescales (de Ruiter et al., 2020). This interconnectedness emphasises the need for cooperation at the scales over which compound event impacts are shared, which vary by event and sector but are typically larger and longer than many existing decision-making frameworks account for. There is a new level of recognition that the impacts of compound events are substantially shaped by local preconditions, whether societal or environmental, making those context features of crucial importance to assess and incorporate.

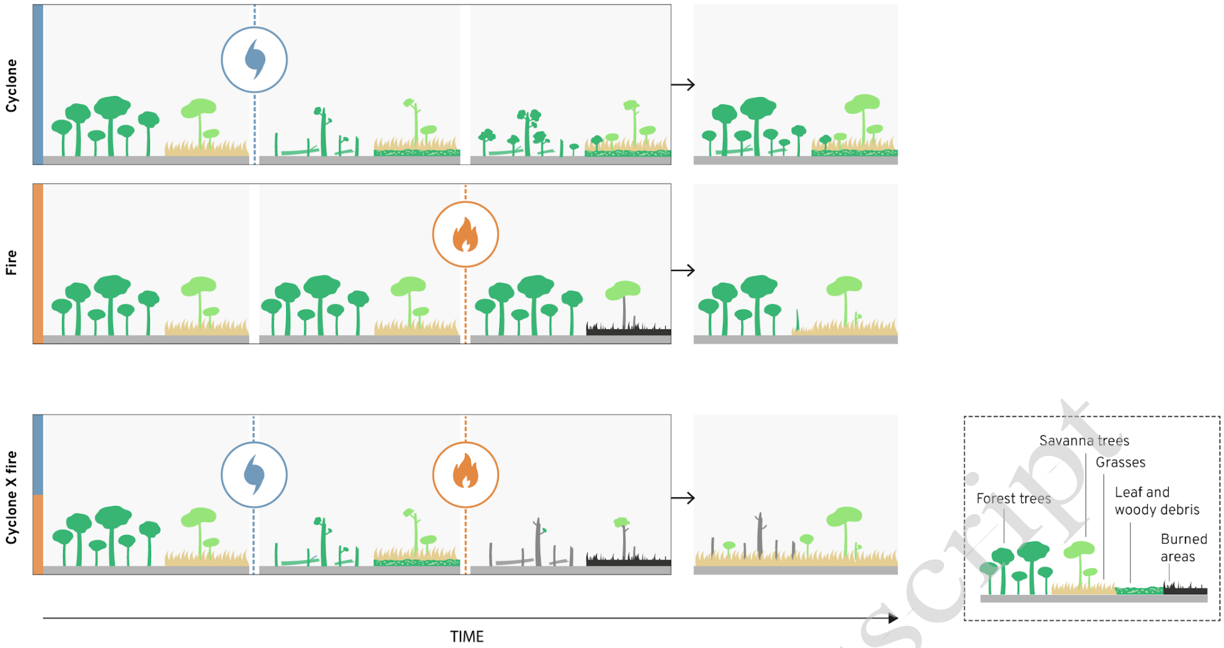


Figure 6. Conceptual illustration of a compound event. The illustration shows how a cyclone followed on by a fire (a temporally compounded event) creates a much larger impact than either one on its own. On the bottom right is an idealised illustration of a 2-dimensional distribution of the same two hazards and a potential impact that gets worse towards the upper right. Based on Ibanez et al. (2022) and Zscheischler et al. (2020).

Insight 7. Accelerated mountain glacier loss

Mountain glaciers are highly sensitive indicators of climate change. Recent advances related to satellite observations and modelling have enhanced our ability to measure glaciers' response to climate change and project their evolution over the next century. In comparison to the vast ice sheets in Greenland and Antarctica, mountain glaciers occupy much smaller areas and account for a sea-level rise potential of only about 30 cm (Millan et al., 2022). However, mountain glaciers respond to changes in atmospheric forcing over shorter temporal scales, compared to ice sheets, such that their mass loss explains almost one quarter of currently observed rates of sea-level rise (Hugonnet et al., 2021). Natural hazards such as glacier outburst floods and collapses are also key threats (Emmer et al., 2022; Taylor et al., 2023). Furthermore, glaciers have considerable touristic, spiritual, and ideological value, and contribute to healthy mountain environments. During the summer, especially in times of drought, glacier meltwater is vital for maintaining river flow (Immerzeel et al., 2020) thereby providing freshwater that supports mountain and downstream regions, groundwater, drinking water, irrigation, water quality, ecosystems, biodiversity, and shipping.

Present-day observations of glacier change reveal a loss of 267±16 Gt yr^{-1} with a clear acceleration over the last two decades (Hugonnet et al., 2021). As these glaciers retreat, biodiversity in high-alpine catchments may strongly decrease leading to species loss and compromised ecosystem function, but also opportunities for species to occupy new territory (Cauvy-Fraunié and Dangles (2019; Wilkes et al., 2023; Bosson et al., 2023). Glacier retreat is further accelerated by the growth of moraine-dammed glacial lakes. Ice melt below the water surface, unaccounted for by available estimates, indicates that glacier mass loss is, for example, 7±2% greater than previously reported in the greater Himalayas (Zhang et al., 2023); that study also estimates the global loss to be 12% greater, though the uncertainties in the underlying data are substantial. Downstream populations are also growing rapidly such that roughly 15 million people worldwide are potentially exposed to glacial lake outburst floods with the greatest impacts found in High Mountain Asia and the Andes (Taylor et al., 2023). In High Mountain Asia, the development and expansion of glacial lakes is expected to triple the risk of moraine-dammed glacial lake outburst floods over the next century (Zheng et al., 2021). However, outburst floods from ice-dammed lakes were found to become less intense, and are expected to decrease in frequency over the next century (Veh et al., 2023).

New global glacier projections estimate that glaciers will lose 26% (+1.5°C) to 41% (+4°C) of their current volume by 2100 depending on the global temperature change scenario (Rounce et al., 2023) (Figure 7). Relative mass loss varies greatly at regional scales, with mid-latitude regions (e.g., Western Canada, Central Europe, Caucasus) being expected to experience widespread deglaciation for scenarios with global average warming beyond 3°C. Limiting the temperature increase by reducing greenhouse gas emissions is thus critical for limiting glacier contribution to sea-level rise and preserving these glacierized regions. Mountain glaciers will thus continue to be one of the primary contributors to sea-level rise throughout the 21st century.

The biggest challenges for quantifying present and future mountain glacier loss are related to observations and modelling. While measuring decadal-scale glacier mass changes from space is now possible for every glacier on Earth (Hugonnet et al., 2021), observations of year-to-year variability at coarser scales need to be integrated, and disentangling mass loss due to changes in snow accumulation and melt is still hampered by limited *in situ* information from data-scarce regions. Despite important advances, global models still rely on estimates of bedrock topography that include large uncertainties (Millan et al., 2022) and are also hampered by a lack of direct ice thickness measurements. Similarly, remote sensing data will continue to provide unique opportunities to improve the representation of important processes in models, such as frontal ablation for marine- and lake-terminating glaciers (Zhang et al., 2023) or the impact of debris cover (Rounce et al., 2023). In all cases, additional *in situ* observations to better constrain remotely sensed data and improve representation of processes in models are key areas of future work that will help reduce uncertainties in glacier projections. Transforming these projections into products that support adaptation and mitigation efforts will benefit from directly coupling atmospheric, cryospheric, and hydrological models (Yao et al., 2022), incorporating high-resolution models to ensure projections are provided at the scale required to inform disaster risk management strategies, and implementing programs that build trust and harmony between governments and local people to ensure the success of adaptation measures.

The impact of climate change on mountain environments is highly diverse. Beyond glacier mass loss, it results in permafrost thaw and various cascading hazards, including avalanches, landslides, debris flows, and flooding. Water resource systems are directly affected, including the drying of springs, changes in mountain snow cover, and expansion of glacial lakes (Prakash, 2020). Consequently, socioeconomic development and ecological environments are impacted (Aggarwal et al., 2022). The sustainable development goals of ensuring well-being and building resilience face challenges in managing these changing mountain ecosystems and capitalising on emerging opportunities. Adaptation strategies vary across sectors and regions, highlighting a need for more stakeholder cooperation to ensure effective implementation and management (Pandey et al., 2021; Aggarwal et al., 2022). The establishment of a Loss and Damage fund at COP27 highlights the need for substantial adaptation implementation in the disaster risk reduction sector while also addressing climate justice issues by supporting the most vulnerable (Wentz et al., 2023) (see Insight 9 on adaptation justice). Still, too few risk control measures have been implemented to date to address the impacts of global climate change in mountain regions (Alcántara-Ayala et al., 2022).

The number of people affected by mountain glacier loss has risen substantially. Regions with significant mountainous areas and high population density, such as the Himalayas, are particularly vulnerable (Figure 7). Since the 1960s the number of people who are largely or fully dependent on water from mountains has increased from approximately 0.6 to 2 billion worldwide (IPCC, 2022a: CCP5). The mountains of the Hindu Kush Himalaya are an essential source of freshwater for 240 million people living in this region and 1.65 billion downstream (Sharma et al., 2019; S. Singh et al., 2020). Substantial atmospheric warming and pronounced dry seasons will continue to drive glacier mass loss and thus amplify water stress. Regions such as Central Asia, South Asia, and tropical and subtropical western South America, are expected to experience the most significant impacts from changing water availability throughout the 21st century (Lutz & Biemans, 2022). The changes to the water cycle, including variable timing of glacier and snow melt, have diverse impacts on water availability and may lead to tensions or conflicts over resources, especially in seasonally dry regions (IPCC, 2022a CCP5). Further commitments to reducing greenhouse gas emissions will help offset the worst of these impacts. However, effective, community-driven adaptation strategies will be key in supporting resource and disaster risk management, especially for vulnerable communities.

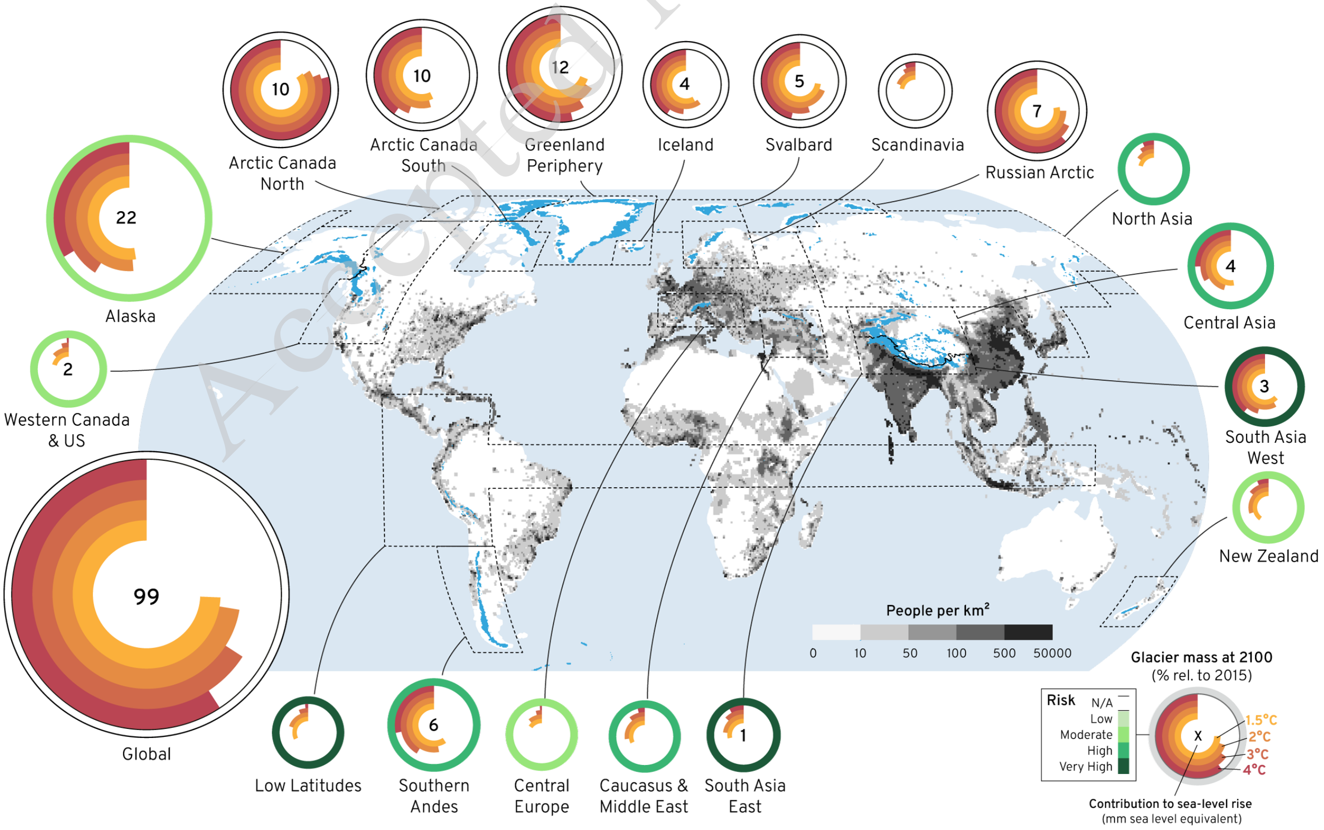


Figure 7. Regional glacier mass change and contributions to sea level rise from 2015 to 2100. Discs show global and regional projections of glacier mass remaining by 2100, relative to 2015, for global mean temperature change scenarios. Discs are scaled based on each region's contribution to global mean sea level rise from 2015 to 2100 for the +2°C scenario by 2100 relative to preindustrial levels and nested rings are coloured by temperature change scenarios showing normalised mass remaining in 2100. Regional sea-level rise contributions larger than 1 mm sea level equivalent (SLE) for the +2°C scenario are printed in the centre of the pie chart. The colour of the region name refers to the risk to livelihoods and the economy from changing mountain water resources between 1.5°C and 2°C global warming (IPCC, 2022a: CCP5.3). The gridded population density (people per km^2) is also shown. Glaciers are shown in blue. Modified from Rounce et al. (2023).

Insight 8. Immobility in the face of climate risks: Between constraints and agency

People who are unable or unwilling to relocate from high-risk areas may face even greater challenges than those who are displaced by climate-related events. Some climate-impacted communities are limited in their mobility options by economic, political, socio-cultural and physical constraints, and are unable to move (Schewel, 2019). Demographic factors, access to information on safe accommodation, safe migration opportunities, and labour markets at destination can also influence (im)mobility outcomes (Siddiqui et al., 2018). Individual differences in ability to move can create gendered and other forms of inequities at household level (Ayeb-Karlsson, 2020). However, not all immobility is involuntary. While involuntary immobility has been recognized since the Foresight report (Foresight UK, 2011), increasing evidence shows that individuals and communities facing high displacement risk are articulating a desire to stay, sometimes in opposition to planned relocation (van der Geest et al., 2023; Wiegel, 2021; Yee et al., 2022b), invoking questions of social justice (Boas et al., 2022). More on adaptation justice in Insight 9.

Recent studies show an increase in involuntary immobility particularly among the poorest populations, due to the negative impacts of climate change on economies and resources. Climate change can decrease emigration rates by over 10% among the lowest-income groups by 2100, under medium development and climate scenarios, compared to no climate change, and up to 35% in more pessimistic scenarios (Benveniste et al., 2022). Rikani et al. (2023) find that climate change decreases immigration and emigration predominantly in countries located in Sub-Saharan Africa and South Asia. In terms of region-level bilateral flows, there is a decrease in migration within Africa, South Asia and West Asia, while migration within Europe and the former Soviet Union has increased, suggesting that mobility is facilitated in wealthier regions and inhibited in the poorest (Rikani et al., 2023).

In coastal Bangladesh, recent studies find that (im)mobility outcomes in climate hazard contexts can result from a rational decision-making process shaped by intersecting community and individual level factors (Khatun et al., 2022; Mallick, Best, et al., 2023; Paul et al., 2022)**.** Community-level factors, including social/community cohesion, economic and political conditions, contribute to overall livelihood conditions and shape place attachment (Figure 8). Climate impacts and risks affect both individual and community levels. At the individual level, personal/household characteristics, risk perception and tolerance, influence self-efficacy. Self-efficacy refers to the perceived coping capacity to withstand or respond to climate impacts and risks, which, in turn, affects an individual's capability and aspiration to migrate (Mallick et al., 2023).

Other recent case studies show that populations at risk of displacement express a strong desire to stay in their current location in response to proposed relocation programs (Farbotko et al., 2020; Wiegel, 2021). Within these communities, individuals possess valuable local knowledge of habitability, exhibit profound place attachment, and prioritise safeguarding cultural identity and political agency, despite climate-related risks. In essence, the perceived risks associated with relocation, including threats to livelihood, social connection, personal safety and access to services, outweigh the perceived risks posed by climate change (Farbotko & Campbell, 2022; Santos & Mourato, 2022; Yee et al., 2022a; 2022b). While relocation programmes can contribute to adaptation (Khatun et al., 2022), the desire of some communities to stay in place despite the climate risks might actually rise in reaction to solutions they perceived as maladaptive or as a threat to established rights (Farbotko et al., 2020); indicating resistance to imposed, top-down policies (Boas et al., 2022). Resistance to relocation can signal mistrust in government, especially where previous relocations have led to reduced employment opportunities, limited access to services and broken social capital (Gunathilake et al., 2023).

Immobility can thus be a political act, representing resistance and defying expectations of future displacement. These findings contest the dominant policy and media discourse on mass migration induced by climate change (Durand-Delacre et al., 2021) by demonstrating that despite environmental degradation and climate risks, some may decide to stay put; thus questioning the notion of a universal aspiration to migrate (Mallick et al., 2022). Such decisions are often constrained by underlying development failures that limit life opportunities and choices.

Recent research highlights the importance of understanding immobility across different scales (Mallick, Priovashini, et al., 2023) and a need to better understand how individual, household, familial, and community experiences of immobility interact. Understanding immobility within temporal and political contexts and recognizing it as part of local response to climate risk (including temporary immobility and symbolic resistance) could enable more nuanced interpretations. This can inform human-centred policymaking that enables informed and culturally respectful choices and provides safer options for migrants and non-migrants. The existing literature on participatory decision-making, and its critique, can serve as a foundation for such research and policy innovation.

While climate mobility has been the focus of climate change and human mobility policy, there are now emerging calls for governance of climate immobility (Naser et al., 2023; Thornton et al., 2023). Addressing involuntary immobility requires policy initiatives that reduce the *need* to move and measures that increase people's *ability* to move, for example by reducing legal and political barriers to mobility.

Policies on adaptation, mitigation, disaster risk reduction and resilience building intersect with climate immobility, but largely fail to explicitly address it (Benveniste et al., 2022; Farbotko et al., 2020; Wiegel et al., 2019). At present, the Global Goal on Adaptation and discussions surrounding Loss and Damage exclude the risks and costs associated with immobility. There is a need for further research into the economic and other costs of immobility to guide the development of adaptation strategies and policies, with a particular focus on marginalised groups, in order to mitigate overall risk. Multiple policy approaches are required, respecting the rights of those who want to move, those who want to stay put and those who resist planned relocation. Viable and effective strategies must be developed considering specific vulnerabilities, risk perceptions, and context-based decision-making processes. Relocation frameworks that are derived from inclusive planning should explicitly recognize and support those who wish to stay (Farbotko et al., 2020).

There is some hope that immobility may be recognized in climate finance through the Loss and Damage fund (Thornton et al., 2023); yet, the lack of attention it has received within loss and damage governance in comparison to climate-induced migration, disaster displacement and international security raises uncertainty about its inclusion (Jackson et al., 2023). This is supported by the recent findings of Mombauer et al. (2023), which indicate that only a minority of National Adaptation Plans and Nationally Determined Contributions integrate considerations for populations unwilling or unable to move.

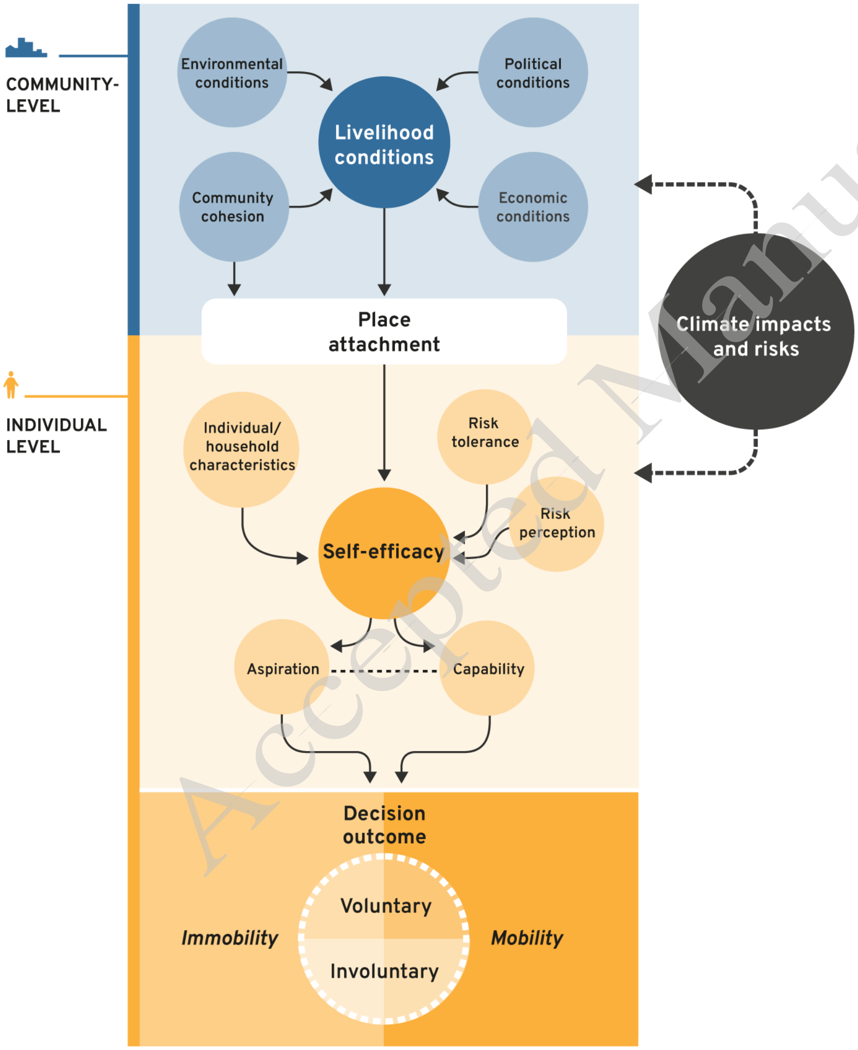


Figure 8. Intersecting community and individual level factors influencing individual decision-making processes regarding immobility in climate-risk contexts. Adapted from Mallick, B. et al. (2023).

Box 8. Voluntary immobility: Challenging government relocation expectations
Voluntary immobility is a characteristic of some communities in Fiji who oppose national government relocation planning (Yee et al., 2022a; 2022b). In a recent study in a remote village in Tuvalu, it was found that the population was increasing due to migration from the urban capital. People were motivated to move to indigenous lands where they held family land rights and sought to nurture indigenous culture. These instances of ‘anti-displacement mobilities’ and ‘re-emplacements’ challenge expectations of Tuvaluans relocating internationally (Farbotko, 2022).

Insight 9. New approaches enhance justice of adaptation action

Adaptation opportunities are unevenly distributed and have varying degrees of success, in large part due to injustices related to who receives and controls funding, who designs and implements strategies, and who is affected by them. The Adaptation Gap Reports (UNEP, 2023) are increasingly mentioning justice concerns, indicating an increased awareness. Justice has emerged as a key condition for effective adaptation, with new empirical work (e.g., Gill et al. 2023; Harper et al. 2022) building on previous theoretical developments. While conceptualisations of adaptation justice exist (Juhola et al., 2022; Orlove, 2022), their application in adaptation planning and implementation remains scarce, ambiguous, and rarely accounted for. A global review of policy tools for adaptation found that the most vulnerable and marginalised, who are also the most heavily impacted by climate change, are not considered in the majority of adaptation plans (Ulibarri et al., 2022). Globally, there is limited evidence of just outcomes from adaptation strategies and plans (Araos et al., 2021) due to a lack of monitoring. More concerns are raised from a review of the effectiveness of adaptation plans. Currently, the attention to social cleavages, such as gender (Roy et al., 2022), poverty and ethnicity (Araos et al., 2021) in adaptation planning is very limited in scope (principally focused on gender) and rarely takes an intersectional approach that might better capture the ways in which vulnerability and risk take shape.

Recent research on adaptation justice highlights the social and political roots of the unevenness of observed and projected impacts of climate change (Juhola et al., 2022; Orlove et al., 2023). While acknowledging the physical processes that shape hazards and exposure, adaptation justice research emphasises the socioeconomic structures that drive climate vulnerability, making adaptation unavailable to many, and destructive to some. These structures have implications for different justice components (Figure 9): distributive, restorative, recognition, procedural, and epistemic.

The factors that produce unjust outcomes have been observed at different scales. At the international scale, insufficient funding and structural biases in funding mechanisms reflect a lack of recognitional justice and procedural justice (Ciplet et al., 2022; Islam, 2022). This prevents funds from reaching those who need them most, in turn hampering distributive and restorative justice (the latter most relevant regarding compensation for losses and damages). At the local level, communities face structural barriers to implementation (e.g., Klepp & Fünfgeld, 2022). Researchers in this field argue for a fundamental reconsideration of how funders operate and how funds are distributed (Browne, 2022; Ciplet et al., 2022). For example, many communities lack the support needed to apply for funding or to complete the burdensome reporting requirements attached to most sources of funding. Similarly, Loss and Damage funds should be arranged as a grant-based programmatic financing mechanism, easily accessible by communities in need.

Brink et al. (2023) documented social resistance emerging in the face of adaptation plans that are not perceived as just. Examples include forced relocation plans (see Insight 8 in immobility), imposition of food crops and technocratic practices, or the use of labels such as ‘climate refugee’ (Brink et al., 2023). Here we highlight three recent conceptual advances for adaptation justice with practical application: the adaptation justice index (Juhola et al., 2022), adaptation rationales (Carr & Nalau, 2023), and locally-led adaptation (LLA) (Rahman et al., 2023). Juhola et al. (2022) developed the ‘adaptation justice index’ and proposed concrete steps towards more just adaptation planning by identifying where in the planning process justice ought to be included. This approach proposes a shift from a narrow model of stakeholder engagement to full and long-term co-produced collaborative partnership (for procedural and distributive justice), operating across scales of social organisation and accounting for short- and long-term implications of adaptation actions (Orlove et al., 2023). Moreover, full, collaborative partnerships bring together the holders of local and Indigenous knowledge systems and values (epistemic justice), while also addressing present-day structural issues, many of which developed historically from colonialism (Orlove et al., 2023; Whyte, 2021).

‘Adaptation rationales’ are impact pathways that represent the logic of an adaptation action, explicitly guiding the development of pathways that link priorities, actions, and outcomes (Carr & Nalau, 2023). They are not focused on technical adaptation fixes alone and can incorporate solutions to improve livelihoods and sustainable development, indicating that good rationals avoid worsening inequality and increasing vulnerability. At smaller scales, many adaptation projects suffer from poorly constructed (non-explicit) adaptation rationales, reflecting gaps in procedural and epistemic justice. To achieve just adaptation, the literature suggests the importance of strengthening the design, implementation, monitoring, and evaluation of adaptation plans (Orlove, 2022). Transparent, well-constructed adaptation rationales with clearly articulated benefits help minimise uneven distribution of those benefits (Carr & Nalau, 2023). By devising plans for a broad set of adaptation benefits framed around reduced exposure, reduced sensitivity, and increased adaptive capacity, justice can be placed at the fore. Moreover, strong adaptation rationales enable the effective monitoring, evaluation, and learning of the different components of justice (Juhola & Käyhkö, 2023).

LLA (Rahman et al., 2023) hinges on fostering bottom-up initiatives and respecting community autonomy that corrects unequal power distribution (Pisor et al., 2022) and sharing knowledge and building capacity (Huggel et al., 2022). Recent examples suggest this approach promotes more just outcomes in adaptation planning and implementation (e.g., Klepp & Fünfgeld, 2022). Allowing adaptation decisions to be made with inputs from different scales, while using tools like the adaptation justice index to deepen the evaluation of adaptation rationales, will help prevent maladaptation and facilitate the co-creation of inclusive pathways towards just climate futures.

These three approaches – the adaptation justice index, adaptation rationales, and LLA – illustrate the concrete, actionable steps proposed and implemented as ways to assure that adaptation activities are just, addressing the needs of the most vulnerable and marginalised.

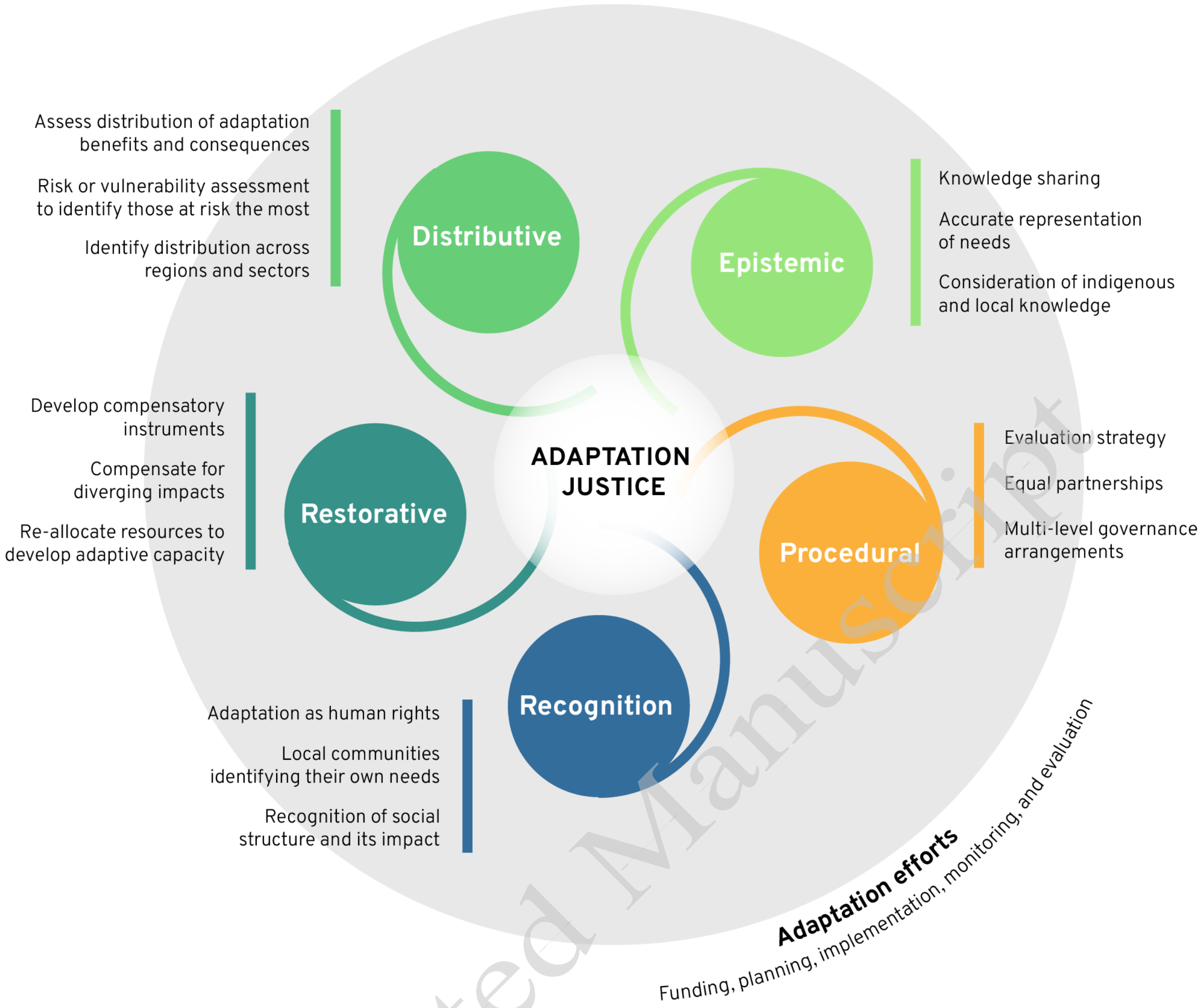


Figure 9. Components of Adaptation Justice and implications in adaptation planning and processes. Based on Juhola et al. (2022) and Orlove et al. (2023).

Box 9. Increases in resilience can be secured in all regions and communities by addressing adaptation justice in adaptation plans.

A. Hurricane Harvey in Harris County, Texas (USA) especially impacted low-income neighbourhoods. Those affected by the hurricane who were based outside of floodplains received no prior warning, affecting their preparedness (Smiley et al., 2022).

B. Drawing on indigenous knowledge and scientific information, villagers in Fiji planned their own relocation of coastal villages impacted by coastal erosion and saltwater intrusion (McMichael et al., 2019). The decision was made possible thanks to land use laws enabling the relocation which in turn supported livelihoods, use of terrestrial and marine resources, and maintained cultural values and connections to ritual sites (Orlove et al., 2023).

Insight 10. A justice lens for mitigation strategies in the food sector

Despite mounting evidence and strategies for mitigation, GHG emissions from food systems still amount to approximately 31% of global emissions (IPCC, 2022b, Ch12 p. 1280). Without significant transformations, current food systems on their own can put at risk the 1.5°C target, pushing global warming towards 2°C by 2100 (under "business as usual trajectories") (Clark et al., 2020). At the same time, over 700 million people are estimated to face hunger while marginalised groups such as women, racial minority groups, Indigenous Communities, and small-scale farmers are disproportionately affected by food insecurity and climate change (FAO et al., 2022; Juskaite & Haug et al., 2023). In the same way as the notion of just transitions has emerged to enable the transformation of energy systems (Heffron & McCauley, 2022), it is also increasingly understood as central for the transformation of food systems (Tribaldos & Kortetmäki, 2022).

The transformation of global food systems for climate action is challenged by the tension to act urgently while ensuring that no one is left behind (Woodhill et al., 2023). This tension is exacerbated by the polarised debate on whether solutions must be localised or coordinated at a more global scale (local-global food debate) (Wood et al., 2023) and the siloed decision-making processes dominating agricultural and policy sectors (FAO et al., 2022; McGreevy et al., 2022) . Current agricultural policies show insufficient consideration of social vulnerabilities, regional disparities in geography, culture and socioeconomic conditions (Ambikapathi et al., 2022), technological readiness, vested interests, and power imbalances (Béné, 2022; Zurek et al., 2022). For decades the agrifood industry, subsidised by national governments and aided by global trade agreements, has created a political economy that contributes to and reinforces unsustainability and injustices worldwide (Woodhill et al., 2022; Juskaite & Haug et al., 2023). Acknowledging and addressing the injustices (re)produced in contemporary food systems (Tribaldos & Kortetmäki, 2022) (see also Insight 9 on adaptation justice) and how structures of power shape socioeconomic change (e.g., Babic & Sharma, 2023) are crucial prerequisites for realising the mitigation potential of food systems transformation (McGreevy et al., 2022). This Insight highlights research developments on food systems transformations with a justice lens, focused on solutions that are more just and climate effective.

Firstly, strategies for low-emission diets and production practices, food waste elimination, among others, to transform food systems cannot be implemented as one-size-fits-all solutions. They must be diverse and embedded in regional heterogeneity. Dietary preferences (Ambikapathi et al., 2022), the needs of small-scale producers (Tschersich & Kok, 2022; Juskaite & Haug, 2023), inequalities in food loss and waste (FAO et al., 2022), regional socioecological contexts (Dengerink et al., 2021), and the governance of innovation (De Boon et al., 2022) are just some of the dimensions that need to be considered. As a result, solutions proposed in food systems transformations require broader, sometimes politically charged, discussions on a mix of multiple solutions. For example, a plurality of different narratives are developing in the debate over sustainable and alternative proteins– synthetic meat, plant-based substitutes, or small-scale farming– which open up critical questions on how existing power asymmetries and industrial control might be replicated or possibly avoided (Bené & Lundy 2023; Sexton et al., 2019). The literature in the field has also argued convincingly for the importance of re-grounding food systems in regional circuits of production and consumption, including shedding light on food system precarity and trade dependencies, M. Li et al., 2022; Mosnier et al., 2023) as well as recognizing the importance of social innovations (e.g., informal community gardening) in creating resilient biodiverse food systems (Hebinck et al., 2021).

Secondly, decision-making processes must acknowledge and address the existing vested interests of decision-making bodies as well as large private actors (Béné, 2022; Zurek et al., 2022), that may overpower the perspectives of stakeholders most vulnerable to the impacts of climate change and food insecurity (for example farmers, women, Indigenous Communities, workers (Juskaite & Haug et al., 2023). Using strategies to curb corporate influence, such as competition policies that account for the impacts of market concentration and measures to strengthen transparency and deprioritize profit making over the right to food, are essential (Clapp, 2021). Actively involving as many food systems stakeholders, with deliberate effort to engage marginalised communities and diverse cultures in safe enough spaces (Pereira et al., 2020),i is also key in garnering legitimacy and accountability in solutions (Tschersich & Kok, 2022; Juskaite & Haug, 2023)). Participatory and inclusive approaches to food system transitions help recognize the inevitability of trade-offs, with winners and losers, and realise more compensatory and just pathways. Without a transformation of governance processes, where appropriate incentives are aligned with actions, the present trajectories of unsustainability may prevail (Béné, 2022). Continuous transdisciplinary engagement with stakeholders from problem defining, evidence gathering, impact monitoring, and solution implementation can create co-ownership of policy processes and minimise the potential for negative trade-offs (Zurek et al., 2022).

Sustainability transformations research shows that fundamental food systems change might take decades (Bodirsky et al., 2022), so it cannot be delayed any further. While some progress has been made in recent years towards fostering the mitigation potential of food systems transformation, greater efforts are needed to develop transformative policy mixes that address negative trade-offs and integrate the welfare and wellbeing of people and the planet. For example, WWF (2022) reported an increase in countries with at least one measure related to food systems in their Nationally Determined Contributions (NDCs), from 79% to 93% of the 134 updated NDCs. Though, less than 50% of the updated NDCs mention the roles of smallholder farmers and Indigenous Peoples and local communities in their food systems measures.

It is clear that transformations within food systems require deliberate design and recognition of inequalities. Policies and strategies must take a multidimensional approach to transformation, incorporating socioeconomic, political, and environmental dimensions and consider multiple solutions at multiple scales, and how these solutions interact to create meaningful change and avoid reproducing power asymmetries. Moreover, inter-sectoral policy mixes that bridge interrelated spheres of food systems and correct or phase-out harmful and unjust policies will be critical for food governance to make a difference. Along these lines, McGreevy et al. (2022) lists sufficiency, regeneration, distribution, commons, and care as principles guiding the restructuring of food systems. Finding the correct resolution of policy mix (national, sub-national, hyperlocal) and engaging deliberative and transparent food governance is critical to establishing the effectiveness of just food systems transformations.

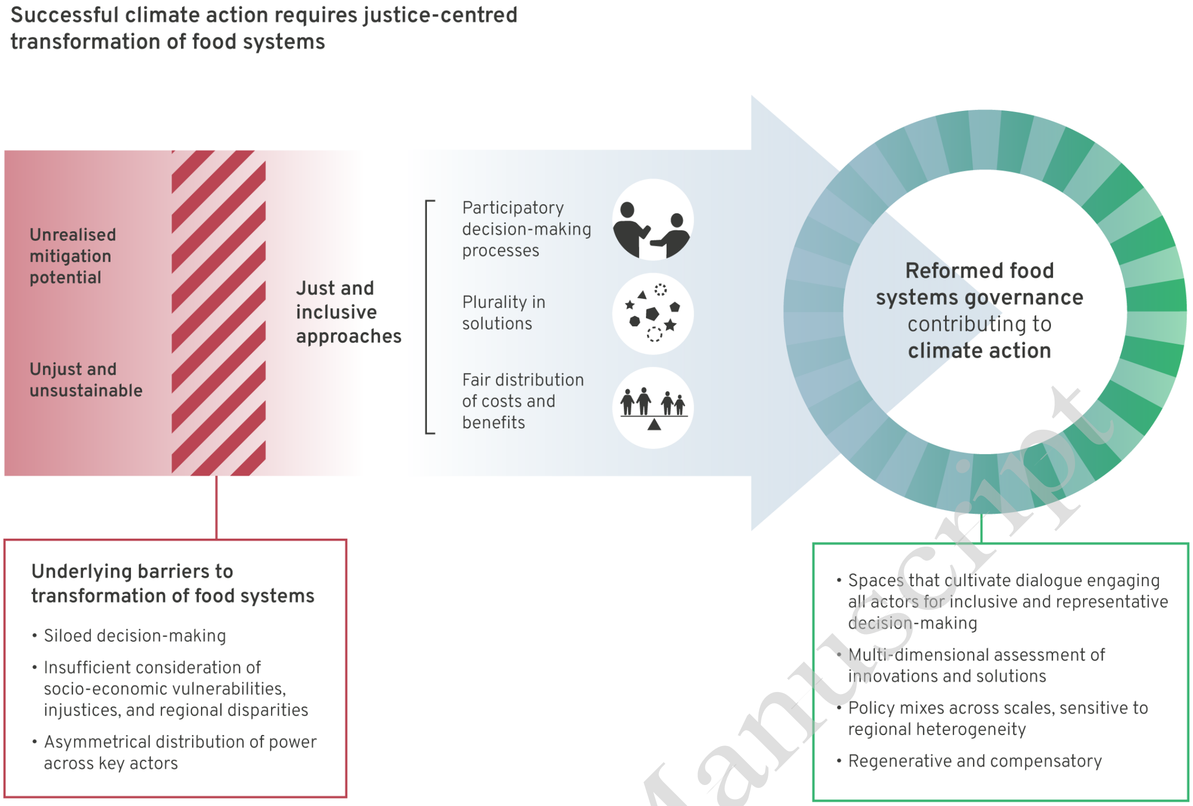


Figure 10. Just climate solutions for food systems transformations

Current food systems transformations for climate action are constrained due to siloed decision-making, insufficient consideration of regional disparities in geographies, innovation, socioeconomic factors, and power asymmetries across key actors, all of which act as barriers to effective climate action and result in unjust and sustainable food systems. Integrating more just and inclusive approaches that engage and empower all stakeholders, particularly those most vulnerable to climate change, including co-designing a plurality of solutions with fair distribution of costs and benefits, can help transition towards a governance system more capable of contributing to climate action in a more effective manner across the food sector.

Discussion

The current trajectory to overshoot is the result of decades of vastly insufficient action. Overshooting 1.5°C is a dangerous gamble: it will have irreversible impacts for life on Earth, with drastic loss of species and ecosystems (Meyer et al., 2022), and a rising risk of triggering climate tipping points (Armstrong McKay et al., 2022). While the impacts on biodiversity and ecosystems can be abrupt, recovery will be much slower than temperature declines (Meyer et al., 2022). Unfortunately, the natural carbon sinks, especially on land, might take up less carbon than expected in a warmer future due, among other factors, to increased climate disturbances. Unexpected additional release of GHG from natural carbon sinks might also result from the triggering of climate tipping elements under overshoot, further delaying eventual warming reversals. These could make temperature stabilisation and reversal increasingly difficult, further exacerbating the emergency. Worryingly, current national mitigation commitments are insufficient to even stay below 2°C of warming (IEA, 2021; Rogelj et al. 2023). Such an outcome would leave a lasting detrimental legacy for life on Earth, unacceptably high risks for human societies and vastly unequal human costs.

The science highlighted in this review makes it clear that overshooting 1.5°C is now all but inevitable in the near term. But the policy implication of this knowledge is decisively *not* that the Paris Agreement to limit warming to 1.5°C has to be abandoned to focus instead on 2°C. All the risks outlined in the sections above are an emphatic call to *minimise* overshoot, both in absolute magnitude and in duration. New projects to expand fossil fuel infrastructure, in particular the so-called "carbon bombs" (Kühne et al., 2022), advanced with the blessing of parties to the UNFCCC, are fundamentally incompatible with the Paris Agreement. The insufficient pace of mitigation over the last three decades has been largely due to a widespread political unwillingness to confront fossil fuel interests (Stoddard et al., 2021). Fossil fuels appeared for the first time in a decision text at COP26 ("phase down coal") (UNFCCC, 2021), and was repeated at COP27 with an effort to broaden to the other fossil fuels (UNFCCC, 2022), supported by 80 governments. The science is clear on the need for fossil fuel phase-out, and a political momentum needs to be built in the lead up to COP28. It is also important to recognise that for some developing countries and regions, there is the legitimate concern about energy security and lack of readily available financial resources to implement the needed managed transition (Nsafon et al., 2023; Walton, 2022). Phase-out must advance fastest in the countries more capable of absorbing the short-term economic costs, while in poorer countries the transition will require adequate financial support (Muttitt & Kartha, 2020). It is crucial, moreover, that the phase-out is done in a rapid but orderly fashion: in tandem with the phase-in of renewables (Blondeel et al., 2021). This is essential for maintaining current energy use and accommodating growing demand from the Global South, through a just energy transition (Heffron & McCauley, 2022).

The decarbonisation of energy systems is pivotal also given the energy needs of many 'novel' CDR options and their expected role in mitigation and eventual stabilisation of global temperature (U. Singh & Colosi, 2021; Terlouw et al., 2021). The IPCC scenarios consistent with Paris Agreement limits include a substantial deployment of CDR (IPCC 2022b: Ch12.3). This underscores the need to address the so-called CDR-gap, through policies that foster the scaling up of these technologies. Closing the CDR-gap will require advances in the 'novel' CDR methods (Figure 3), while most of the current CDR capability, by far, is nature-based. Afforestation/Reforestation, in particular, is perhaps the most well-known nature-based CDR option, yet there are concerns regarding durability and MRV robustness. Moreover, concerns are also raised for their impacts on specific ecosystems and communities. For example, while some agroforestry systems can offer valuable co-benefits, less thoughtful tree planting initiatives can have substantial negative impacts on livelihoods and biodiversity (Dobson et al., 2022; Veldman et al., 2019). Hence, these interventions should be carefully weighed against robust estimations of carbon sequestration potential gains (Seddon, 2022; Seddon et al., 2021). For international policy discussions regarding Nature-based CDR, justice considerations have to be front and centre: NbS implemented in the Global South cannot be the strategy for continued emissions in the Global North. The CDR-gap has to be closed, with more and better CDR, but these technologies should under no circumstance be part of a narrative to excuse or distract from the primary focus of advancing an managed phase-out of fossil fuels. In fact, the uncertainties regarding sequestration potential of CDR options, their scalability and MRV, should rather accelerate the political impetus to reduce CO_2 emissions as rapidly as possible.

The urgency for mitigation is reinforced by the urgency for adaptation, especially in the most vulnerable regions and segments of society. We have highlighted recent work on compound events, which are of concern for adaptation, as they pose a particular threat to food security and livelihoods associated with agriculture and fisheries (Gruber et al., 2021; Yin et al., 2023). The new reality of compound events is not yet widely recognised and incorporated into adaptation strategies, a shortcoming that might lead to maladaptive responses (Simpson et al., 2023), Similarly, accelerated deglaciation affects water availability and the livelihoods of mountain populations, which are often marginalised and highly vulnerable (IPCC, 2022b CCP5; S. Singh et al., 2020). Yet, the urgency for adaptation does not justify top-down impositions on what strategies local communities are to implement. Planned relocation, for example, tends to be resisted when it is not the result of a highly inclusive and participatory process (Farbotko et al., 2020; Lund, 2021). We highlighted recent advances for the operationalisation of a justice lens on adaptation planning and implementation, including specific attention to immobility, whether voluntary or involuntary, in the face of heightened climate risks. Among these advances, locally-led adaptation (Rahman et al., 2023) is hailed as a promising approach conducive to adaptation justice. With climate stabilisation still nowhere close on the horizon, adaptation challenges will demand a continuous effort of shifting priorities, requiring monitoring and careful assessment to prevent maladaptation.

Food systems are at the centre of most sustainability issues, interacting tightly with the climate, biodiversity, human health, and social justice (Gordon et al., 2017; Turnhout et al., 2021; Willett et al., 2019). The potential contribution of changes in food systems for climate change mitigation and adaptation have to be balanced with socioeconomic needs (Zurek et al., 2022) and the protection of biodiversity (Pörtner et al., 2021), enhancing synergies and minimising trade-offs. Food systems transformations have to be a major part of the solution to the climate emergency, but in order to realise their potential, justice needs to be prioritised here as well. This means: broadly inclusive, highly participatory approaches to planning and implementation, grounded on the local and regional specificities of the socioecological context. Such *just* food systems transformations have to be better integrated into climate financing (IFPRI, 2022) and climate action, in particular as part of NDCs (FOLU, 2022; WWF, 2022).

The most celebrated outcome from COP27 was undoubtedly the agreement on creating a Loss and Damage fund, which will be finalised in COP28. But COP27 clearly showed, once again, the difficulties to set a commitment to phase out fossil fuels, even though the final document reinforced the need for “rapid, deep and sustained reductions in greenhouse gas emissions” by 2030. At COP28, the negotiation will need to start from that statement towards a clear plan for managed phase out. The blatant contradiction is that parties to the UNFCCC continue to invest in new infrastructure for fossil fuel extraction and consumption, which will directly lead to higher temperatures and longer overshoot, and consequently ever greater losses and damages. The expectations for COP28 will continue around fossil fuel phasing-out, which is now included in the mandate of several governments going into COP28 (Jones et al., 2023) and is being championed by the UN Secretary General toward the *Acceleration Agenda* at the Climate Ambition Summit in September (UN Press, 2023). For this negotiation to be successful it will be necessary to also have a meaningful unlocking of climate financing in support of just transitions in developing countries.

Looking back at the previous six editions of the 10 New Insights in Climate Science, some areas of stronger emphasis can be identified. A signature of the report has been the understanding of the climate as one among several Earth system domains, interacting with the others, and particularly emphasising the linkages with the biosphere and the implications for the stability and resilience of the planet. The report has regularly paid attention to the climate tipping elements, stressing the need to consider more seriously the risks and uncertainties associated with these high-impact destabilising phenomena. We have been pleased to notice that, in recent years, these issues have gained much more prominence in public debate and climate policy discussions. Regarding the impacts of climate change, the focus has been stronger on health, food and water security, and extreme events. Different dimensions of human mobility (migration, displacement, immobility) have been highlighted in different years, reflecting an increasingly nuanced messaging on this sensitive topic. Different kinds of mitigation strategies (technical, nature-based, and behavioural) have been featured, as well as policy options to deal with government and market failures around fossil fuels (e.g., elimination of subsidies, and implementation of carbon pricing mechanisms). The '10 New Insights' report has also emphasised different ways in which climate change has exacerbated socioeconomic inequalities and stressed the importance of inclusive decision-making for effective and just climate action. The reports have also included reflections on the implications for the climate system and climate action of major developments on the world stage, such as COVID in 2020 and 2021, and the Russian invasion of Ukraine in 2022.

In the most recent editions of the series, we have increasingly spotlighted research on socioeconomic, cultural, and political dimensions of adaptation (and loss & damage), and the political economy barriers to effective and just climate action. We have synthesised scientific knowledge to counter misguided narratives (e.g., 'endless adaptation' and 'readiness of CDR'), to prevent further delay on decisive action to minimise GHG emissions. The '10 New Insights' will continue to provide timely and accessible updates from across the diverse research areas on climate change. As the IPCC begins a long task of reconstituting itself for the 7th Assessment, the mission of the '10 New Insights' is to contribute to raising the 'voice of science' in the remaining years of this crucial decade for climate action.

Author contributions

WB, MB, JGC, DC, HAC, KLE SF, SL, AM, CO, NSO, ÅP, JRoc, RR, JRoy, LFS, PS, YS, DS, RS constitute to the Editorial Board, conceiving and designing the study, selecting the Insights to be highlighted, and providing initial guidance on the outlines. MB, JRoy, and DOsp led the overall writing. Investigations and writing for each Insight: FL, LMP, NJS, NW, and KZ (Insight 1); PA, GM, GS, and GT (Insight 2), OG, ZH, GFN, and JP (Insight 3); AB, MFM, NG, JH, PKP, and ARam (Insight 4); DObu, TO, and YJS (Insight 5); TLF, LJH, CRay, VT, JY, and JZ (Insight 6); DRR, MH, AA, and AP (Insight 7); CF, BM, MP, TAS, LT, and KG (Insight 8), ARC, SHuq, LPJ, SJ, BO, and SEW (Insight 9); AH, VS, OS, and SM (Insight 10). Additional investigation and writing, as well as coordination for each Insight: SHeb (Insight 1), SS (Insight 2), ARed (Insights 3 and 6), MAM (Insight 4), TW (Insight 5), CRev (Insight 7), PM (Insight 8), GBS (Insight 9), and NK (Insight 10). DOsp and CE coordinated the overall process.

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Conflict of interest

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Research transparency and reproducibility

All potential additional resources such as anonymised data and protocols (if not referenced in the manuscript or provided in the Supplementary material) can be requested via e-mail to the corresponding author.

References cited

Achakulwisut, P., Erickson, P., Guivarch, C., Schaeffer, R., Brutschin, E., & Pye, S. (2023). Global fossil fuel reduction path-ways under different climate mitigation strategies and ambitions. *Nature communications*, 14, 5425.https://doi.org/10.1038/s41467-023-41105-z

Aggarwal, A., Frey, H., McDowell, G., Drenkhan, F., Nüsser, M., Racoviteanu, A., & Hoelzle, M. (2022). Adaptation to climate change induced water stress in major glacierized mountain regions. *Climate and Development*, *14*(7), 665–677. https://doi.org/10.1080/17565529.2021.1971059

Alcántara-Ayala, I., Pasuto, A., & Cui, P. (2022). Disaster risk reduction in mountain areas: An initial overview on seeking pathways to global sustainability. *Journal of Mountain Science*, *19*(6), 1838–1846. https://doi.org/10.1007/s11629-022-7468-5

Allen, M. R., Friedlingstein, P., Girardin, C. A. J., Jenkins, S., Malhi, Y., Mitchell-Larson, E., Peters, G. P., & Rajamani, L. (2022). Net Zero: Science, Origins, and Implications. *Annual Review of Environment and Resources*, *47*(1), 849–887. https://doi.org/10.1146/annurev-environ-112320-105050

Ambikapathi, R., Schneider, K. R., Davis, B., Herrero, M., Winters, P., & Fanzo, J. C. (2022). Global food systems transitions have enabled affordable diets but had less favourable outcomes for nutrition, environmental health, inclusion and equity. *Nature Food*, *3*(9), 764–779. https://doi.org/10.1038/s43016-022-00588-7

Anderegg, W. R. L., Wu, C., Acil, N., Carvalhais, N., Pugh, T. A. M., Sadler, J. P., & Seidl, R. (2022). A climate risk analysis of Earth's forests in the 21st century. *Science*, *377*(6610), 1099–1103. https://doi.org/10.1126/science.abp9723

Araos, M., Jagannathan, K., Shukla, R., Ajibade, I., Coughlan de Perez, E., Davis, K., Ford, J. D., Galappaththi, E. K., Grady, C., Hudson, A. J., Joe, E. T., Kirchhoff, C. J., Lesnikowski, A., Alverio, G. N., Nielsen, M., Orlove, B., Pentz, B., Reckien, D., Siders, A. R., … Turek-Hankins, L. L. (2021). Equity in human adaptation-related responses: A systematic global review. *One Earth*, *4*(10), 1454–1467. https://doi.org/10.1016/j.oneear.2021.09.001

Armani, M., Asefa, M., Zakari, S., & Agyekum, E. O. (2022). Enhancing climate change adaptation and mitigation actions on land in Africa. In S. A. Archibald, L. M. Pereira, & K. L. Coetzer (Eds.), *Future Ecosystems for Africa (FEFA)*. University of the Witwatersrand, Johannesburg. https://futureecosystemsafrica.org/reports/Land-Evidence-Base.pdf

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., & Lenton, T. M. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*, *377*(6611), 1–10. https://doi.org/10.1126/science.abn7950

Arneth, A., Leadley, P., Claudet, J., Coll, M., Rondinini, C., Rounsevell, M. D. A., Shin, Y., Alexander, P., & Fuchs, R. (2023). Making protected areas effective for biodiversity, climate and food. *Global Change Biology*, *00*, 1–12. https://doi.org/10.1111/gcb.16664

Arneth, A., Shin, Y.-J., Leadley, P., Rondinini, C., Bukvareva, E., Kolb, M., Midgley, G. F., Oberdorff, T., Palomo, I., & Saito, O. (2020). Post-2020 biodiversity targets need to embrace climate change. *Proceedings of the National Academy of Sciences*, *117*(49), 30882–30891. https://doi.org/10.1073/pnas.2009584117

Ayeb-Karlsson, S. (2020). When the disaster strikes: Gendered (im)mobility in Bangladesh. *Climate Risk Management*, *29*, 1–24. https://doi.org/10.1016/j.crm.2020.100237

Babic, M., & Sharma, S. E. (2023). Mobilising critical international political economy for the age of climate breakdown. *New Political Economy*, *28*(5), 758–779. https://doi.org/10.1080/13563467.2023.2184468

Bach, L. T., Ho, D. T., Boyd, P. W., & Tyka, M. D. (2023). Toward a consensus framework to evaluate air–sea CO_2 equilibration for marine CO_2 removal. *Limnology and Oceanography Letters*, (Early View). https://doi.org/10.1002/lol2.10330

Baines, J., & Hager, S. B. (2023). From passive owners to planet savers? Asset managers, carbon majors and the limits of sustainable finance. *Competition & Change*, *27*(3–4), 449–471. https://doi.org/10.1177/10245294221130432

Bartusek, S., Kornhuber, K., & Ting, M. (2022). 2021 North American heatwave amplified by climate change-driven nonlinear interactions. *Nature Climate Change*, *12*(12). https://doi.org/10.1038/s41558-022-01520-4

Bastos, A., Ciais, P., Sitch, S., Aragão, L. E. O. C., Chevallier, F., Fawcett, D., Rosan, T. M., Saunois, M., Günther, D., Perugini, L., Robert, C., Deng, Z., Pongratz, J., Ganzenmüller, R., Fuchs, R., Winkler, K., Zaehle, S., & Albergel, C. (2022). On the use of Earth Observation to support estimates of national greenhouse gas emissions and sinks for the Global stocktake process: Lessons learned from ESA-CCI RECCAP2. *Carbon Balance and Management*, *17*(1), 1–16. https://doi.org/10.1186/s13021-022-00214-w

Bauer, N., Keller, D. P., Garbe, J., Karstens, K., Piontek, F., Bloh, W. von, Thiery, W., Zeitz, M., Mengel, M., Strefler, J., Thonicke, K., & Winkelmann, R. (2023). Exploring risks and benefits of overshooting a 1.5 °C carbon budget over space and time. *Environmental Research Letters*, *18*(5), 1–18. https://doi.org/10.1088/1748-9326/accd83

Béné, C. (2022). Why the Great Food Transformation may not happen – A deep-dive into our food systems' political economy, controversies and politics of evidence. *World Development*, *154*, 1–14. https://doi.org/10.1016/j.worlddev.2022.105881

Béné, C., & Lundy, M. (2023). Political economy of protein transition: Battles of power, framings and narratives around a false wicked problem. *Frontiers in Sustainability*, 4, 1098011. https://doi.org/10.3389/frsus.2023.1098011

Benveniste, H., Oppenheimer, M., & Fleurbaey, M. (2022). Climate change increases resource-constrained international immobility. *Nature Climate Change*, *12*, 634–641. https://doi.org/10.1038/s41558-022-01401-w

Blondeel, M., Bradshaw, M. J., Bridge, G., & Kuzemko, C. (2021). The geopolitics of energy system transformation: A review. *Geography Compass*, *15*(7), e12580. https://doi.org/10.1111/gec3.12580

Boas, I., Wiegel, H., Farbotko, C., Warner, J., & Sheller, M. (2022). Climate mobilities: Migration, im/mobilities and mobility regimes in a changing climate. *Journal of Ethnic and Migration Studies*, *48*(14), 3365–3379. https://doi.org/10.1080/1369183X.2022.2066264

Bodirsky, B. L., Chen, D. M.-C., Weindl, I., Soergel, B., Beier, F., Molina Bacca, E. J., Gaupp, F., Popp, A., & Lotze-Campen, H. (2022). Integrating degrowth and efficiency perspectives enables an emission-neutral food system by 2100. *Nature Food*, *3*(5), 341–348. https://doi.org/10.1038/s43016-022-00500-3

Bosson, J. B., Huss, M., Cauvy-Fraunié, S., Clément, J. C., Costes, G., Fischer, M., Poulenard, J. & Arthaud, F. (2023). Future emergence of new ecosystems caused by glacial retreat. *Nature*, 620(7974), 562-569. https://doi.org/10.1038/s41586-023-06302-2

Brink, E., Falla, A. M. V., & Boyd, E. (2023). Weapons of the vulnerable? A review of popular resistance to climate adaptation. *Global Environmental Change*, *80*, 1–19. https://doi.org/10.1016/j.gloenvcha.2023.102656

Browne, K. E. (2022). Rethinking governance in international climate finance: Structural change and alternative approaches. *WIREs Climate Change*, *13*(5), 1–23. https://doi.org/10.1002/wcc.795

Brutschin, E., Pianta, S., Tavoni, M., Riahi, K., Bosetti, V., Marangoni, G., & Ruijven, B. J. V. (2021). A multidimensional feasibility evaluation of low-carbon scenarios. *Environmental Research Letters*, *16*(6), 1–13. https://doi.org/10.1088/1748-9326/abf0ce

Buck, H. J., Carton, W., Lund, J. F., & Markusson, N. (2023). Why residual emissions matter right now. *Nature Climate Change*, 1–8. https://doi.org/10.1038/s41558-022-01592-2

Buckingham, F. L., Henderson, G. M., Holdship, P., & Renforth, P. (2022). Soil core study indicates limited CO_2 removal by enhanced weathering in dry croplands in the UK. *Applied Geochemistry*, *147*, 105482. https://doi.org/10.1016/j.apgeochem.2022.105482

Burger, F. A., Terhaar, J., & Frölicher, T. L. (2022). Compound marine heatwaves and ocean acidity extremes. *Nature Communications*, *13*(1). https://doi.org/10.1038/s41467-022-32120-7

Calverley, D., & Anderson, K. (2022). *Phaseout Pathways for Fossil Fuel Production within Paris-compliant carbon budgets* [Tyndall Production Phaseout Report]. The University of Manchester Research.

https://pure.manchester.ac.uk/ws/portalfiles/portal/213256008/Tyndall_Production_Phaseout_Report_final_text_3_.pdf

Campiglio, E., & van der Ploeg, F. (2022). Macrofinancial Risks of the Transition to a Low-Carbon Economy. *Review of Environmental Economics and Policy*, *16*(2), 173–195. https://doi.org/10.1086/721016

Canadell, J. G., Meyer, C. P. M., Cook, G. D., Dowdy, A., Briggs, P. R., Knauer, J., Pepler, A., & Haverd, V. (2021). Multi-decadal increase of forest burned area in Australia is linked to climate change. *Nature Communications*, *12*(1), 6921.

Carr, E. R., & Nalau, J. (2023). Adaptation rationales and benefits: A foundation for understanding adaptation impact. *Climate Risk Management*, *39*, 1–9. https://doi.org/10.1016/j.crm.2023.100479

Carton, W., Hougaard, I.-M., Markusson, N., & Lund, J. F. (2023). Is carbon removal delaying emission reductions? *WIREs Climate Change*, (Early View), e826. https://doi.org/10.1002/wcc.826

Chandra, N., Patra, P. K., Niwa, Y., Ito, A., Iida, Y., Goto, D., Morimoto, S., Kondo, M., Takigawa, M., Hajima, T., & Watanabe, M. (2022). Estimated regional CO_2 flux and uncertainty based on an ensemble of atmospheric CO_2 inversions. *Atmospheric Chemistry and Physics*, *22*(14), 9215–9243. https://doi.org/10.5194/acp-22-9215-2022

Ciplet, D., Falzon, D., Uri, I., Robinson, S., Weikmans, R., & Roberts, J. T. (2022). The unequal geographies of climate finance: Climate injustice and dependency in the world system. *Political Geography*, *99*, 1–12. https://doi.org/10.1016/j.polgeo.2022.102769

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

Clark, M. A., Domingo, N. G. G., Colgan, K., Thakrar, S. K., Tilman, D., Lynch, J., Azevedo, I. L., & Hill, J. D. (2020). Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. *Science*, *370*(6517), 705–708. https://doi.org/10.1126/science.aba7357

Cauvy-Fraunié, S. & Dangles, O. (2019). A global synthesis of biodiversity responses to glacier retreat. *Nature Ecology & Evolution*, 3(12), 1675-1685. https://doi.org/10.1038/s41559-019-1042-8

Coughlan de Perez, E., Ganapathi, H., Masukwedza, G. I. T., Griffin, T., & Kelder, T. (2023). Potential for surprising heat and drought events in wheat-producing regions of USA and China. *Npj Climate and Atmospheric Science*, *6*(1). https://doi.org/10.1038/s41612-023-00361-y

Crisp, D., Dolman, H., Tanhua, T., McKinley, G. A., Hauck, J., Bastos, A., Sitch, S., Eggleston, S., & Aich, V. (2022). How Well Do We Understand the Land-Ocean-Atmosphere Carbon Cycle? *Reviews of Geophysics*, *60*(2), 1–64. https://doi.org/10.1029/2021RG000736

Dasgupta, P. (2021). *The Economics of Biodiversity: The Dasgupta Review*. HM Treasury, London.

De Boon, A., Sandström, C., & Rose, D. C. (2022). Governing agricultural innovation: A comprehensive framework to underpin sustainable transitions. *Journal of Rural Studies*, *89*, 407–422. https://doi.org/10.1016/j.jrurstud.2021.07.019

De Angeli, S., Malamud, B. D., Rossi, L., Taylor, F. E., Trasforini, E. & Rudari, R., 2022. A multi-hazard framework for spatial-temporal impact analysis. *International Journal of Disaster Risk Reduction*, 73, 102829. https://doi.org/10.1016/j.ijdrr.2022.102829

de Ruiter, M. C., Couasnon, A., van den Homberg, M. J., Daniell, J.E., Gill, J. C. & Ward, P. J., 2020. Why we can no longer ignore consecutive disasters. *Earth's future*, 8(3), e2019EF001425. https://doi.org/10.1029/2019EF001425

Dengerink, J., Dirks, F., Likoko, E., & Guijt, J. (2021). One size doesn't fit all: Regional differences in priorities for food system transformation. *Food Security*, *13*(6), 1455–1466. https://doi.org/10.1007/s12571-021-01222-3

Diluiso, F., Walk, P., Manych, N., Cerutti, N., Chipiga, V., Workman, A., Ayas, C., Cui, R. Y., Cui, D., Song, K., Banisch, L. A., Moretti, N., Callaghan, M. W., Clarke, L., Creutzig, F., Hilaire, J., Jotzo, F., Kalkuhl, M., Lamb, W. F., … Minx, J. C. (2021). Coal transitions—part 1: A systematic map and review of case study learnings from regional, national, and local coal phase-out experiences. *Environmental Research Letters*, *16*(11), 1–40. https://doi.org/10.1088/1748-9326/ac1b58

Dobson, A., Hopcraft, G., Mduma, S., Ogutu, J. O., Fryxell, J., Anderson, T. M., Archibald, S., Lehmann, C., Poole, J., Caro, T., Mulder, M. B., Holt, R. D., Berger, J., Rubenstein, D. I., Kahumbu, P., Chidumayo, E. N., Milner-Gulland, E. J., Schluter, D., Otto, S., … Sinclair, A. R. E. (2022). Savannas are vital but overlooked carbon sinks. *Science*, *375*(6579), 392–392. https://doi.org/10.1126/science.abn4482

Dordi, T., Gehricke, S. A., Naef, A., & Weber, O. (2022). Ten financial actors can accelerate a transition away from fossil fuels. *Environmental Innovation and Societal Transitions*, *44*, 60–78. https://doi.org/10.1016/j.eist.2022.05.006

Durand-Delacre, D., Bettini, G., Nash, S. L., Sterly, H., Gioli, G., Hut, E., ... & Hulme, M. (2021). Climate Migration Is about People, Not Numbers. In S. Bohm & S. Sullivan (Eds.), *Negotiating Climate Change in Crisis* (pp. 63-81). Open Book Publishers.

Dvorak, M. T., Armour, K. C., Frierson, D. M. W., Proistosescu, C., Baker, M. B., & Smith, C. J. (2022). Estimating the timing of geophysical commitment to 1.5 and 2.0 °C of global warming. *Nature Climate Change*, *12*(6), 547–552. https://doi.org/10.1038/s41558-022-01372-y

Edenhofer, O., Franks, M., Kalkuhl, M., & Runge-Metzger, A. (2023). *On the Governance of Carbon Dioxide Removal – a Public Economics Perspective* (SSRN Scholarly Paper No. 4422845). https://doi.org/10.2139/ssrn.4422845

Emmer, A., Allen, S. K., Carey, M., Frey, H., Huggel, C., Korup, O., ... & Yde, J. C. (2022). Progress and challenges in glacial lake outburst flood research (2017–2021): a research community perspective. *Natural Hazards and Earth System Sciences*, 22(9), 3041-3061.

Espagne, E., Oman,, W., Mercure, J-F., Svartzman, R., Volz, U., Pollitt, H., Semieniuk, G., & Campiglio, E.(2023). *Cross-Border Risks of a Global Economy in Mid-Transition*. IMF Working paper. IMF eLIBRARY. https://www.elibrary.imf.org/view/journals/001/2023/184/article-A001-en.xml

Estoque, R. C. (2023). *Complexity and diversity of nexuses: A review of the nexus approach in the sustainability context*. *854*. https://doi.org/10.1016/j.scitotenv.2022.158612

European Commission. (2022a). *A European Green Deal*. A European Green Deal. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

European Commission. (2022b). *Biodiversity strategy for 2030*. Biodiversity Strategy for 2030. https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en

European Commission. (2022c). *European Green Deal: Commission proposes certification of carbon removals to help reach net zero emissions.* European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7156

European Parliament. (2023). *Beyond growth: Pathways towards sustainable prosperity in the EU.* Publications Office. https://data.europa.eu/doi/10.2861/602232

FAO, IFAD, UNICEF, WFP, & WHO. (2022). *The State of Food Security and Nutrition in the World 2022. Repurposing food and agricultural policies to make healthy diets more affordable*. FAO, Rome. https://doi.org/10.4060/cc0639en

Farbotko, C. (2022). Anti-displacement mobilities and re-emplacements: Alternative climate mobilities in Funafala. *Journal of Ethnic and Migration Studies*, *48*(14), 3380–3396. https://doi.org/10.1080/1369183X.2022.2066259

Farbotko, C., & Campbell, J. (2022). Who defines atoll ‘uninhabitability’? *Environmental Science and Policy*, *138*, 182–190. https://doi.org/10.1016/j.envsci.2022.10.001

Farbotko, C., Dun, O., Thornton, F., McNamara, K. E., & McMichael, C. (2020). Relocation planning must address voluntary immobility. *Nature Climate Change*, *10*(8). https://doi.org/10.1038/s41558-020-0829-6

Fernández-Martínez, M., Peñuelas, J., Chevallier, F., Ciais, P., Obersteiner, M., Rödenbeck, C., Sardans, J., Vicca, S., Yang, H., Sitch, S., Friedlingstein, P., Arora, V. K., Goll, D. S., Jain, A. K., Lombardozzi, D. L., McGuire, P. C., & Janssens, I. A. (2023). Diagnosing destabilization risk in global land carbon sinks. *Nature*, *615*, 848–854. https://doi.org/10.1038/s41586-023-05725-1

FOLU. (2022). *Food, Environment, Land and Development (FELD) Action Tracker. 2022 Update: From Global Commitments to National Action: A Closer Look at Nationally Determined Contributions from a Food and Land Perspective*. Sustainable Development Solutions Network (SDSN), Paris.

Foresight UK. (2011). *Migration and Global Environmental Change: Future Challenges and Opportunities (R. Black, N. Adger, N. Arnell, S. Dercon, A. Geddes, & D. Thomas, EDS.)*. Government Office for Science.

Forster, P. M., Smith, C. J., Walsh, T., Lamb, W. F., Lamboll, R., Hauser, M., Ribes, A., Rosen, D., Gillett, N., Palmer, M. D., Rogelj, J., von Schuckmann, K., Seneviratne, S. I., Trewin, B., Zhang, X., Allen, M., Andrew, R., Birt, A., Borger, A., … Zhai, P. (2023). Indicators of Global Climate Change 2022: Annual update of large-scale indicators of the state of the climate system and human influence. *Earth System Science Data*, *15*(6), 2295–2327. https://doi.org/10.5194/essd-15-2295-2023

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I. T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Alkama, R., … Zheng, B. (2022). Global Carbon Budget 2022. *Earth System Science Data*, *14*(11), 4811–4900. https://doi.org/10.5194/essd-14-4811-2022

Fuhrman, J., Bergero, C., Weber, M., Monteith, S., Wang, F. M., Clarens, A. F., Doney, S. C., Shobe, W., & McJeon, H. (2023). Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system. *Nature Climate Change*, *13*(4). https://doi.org/10.1038/s41558-023-01604-9

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., Garcia, W. de O., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., Dominguez, M. del M. Z., & Minx, J. C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 341–350. https://doi.org/10.1088/1748-9326/aabf9f

Fyson, C., Ganti, G., Grant, N., & Hare, B. (2022). *Fossil gas: A bridge to nowhere. Phase-out requirements for gas power to limit global warming to 1.5°C*. Climate Analytics. https://climateanalytics.org/media/fossil_gas_a_bridge_to_nowhere.pdf

Gatti, L. V., Basso, L. S., Miller, J. B., Gloor, M., Gatti Domingues, L., Cassol, H. L. G., Tejada, G., Aragão, L. E. O. C., Nobre, C., Peters, W., Marani, L., Arai, E., Sanches, A. H., Corrêa, S. M., Anderson, L., Von Randow, C., Correia, C. S. C., Crispim, S. P., & Neves, R. A. L. (2021). Amazonia as a carbon source linked to deforestation and climate change. *Nature*, 595(7867), 388–393. https://doi.org/10.1038/s41586-021-03629-6

Gattuso, J.-P., Williamson, P., Duarte, C. M., & Magnan, A. K. (2021). The Potential for Ocean-Based Climate Action: Negative Emissions Technologies and Beyond. *Frontiers in Climate*, *2,575716*. https://doi.org/10.3389/fclim.2020.575716

Gaupp, F., Hall, J., Hochrainer-Stigler, S., & Dadson, S. (2020). Changing risks of simultaneous global breadbasket failure. *Nature Climate Change*, *10*(1), Article 1. https://doi.org/10.1038/s41558-019-0600-z

GFANZ. (2022). *The Managed Phaseout of High-emitting Assets*. Glasgow Financial Alliance for Net Zero. https://assets.bbhub.io/company/sites/63/2022/06/GFANZ_-Managed-Phaseout-of-High-emitting-Assets_June2022.pdf

Gordon, L. J., Bignet, V., Crona, B., Henriksson, P. J. G., Holt, T. V., Jonell, M., Lindahl, T., Troell, M., Barthel, S., Deutsch, L., Folke, C., Haider, L. J., Rockström, J., & Queiroz, C. (2017). Rewiring food systems to enhance human health and biosphere stewardship. *Environmental Research Letters*, *12*(10), 100201. https://doi.org/10.1088/1748-9326/aa81dc

Gruber, N., Bakker, D. C. E., DeVries, T., Gregor, L., Hauck, J., Landschützer, P., McKinley, G. A., & Müller, J. D. (2023). Trends and variability in the ocean carbon sink. *Nature Reviews Earth & Environment*, *4*, 119–134. https://doi.org/10.1038/s43017-022-00381-x

Gruber, N., Boyd, P. W., Frölicher, T. L., & Vogt, M. (2021). Biogeochemical extremes and compound events in the ocean. *Nature*, *600*, 395–407. https://doi.org/10.1038/s41586-021-03981-7

Grubert, E., & Hastings-Simon, S., (2022). Designing the mid-transition: A review of medium-term challenges for coordinated decarbonization in the United States. Wires Climate Change, Vol13, Issue 3. e768.

https://doi.org/10.1002/wcc.768

Gu, L., Chen, J., Yin, J., Slater, L. J., Wang, H.-M., Guo, Q., Feng, M., Qin, H., & Zhao, T. (2022). Global Increases in Compound Flood-Hot Extreme Hazards Under Climate Warming. *Geophysical Research Letters*, *49*(8), e2022GL097726. https://doi.org/10.1029/2022GL097726

Gunathilake, K. L. W. I., Jayathilake, P. P. G., Fernando, N., Jayasinghe, N., Amaratunga, D., & Haigh, R. (2023). Living with Landslide Risks: A Case of Resistance to Relocation Among Vulnerable Households Residing in the Kegalle District of Sri Lanka. In M. Hamza, D. Amaratunga, R. Haigh, C. Malalgoda, C. Jayakody, & A. Senanayake (Eds.), *Rebuilding Communities After Displacement: Sustainable and Resilience Approaches* (pp. 145–163). Springer International Publishing. https://doi.org/10.1007/978-3-031-21414-1_7

Hartmann, H., Bastos, A., Das, A. J., Esquivel-Muelbert, A., Hammond, W. M., Martínez-Vilalta, J., McDowell, N. G., Powers, J. S., Pugh, T. A., Ruthrof, K. X. & Allen, C.D. (2022). Climate change risks to global forest health: emergence of unexpected events of elevated tree mortality worldwide. *Annual Review of Plant Biology*, 73, pp.673-702. https://doi.org/10.1146/annurev-arplant-102820-012804

Hartmann, J., Suitner, N., Lim, C., Schneider, J., Marín-Samper, L., Arístegui, J., Renforth, P., Taucher, J., & Riebesell, U. (2023). Stability of alkalinity in ocean alkalinity enhancement (OAE) approaches – consequences for durability of CO_2 storage. *Biogeosciences*, *20*(4), 781–802. https://doi.org/10.5194/bg-20-781-2023

Hauck, J., Gregor, L., Nissen, C., Patara, L., Hague, M., Mongwe, P., Bushinsky, S. M., Doney, S. C., Gruber, N., Quéré, C. L., Manizza, M., Mazloff, M. R., Monteiro, P. M. S., & Terhaar, J. (2023). *The Southern Ocean carbon cycle 1985-2018: Mean, seasonal cycle, trends and storage* [Accepted in *Global Biogeochemical Cycles*

Hausfather, Z., Klitzke, J., & Chay, F. (2022). *Quantifying MRV uncertainties across a range of permanent CDR pathways*. American Geophysical Union (AGU) Fall Meeting 2022. https://agu.confex.com/agu/fm22/meetingapp.cgi/Paper/1182348

Hebinck, A., Selomane, O., Veen, E., de Vrieze, A., Hasnain, S., Sellberg, M., Sovová, L., Thompson, K., Vervoort, J., & Wood, A. (2021). Exploring the transformative potential of urban food. *Npj Urban Sustainability*, *1*(1), 1–9. https://doi.org/10.1038/s42949-021-00041-x

Heffron, R. J., & McCauley, D. (2022). The 'just transition' threat to our Energy and Climate 2030 targets. *Energy Policy*, *165*, 112949. https://doi.org/10.1016/j.enpol.2022.112949

Herbert-Read, J. E., Thornton, A., Amon, D. J., Birchenough, S. N. R., Côté, I. M., Dias, M. P., Godley, B. J., Keith, S. A., McKinley, E., Peck, L. S., Calado, R., Defeo, O., Degraer, S., Johnston, E. L., Kaartokallio, H., Macreadie, P. I., Metaxas, A., Muthumbi, A. W. N., Obura, D. O., … Sutherland, W. J. (2022). A global horizon scan of issues impacting marine and coastal biodiversity conservation. *Nature Ecology & Evolution*, *6*(9), 1262–1270. https://doi.org/10.1038/s41559-022-01812-0

Hubau, W., Lewis, S. L., Phillips, O. L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A., Daniels, A. K., Ewango, C. E. N., Fauset, S., Mukinzi, J. M., Sheil, D., Sonké, B., Sullivan, M. J. P., Sunderland, T. C. H., Taedoumg, H., Thomas, S. C., White, L. J. T., Abernethy, K. A., Adu-Bredu, S., … Zemagho, L. (2020). Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature*, *579*(7797), 80–87. https://doi.org/10.1038/s41586-020-2035-0

Huggel, C., Bouwer, Laurens M., Juhola, Sirkku, Mechler, Reinhard, Muccione, Veruska, Orlove, Ben, & Wallimann-Helmer, Ivo. (2022). *The existential risk space of climate change*. *174*(8), 1–20. https://doi.org/10.1007/s10584-022-03430-y

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., Brun, F., & Kääb, A. (2021). Accelerated global glacier mass loss in the early twenty-first century. *Nature*, *592*(7856), 726–731. https://doi.org/10.1038/s41586-021-03436-z

Ibanez, T., Platt, W. J., Bellingham, P. J., Vieilledent, G., Franklin, J., Martin, P. H., Menkes, C., Pérez-Salicrup, D. R., Russell-Smith, J., & Keppel, G. (2022). Altered cyclone–fire interactions are changing ecosystems. *Trends in Plant Science*, *27*(12), 1218–1230. https://doi.org/10.1016/j.tplants.2022.08.005

IEA. (2021). *Net Zero by 2050—A Roadmap for the Global Energy Sector*. International Energy Agency. https://www.iea.org/reports/net-zero-by-2050

IEA. (2023a). *Emissions from Oil and Gas Operations in Net Zero Transitions*. International Energy Agency. https://www.iea.org/reports/emissions-from-oil-and-gas-operations-in-net-zero-transitions

IEA. (2023b). *Fossil Fuels Consumption Subsidies 2022*. International Energy Agency. https://www.iea.org/reports/fossil-fuels-consumption-subsidies-2022

IEA. (2023c). *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach-A renewed pathway to net zero emissions.* International Energy Agency. https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach/a-renewed-pathway-to-net-zero-emissions

IFPRI. (2022). *2022 Global Food Policy Report: Climate Change and Food Systems*. Washington, DC: International Food Policy Research Institute. https://doi.org/10.2499/9780896294257

IISD. (2022). *Navigating Energy Transitions Mapping the road to 1.5°C*. International Institute for Sustainable Development. https://www.iisd.org/system/files/2022-10/navigating-energy-transitions-mapping-road-to-1.5.pdf

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., … Baillie, J. E. M. (2020). Importance and vulnerability of the world’s water towers. *Nature*, *577*(7790), 364–369. https://doi.org/10.1038/s41586-019-1822-y

IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. 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, B. Zhou, Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press.

IPCC (2022a). *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.

IPCC (2022b). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926*. Intergovernmental Panel on Climate Change.

IPCC (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Core Writing Team, H. Lee and J. Romero. Eds.). IPCC, Geneva, Switzerland, 184 pp., https://doi.org/10.59327/IPCC/AR6-9789291691647

Isbell, F., Balvanera, P., Mori, A. S., He, J., Bullock, J. M., Regmi, G. R., Seabloom, E. W., Ferrier, S., Sala, O. E., Guerrero‐Ramírez, N. R., Tavella, J., Larkin, D. J., Schmid, B., Outhwaite, C. L., Pramual, P., Borer, E. T., Loreau, M., Omotoriogun, T. C., Obura, D. O., … Palmer, M. S. (2023). Expert perspectives on global biodiversity loss and its drivers and impacts on people. *Frontiers in Ecology and the Environment*, *21*(2), 94–103. https://doi.org/10.1002/fee.2536

Islam, Md. M. (2022). Distributive justice in global climate finance – Recipients’ climate vulnerability and the allocation of climate funds. *Global Environmental Change*, *73*, 1–15. https://doi.org/10.1016/j.gloenvcha.2022.102475

Jackson, G., N’Guetta, A., De Rosa, S. P., Scown, M., Dorkenoo, K., Chaffin, B., & Boyd, E. (2023). An emerging governmentality of climate change loss and damage. *Progress in Environmental Geography*, 1–25. https://doi.org/10.1177/27539687221148748

Jayakrishnan, K. U., Bala, G., Cao, L., & Caldeira, K. (2022). Contrasting climate and carbon-cycle consequences of fossil-fuel use versus deforestation disturbance. *Environmental Research Letters*, *17*(6), 064020. https://doi.org/10.1088/1748-9326/ac69fd

Jones, M. W., Abatzoglou, J. T., Veraverbeke, S., Andela, N., Lasslop, G., Forkel, M., Smith, A. J. P., Burton, C., Betts, R. A., van der Werf, G. R., Sitch, S., Canadell, J. G., Santín, C., Kolden, C., Doerr, S. H., & Le Quéré, C. (2022). Global and regional trends and drivers of fire under climate change. *Reviews of Geophysics*, *60*(3). https://doi.org/10.1029/2020rg000726

Jones, N., Verkuijl, C., Cabré, M. M., & Piggot, G. (2023). *Connecting the dots: Mapping references to fossil fuel production in national plans under the UNFCCC for the 2023 Global Stocktake*. https://doi.org/10.51414/sei2023.040

Juhola, S., Heikkinen, M., Pietilä, T., Groundstroem, F., & Käyhkö, J. (2022). Connecting climate justice and adaptation planning: An adaptation justice index. *Environmental Science and Policy*, *136*, 609–619. https://doi.org/10.1016/j.envsci.2022.07.024

Juhola, S., & Käyhkö, J. (2023). Maladaptation as a concept and a metric in national adaptation policy - Should we, would we, could we? *PLOS Climate*, *2*(5), 1–11. https://doi.org/10.1371/journal.pclm.0000213

Juskaite, G., & Haug, R. (2023). Multiple meanings of “equitable food systems”: food systems and discursive politics of change. *Frontiers in Sustainable Food Systems*, 7, 1127562. https://doi.org/10.3389/fsufs.2023.1127562

Kedward, K., Ryan-Collins, J., & Chenet, H. (2022). Biodiversity loss and climate change interactions: Financial stability implications for central banks and financial supervisors. *Climate Policy*, 1–19. https://doi.org/10.1080/14693062.2022.2107475

Keller, D. P., Lenton, A., Littleton, E. W., Oschlies, A., Scott, V. & Vaughan, N. E. (2018). The effects of carbon dioxide removal on the carbon cycle. *Current Climate Change Reports*, 4(3), 250-265. https://doi.org/10.1007/s40641-018-0104-3

Kemfert, C., Präger, F., Braunger, I., Hoffart, F. M., & Brauers, H. (2022). The expansion of natural gas infrastructure puts energy transitions at risk. *Nature Energy*, *7*(7). https://doi.org/10.1038/s41560-022-01060-3

Keppler, L., Landschützer, P., Lauvset, S. K., & Gruber, N. (2023). Recent Trends and Variability in the Oceanic Storage of Dissolved Inorganic Carbon. *Global Biogeochemical Cycles*, *37*(5), 1–25. https://doi.org/10.1029/2022GB007677

Kerr, N., & Winskel, M. (2022). Have we been here before? Reviewing evidence of energy technology phase-out to inform home heating transitions. *Energy Research & Social Science*, *89*, 1–25. https://doi.org/10.1016/j.erss.2022.102640

Khatun, F., Ahsan, Md. N., Afrin, S., Warner, J., Ahsan, R., Mallick, B., & Kumar, P. (2022). Environmental non-migration as adaptation in hazard-prone areas: Evidence from coastal Bangladesh. *Global Environmental Change*, *77*, 1–16. https://doi.org/10.1016/j.gloenvcha.2022.102610

Kim, S. K., Shin, J., An, S. I., Kim, H. J., Im, N., Xie, S. P., Kug, J. S., & Yeh, S. W. (2022). Widespread irreversible changes in surface temperature and precipitation in response to CO_2 forcing. *Nature Climate Change*, *12*(9), 834–840. https://doi.org/10.1038/s41558-022-01452-z

Klepp, S., & Fünfgeld, H. (2022). Tackling knowledge and power: An environmental justice perspective on climate change adaptation in Kiribati. *Climate and Development*, *14*(8), 757–769. https://doi.org/10.1080/17565529.2021.1984866

Kühne, K., Bartsch, N., Tate, R. D., Higson, J., & Habet, A. (2022). “Carbon Bombs”—Mapping key fossil fuel projects. *Energy Policy*, *166*, 1–10. https://doi.org/10.1016/j.enpol.2022.112950

Lapola, D. M., Pinho, P., Barlow, J., Aragão, L. E., Berenguer, E., Carmenta, R., Liddy, H.M., Seixas H., Silva C. V. J., Silva-Junior C. H. L., Alencar A. A. C., Anderson L. O., Armenteras D., Brovkin V., Calders K., Chambers J., Chini L., Costa M. H., Faria B. L., … Walker, W. S. (2023). The drivers and impacts of Amazon forest degradation. *Science*, 379(6630), eabp8622. https://doi.org/10.1126/science.abp8622

Le Grix, N., Zscheischler, J., Rodgers, K. B., Yamaguchi, R., & Frölicher, T. L. (2022). Hotspots and drivers of compound marine heatwaves and low net primary production extremes. *Biogeosciences*, *19*(24), 5807–5835. https://doi.org/10.5194/bg-19-5807-2022

Leonard, M., Westra, S., Phatak, A., Lambert, M., van den Hurk, B., McInnes, K., Risbey, J., Schuster, S., Jakob, D., & Stafford-Smith, M. (2013). A compound event framework for understanding extreme impacts. *WIREs Climate Change*, *5*(1), 113–128. https://doi.org/10.1002/wcc.252

Lesk, C., Anderson, W., Rigden, A., Coast, O., Jägermeyr, J., McDermid, S., Davis, K. F., & Konar, M. (2022). Compound heat and moisture extreme impacts on global crop yields under climate change. *Nature Reviews Earth & Environment*, *3*(12). https://doi.org/10.1038/s43017-022-00368-8

Li, M., Jia, N., Lenzen, M., Malik, A., Wei, L., Jin, Y., & Raubenheimer, D. (2022). Global food-miles account for nearly 20% of total food-systems emissions. *Nature Food*, *3*(6), 445–453. https://doi.org/10.1038/s43016-022-00531-w

Li, N., Sippel, S., Winkler, A. J., Mahecha, M. D., Reichstein, M., & Bastos, A. (2022). Interannual global carbon cycle variations linked to atmospheric circulation variability. *Earth System Dynamics*, *13*(4), 1505–1533. https://doi.org/10.5194/esd-13-1505-2022

Liu, L., Ciais, P., Wu, M., Padrón, R. S., Friedlingstein, P., Schwaab, J., Gudmundsson, L., & Seneviratne, S. I. (2023). Increasingly negative tropical water–interannual CO_2 growth rate coupling. *Nature*, 1–6. https://doi.org/10.1038/s41586-023-06056-x

Liu, Q., Peng, C., Schneider, R., Cyr, D., McDowell, N. G., & Kneeshaw, D. (2023). Drought-induced increase in tree mortality and corresponding decrease in the carbon sink capacity of Canada's boreal forests from 1970 to 2020. *Global Change Biology*, *29*(8), 2274–2285. https://doi.org/10.1111/gcb.16599

Lund, D. (2021). Navigating slow-onset risks through foresight and flexibility in Fiji: Emerging recommendations for the planned relocation of climate-vulnerable communities. *Current Opinion in Environmental Sustainability*, *50*, 12–20. https://doi.org/10.1016/j.cosust.2020.12.004

Lutz, A., & Biemans, H. (2022). Projecting changes in the water sources used for irrigation in South Asia. *Nature Climate Change*, 12(6), 514-515. https://doi.org/10.1038/s41558-022-01360-2

Mallick, B., Best, K., Carrico, A., Ghosh, T., Priodarshini, R., Sultana, Z., & Samanta, G. (2023). How do migration decisions and drivers differ against extreme environmental events? *Environmental Hazards*, 1–23. https://doi.org/10.1080/17477891.2023.2195152

Mallick, B., Priovashini, C., & Schanze, J. (2023). "I can migrate, but why should I?"—Voluntary non-migration despite creeping environmental risks. *Humanities and Social Sciences Communications*, *10*, 1–14. https://doi.org/10.1057/s41599-023-01516-1

Mallick, B., Rogers, K. G., & Sultana, Z. (2022). In harm's way: Non-migration decisions of people at risk of slow-onset coastal hazards in Bangladesh. *Ambio*, *51*, 114–134. https://doi.org/10.1007/s13280-021-01552-8

Mariani, G., Moullec, F., Atwood, T. B., Clarkson, B., Conant, R. T., Cullen-Unsworth, L., Griscom, B., Gutt, J., Howard, J., Krause-Jensen, D., Leavitt, S. M., Lee, S. Y., Livesley, S. Y., Macreadie, P. I., St-John, M., Zganjar, C., Cheung, W. W. L., Duarte, C. M., Shin, Y. J., … Mouillot, D. (in revision). Co-benefits and trade-offs between Natural Climate Solutions and Sustainable Development Goals. *Frontiers in Ecology and the Environment*.

Marske, K. A., Lanier, H. C., Siler, C. D., Rowe, A. H., & Stein, L. R. (2023). Integrating biogeography and behavioral ecology to rapidly address biodiversity loss. *Proceedings of the National Academy of Sciences*, *120*(15), 1–10. https://doi.org/10.1073/pnas.2110866120

Martín, E. G., Giordano, R., Pagano, A., Van Der Keur, P. & Costa, M.M. (2020). Using a system thinking approach to assess the contribution of nature based solutions to sustainable development goals. *Science of the Total Environment*, 738, p.139693. https://doi.org/10.1016/j.scitotenv.2020.139693

Martin, M. A., Alcaraz Sendra, O., Bastos, A., Bauer, N., Bertram, C., Blenckner, T., Bowen, K., Brando, P. M., Brodie Rudolph, T., Büchs, M., Bustamante, M., Chen, D., Cleugh, H., Dasgupta, P., Denton, F., Donges, J. F., Donkor, F. K., Duan, H., Duarte, C. M., … Woodcock, J. (2021). Ten new insights in climate science 2021: A horizon scan. *Global Sustainability*, *4*(e25), 1–20. https://doi.org/10.1017/sus.2021.25

Martin, M. A., Boakye, E. A., Boyd, E., Broadgate, W., Bustamante, M., Canadell, J. G., Carr, E. R., Chu, E. K., Cleugh, H., Csevar, S., Daoudy, M., Bremond, A. de, Dhimal, M., Ebi, K. L., Edwards, C., Fuss, S., Girardin, M. P., Glavovic, B., Hebden, S., … Zhao, Z. J. (2022). Ten new insights in climate science 2022. *Global Sustainability*, *5*, 1–20. https://doi.org/10.1017/sus.2022.17

McGreevy, S. R., Rupprecht, C. D. D., Niles, D., Wiek, A., Carolan, M., Kallis, G., Kantamaturapoj, K., Mangnus, A., Jehlička, P., Taherzadeh, O., Sahakian, M., Chabay, I., Colby, A., Vivero-Pol, J.-L., Chaudhuri, R., Spiegelberg, M., Kobayashi, M., Balázs, B., Tsuchiya, K., … Tachikawa, M. (2022). Sustainable agrifood systems for a post-growth world. *Nature Sustainability*, *5*(12), 1011–1017. https://doi.org/10.1038/s41893-022-00933-5

McMichael, C., Katonivualiku, M., & Powell, T. (2019). Planned relocation and everyday agency in low-lying coastal villages in Fiji. *The Geographical Journal*, *185*(3), 325–337. https://doi.org/10.1111/geoj.12312

Meinshausen, M., Lewis, J., McGlade, C., Gütschow, J., Nicholls, Z., Burdon, R., Cozzi, L., & Hackmann, B. (2022). Realization of Paris Agreement pledges may limit warming just below 2 °C. *Nature*, *604*(7905), 304–309. https://doi.org/10.1038/s41586-022-04553-z

Mercer, L., & Burke, J. (2023). *Strengthening MRV standards for greenhouse gas removals to improve climate change governance*. Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London School of Economics and Political Science. https://www.lse.ac.uk/granthaminstitute/publication/strengthening-mrv-standards-for-greenhouse-gas-removals/

Meyer, A. L. S., Bentley, J., Odoulami, R. C., Pigot, A. L., & Trisos, C. H. (2022). Risks to biodiversity from temperature overshoot pathways. *Philosophical Transactions of the Royal Society Biological Science*, *377*(1857), 1–11. https://doi.org/10.1098/rstb.2021.0394

Michaelowa, A., Honegger, M., Poralla, M., Winkler, M., Dalfiume, S., & Nayak, A. (2023). International carbon markets for carbon dioxide removal. *PLOS Climate*, *2*(5), e0000118. https://doi.org/10.1371/journal.pclm.0000118

Mignot, A., von Schuckmann, K., Landschützer, P., Gasparin, F., van Gennip, S., Perruche, C., Lamouroux, J., & Amm, T. (2022). Decrease in air-sea CO_2 fluxes caused by persistent marine heatwaves. *Nature Communications*, *13*, 1–9. https://doi.org/10.1038/s41467-022-31983-0

Millan, R., Mouginot, J., Rabatel, A., & Morlighem, M. (2022). Ice velocity and thickness of the world's glaciers. *Nature Geoscience*, *15*(2), 124–129. https://doi.org/10.1038/s41561-021-00885-z

Mombauer, D., Link, A. C., & van der Geest, K. (2023). Addressing climate-related human mobility through NDCs and NAPs: State of play, good practices, and the ways forward. *Frontiers in Climate*, 5, 1125936.

Mosnier, A., Javalera-Rincon, V., Jones, S. K., Andrew, R., Bai, Z., Baker, J., Basnet, S., Boer, R., Chavarro, J., Costa, W., Daloz, A. S., DeClerck, F. A., Diaz, M., Douzal, C., Howe Fan, A. C., Fetzer, I., Frank, F., Gonzalez-Abraham, C. E., Habiburrachman, A. H. F., … Zerriffi, H. (2023). A decentralized approach to model national and global food and land use systems. *Environmental Research Letters*, *18*(4), 045001. https://doi.org/10.1088/1748-9326/acc044

Moullec, F., Barrier, N., Drira, S., Guilhaumon, F., Hattab, T., Peck, M. A., & Shin, Y.-J. (2022). Using species distribution models only may underestimate climate change impacts on future marine biodiversity. *Ecological Modelling*, *464*, 1–11. https://doi.org/10.1016/j.ecolmodel.2021.109826

Müller, J. D., Gruber, N., Carter, B. R., Feely, R. A., Ishii, M., Lange, N., Lauvset, S. K., Murata, A. M., Olsen, A., Pérez, F. F., Sabine, C. L., Tanhua, T., Wanninkhof, R., & Zhu, D. (2023). *Decadal Trends in the Oceanic Storage of Anthropogenic Carbon from 1994 to 2014* [Preprint]. https://doi.org/10.22541/essoar.167525217.76035050/v1

Muttitt, G., & Kartha, S. (2020). Equity, climate justice and fossil fuel extraction: Principles for a managed phase out. *Climate Policy*, *20*(8), 1024–1042. https://doi.org/10.1080/14693062.2020.1763900

Muttitt, G., Price, J., Pye, S., & Welsby, D. (2023). Socio-political feasibility of coal power phase-out and its role in mitigation pathways. *Nature Climate Change*, *13*(2), 140–147. https://doi.org/10.1038/s41558-022-01576-2

Naser, M. M., Mallick, B., Priodarshini, R., Huq, S., & Bailey, A. (2023). Policy challenges and responses to environmental non-migration. *Npj Climate Action*, *2*(5), 1–9. https://doi.org/10.1038/s44168-023-00033-w

Niggli, L., Huggel, C., Muccione, V., Neukom, R., & Salzmann, N. (2022). Towards improved understanding of cascading and interconnected risks from concurrent weather extremes: Analysis of historical heat and drought extreme events. *PLOS Climate*, *1*(8), e0000057. https://doi.org/10.1371/journal.pclm.0000057

Nsafon, B. E. K., Same, N. N., Yakub, A. O., Chaulagain, D., Kumar, N. M., & Huh, J.-S. (2023). The justice and policy implications of clean energy transition in Africa. *Frontiers in Environmental Science*, *11*. https://www.frontiersin.org/articles/10.3389/fenvs.2023.1089391

Obura, D., Gudka, M., Samoilys, M., Osuka, K., Mbugua, J., Keith, D. A., Porter, S., Roche, R., Van Hooidonk, R., Ahamada, S., Araman, A., Karisa, J., Komakoma, J., Madi, M., Ravinia, I., Razafindrainibe, H., Yahya, S., & Zivane, F. (2021). Vulnerability to collapse of coral reef ecosystems in the Western Indian Ocean. *Nature Sustainability*, *5*(2), 104–113. https://doi.org/10.1038/s41893-021-00817-0

Oh, J. H., An, S. I., Shin, J., & Kug, J. S. (2022). Centennial Memory of the Arctic Ocean for Future Arctic Climate Recovery in Response to a Carbon Dioxide Removal. *Earth's Future*, *10*(8), 1–12. https://doi.org/10.1029/2022EF002804

Orlove, B. (2022). The Concept of Adaptation. *Annual Review of Environment and Resources*, *47*, 535–581. https://doi.org/10.1146/annurev-environ-112320-095719

Orlove, B., Sherpa, P., Dawson, N., Adelekan, I., Alangui, W., Carmona, R., Coen, D., Nelson, M. K., Reyes-García, V., Rubis, J., Sanago, G., & Wilson, A. (2023). Placing diverse knowledge systems at the core of transformative climate research. *Ambio*, 1–17. https://doi.org/10.1007/s13280-023-01857-w

Pachauri, S., Pelz, S., Bertram, C., Kreibiehl, S., Rao, N. D., Sokona, Y., & Riahi, K. (2022). Fairness considerations in global mitigation investments. *Science*, *378*(6624), 1057–1059. https://doi.org/10.1126/science.adf0067

Pandey, A., Prakash, A., & Werners, S. E. (2021). Matches, mismatches and priorities of pathways from a climate-resilient development perspective in the mountains of Nepal. *Environmental Science & Policy*, *125*, 135–145. https://doi.org/10.1016/j.envsci.2021.08.013

Pathmeswaran, C., Sen Gupta, A., Perkins-Kirkpatrick, S. E., & Hart, M. A. (2022). Exploring Potential Links Between Co-occurring Coastal Terrestrial and Marine Heatwaves in Australia. *Frontiers in Climate*, *4*. https://www.frontiersin.org/articles/10.3389/fclim.2022.792730

Paul, B. K., Rahman, M. K., Lu, M., & Crawford, T. W. (2022). Household Migration and Intentions for Future Migration in the Climate Change Vulnerable Lower Meghna Estuary of Coastal Bangladesh. *Sustainability*, *14*(8), 1–17. https://doi.org/10.3390/su14084686

Pigot, A. L., Merow, C., Wilson, A., & Trisos, C. H. (2023). Abrupt expansion of climate change risks for species globally. *Nature Ecology & Evolution*, 1–24. https://doi.org/10.1038/s41559-023-02070-4

Pihl, E., Alfredsson, E., Bengtsson, M., Bowen, K. J., Broto, V. C., Chou, K. T., Cleugh, H., Ebi, K., Edwards, C. M., Fisher, E., Friedlingstein, P., Godoy-Faúndez, A., Gupta, M., Harrington, A. R., Hayes, K., Hayward, B. M., Hebden, S. R., Hickmann, T., Hugelius, G., … Zelinka, M. D. (2021). Ten new insights in climate science 2020 – a horizon scan. *Global Sustainability*, *4*, 1–18. https://doi.org/10.1017/sus.2021.2

Pisor, A. C., Basurto, X., Douglass, K. G., Mach, K. J., Ready, E., Tylianakis, J. M., Hazel, A., Kline, M. A., Kramer, K. L., Lansing, J. S., Moritz, M., Smaldino, P. E., Thornton, T. F., & Jones, J. H. (2022). Effective climate change adaptation means supporting community autonomy. *Nature Climate Change*, *12*(3), 213–215. https://doi.org/10.1038/s41558-022-01303-x

Pongratz, J., Schwingshackl, C., Bultan, S., Obermeier, W., Havermann, F., & Guo, S. (2021). Land Use Effects on Climate: Current State, Recent Progress, and Emerging Topics. *Current Climate Change Reports*, *7*(4), 99–120. https://doi.org/10.1007/s40641-021-00178-y

Pörtner, H. O., Scholes, R. J., Agard, J., Archer, E., Arneth, A., Bai, X., Barnes, D., Burrows, M., Chan, L., Cheung, W. L., Diamond, S., Donatti, C., Duarte, C., Eisenhauer, N., Foden, W., Gasalla, M. A., Hanada, C., Hickler, T., Hoegh-Guldberg, O., … Ngo, H. T. (2021). *Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change*. IPBES secretariat. DOI: 10.5281/zenodo.4659158

Powis, C. M., Smith, S. M., Minx, J. C., & Gasser, T. (2023). Quantifying global carbon dioxide removal deployment. *Environmental Research Letters*, *18*(2), 024022. https://doi.org/10.1088/1748-9326/acb450

Prado, A., & Mac Dowell, N. (2023). The cost of permanent carbon dioxide removal. *Joule*, *7*(4), 700–712. https://doi.org/10.1016/j.joule.2023.03.006

Prakash, A. (2020). *Retreating Glaciers and Water Flows in the Himalayas: Implications for Governance*. Observer Research Foundation.

Rahman, M. F., Falzon, D., Robinson, S., Kuhl, L., Westoby, R., Omukuti, J., Schipper, E. L. F., McNamara, K. E., Resurrección, B. P., Mfitumukiza, D., & Nadiruzzaman, Md. (2023). Locally led adaptation: Promise, pitfalls, and possibilities. *Ambio*, 1–15. https://doi.org/10.1007/s13280-023-01884-7

Rainforest Action Network, Banktrack, Indigenous environmental network, Oilchange, Reclaim finance, Sierra club, & Urgewald. (2023). *Banking on Climate Chaos-Fossil Fuel Finance Report 2023*. https://www.bankingonclimatechaos.org

Raymond, C., Suarez-Gutierrez, L., Kornhuber, K., Pascolini-Campbell, M., Sillmann, J., & Waliser, D. E. (2022). Increasing spatiotemporal proximity of heat and precipitation extremes in a warming world quantified by a large model ensemble. *Environmental Research Letters*, *17*(3), 035005. https://doi.org/10.1088/1748-9326/ac5712

Rekker, S., Chen, G., Heede, R. (2023). Evaluating fossil fuel companies' alignment with 1.5 °C climate pathways. *Nat. Clim. Chang.* 13, 927–934 (2023). https://doi.org/10.1038/s41558-023-01734-0

Rikani, A., Otto, C., Levermann, A., & Schewe, J. (2023). More people too poor to move: Divergent effects of climate change on global migration patterns. *Environmental Research Letters*, *18*(2), 1–12. https://doi.org/10.1088/1748-9326/aca6fe

Roebroek, C. T. J., Duveiller, G., Seneviratne, S. I., Davin, E. L., & Cescatti, A. (2023). Releasing global forests from human management: How much more carbon could be stored? *Science*, *380*(6646), 749–753. https://doi.org/10.1126/science.add5878

Rohatyn, S., Yakir, D., Rotenberg, E., & Carmel, Y. (2022). Limited climate change mitigation potential through forestation of the vast dryland regions. *Science*, *377*(6613), 1436–1439. https://doi.org/10.1126/science.abm9684

Rosan, T. M., Sitch, S., Mercado, L. M., Heinrich, V., Friedlingstein, P., & Aragão, L. E. O. C. (2022). Fragmentation-Driven Divergent Trends in Burned Area in Amazonia and Cerrado. *Frontiers in Forests and Global Change*, *5*(801408), 1–10. https://doi.org/10.3389/ffgc.2022.801408

Rosan, T. M., Sitch, S., O'Sullivan, M., Basso, L., Wilson, C., Silva, C. V. J., Gloor, M., Fawcett, D., Heinrich, V., De Souza, J. G., Bezerra, F., Von Randow, C., Mercado, L., Gatti, L., Wiltshire, A., Friedlingstein, P., Pongratz, J., Schwingshackl, C., Williams, M., … Aragão, L. (2023). *Amazon forests a net carbon source during drought and under high rates of human-disturbance* [Preprint]. https://doi.org/10.21203/rs.3.rs-2598162/v1

Rosenthal, N., Benmarhnia, T., Ahmadov, R., James, E. & Marlier, M. E. 2022. Population co-exposure to extreme heat and wildfire smoke pollution in California during 2020. *Environmental Research: Climate*, 1(2), p.025004.

Rounce, D. R., Hock, R., Maussion, F., Hugonnet, R., Kochtitzky, W., Huss, M., Berthier, E., Brinkerhoff, D., Compagno, L., Copland, L., Farinotti, D., Menounos, B., & Mcnabb, R. W. (2023). Global glacier change in the 21st century: Every increase in temperature matters. *Science 379*(6627), 78-83.

Roy, J., Prakash, A., Some, S., Singh, C., Bezner Kerr, R., Caretta, M. A., Conde, C., Ferre, M. R., Schuster-Wallace, C., Tirado-von Der Pahlen, M. C., Totin, E., Vij, S., Baker, E., Dean, G., Hillenbrand, E., Irvine, A., Islam, F., McGlade, K., Nyantakyi-Frimpong, H., … Tandon, I. (2022). Synergies and trade-offs between climate change adaptation options and gender equality: A review of the global literature. *Humanities and Social Sciences Communications*, *9*(1), 1–13. https://doi.org/10.1057/s41599-022-01266-6

Saha, C. K., & Carter, A. V. (2022). Phase-out or lock-in fossil fuels? Least developed countries' burning dilemma. *The Extractive Industries and Society*, *11*, 101140. https://doi.org/10.1016/j.exis.2022.101140

Santos, C., & Mourato, J. M. (2022). 'I was born here, I will die here': Climate change and migration decisions from coastal and insular Guinea-Bissau. *Geografiska Annaler: Series B, Human Geography*, 1–19. https://doi.org/10.1080/04353684.2022.2154689

SBTi. (2020). *The Net-Zero Standard. Science Based Targets*. Science Based Targets Initiative. https://sciencebasedtargets.org/net-zero

Schewel, K. (2019). Understanding Immobility: Moving Beyond the Mobility Bias in Migration Studies. *International Migration Review*, *54*(2), 328–355. https://doi.org/10.1177/0197918319831952

Schlumberger, J., Haasnoot, M., Aerts, J., & de Ruiter, M. (2022). Proposing DAPP-MR as a disaster risk management pathways framework for complex, dynamic multi-risk. *iScience*, *25*(10), 105219. https://doi.org/10.1016/j.isci.2022.105219

Schwinger, J., Asaadi, A., Steinert, N. J., & Lee, H. (2022). Emit now, mitigate later? Earth system reversibility under overshoots of different magnitudes and durations. *Earth Syst. Dyn.*, *13*(4), 1641–1665. https://doi.org/10.5194/esd-13-1641-2022

Seddon, N. (2022). Harnessing the potential of nature-based solutions for mitigating and adapting to climate change. *Science*, *376*(6600), 1410–1416. https://doi.org/10.1126/science.abn9668

Seddon, N., Smith, A., Smith, P., Key, I., Chausson, A., Girardin, C., House, J., Srivastava, S., & Turner, B. (2021). *Getting the message right on nature-based solutions to climate change*. *27*, 1518–1546. https://doi.org/10.1111/gcb.15513

SEI, Climate Analytics, E3G, IISD, & UNEP (2023). *The Production Gap: Phasing down or phasing up? Top fossil fuel producers plan even more extraction despite climate promises.* Stockholm Environment Institute, Climate Analytics, E3G, International Institute for Sustainable Development and United Nations

Semieniuk, G., Chancel, L., Saïsset, E., Holden, P. B., Mercure, J.-F., & Edwards, N. R. (2023). Potential pension fund losses should not deter high-income countries from bold climate action. *Joule*, *0*(0). https://doi.org/10.1016/j.joule.2023.05.023

Semieniuk, G., Holden, P. B., Mercure, J.-F., Salas, P., Pollitt, H., Jobson, K., Vercoulen, P., Chewpreecha, U., Edwards, N. R., & Viñuales, J. E. (2022). Stranded fossil-fuel assets translate to major losses for investors in advanced economies. *Nature Climate Change*, *12*(6), 532–538. https://doi.org/10.1038/s41558-022-01356-y

Seneviratne, S., Nicholls, N., Easterling, D., Goodess, C., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., Zhang, X., Alexander, L. V., Allen, S., Benito, G., Cavazos, T., Clague, J., … Zwiers, F. W. (2012). *Changes in climate extremes and their impacts on the natural physical environment*. 109–230. https://doi.org/10.7916/d8-6nbt-s431

Sexton, A. E., Garnett, T., & Lorimer, J. (2019). Framing the future of food: The contested promises of alternative proteins. *Environment and Planning E: Nature and Space*, 2(1), 47–72. https://doi.org/10.1177/2514848619827009

Sharma, E., Molden, D., Rahman, A., Khatiwada, Y. R., Zhang, L., Singh, S. P., Yao, T., & Wester, P. (2019). Introduction to the Hindu Kush Himalaya Assessment. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya Assessment* (pp. 1–16). Springer International Publishing. https://doi.org/10.1007/978-3-319-92288-1_1

Shin, Y., Midgley, G. F., Archer, E. R. M., Arneth, A., Barnes, D. K. A., Chan, L., Hashimoto, S., Hoegh‐Guldberg, O., Insarov, G., Leadley, P., Levin, L. A., Ngo, H. T., Pandit, R., Pires, A. P. F., Pörtner, H., Rogers, A. D., Scholes, R. J., Settele, J., & Smith, P. (2022). Actions to halt biodiversity loss generally benefit the climate. *Global Change Biology*, *28*(9), 2846–2874. https://doi.org/10.1111/gcb.16109

Siddiqui, T., Bhuiyan, Md. R. A., Das, P. K., Chakraborty, G., & Hasan, M. (2018). *Accommodating migration in climate change adaptation: A GBM delta Bangladesh perspective*. Refugee and Migratory Movements Research Unit.

Simpson, N. P., Williams, P. A., Mach, K. J., Berrang-Ford, L., Biesbroek, R., Haasnoot, M., Segnon, A. C., Campbell, D., Musah-Surugu, J. I., & Joe, E. T. (2023). Adaptation to compound climate risks: A systematic global stocktake. *iScience*, *26*(2). https://doi.org/10.1038/s41893-022-01024-1

Singh, S., Tanvir Hassan, S. M., Hassan, M., & Bharti, N. (2020). Urbanisation and water insecurity in the Hindu

Kush Himalaya: Insights from Bangladesh, India, Nepal and Pakistan. *Water Policy*, *22*(S1), 9–32. https://doi.org/10.2166/wp.2019.215

Singh, U., & Colosi, L. M. (2021). The case for estimating carbon return on investment (CROI) for CCUS platforms. *Applied Energy*, *285*, 116394. https://doi.org/10.1016/j.apenergy.2020.116394

Skjølsvold, T. M., & Coenen, L. (2021). Are rapid and inclusive energy and climate transitions oxymorons? Towards principles of responsible acceleration. *Energy Research & Social Science*, *79*, 1–7. https://doi.org/10.1016/j.erss.2021.102164

Smiley, K. T., Noy, I., Wehner, M. F., Frame, D., Sampson, C. C., & Wing, O. E. J. (2022). Social inequalities in climate change-attributed impacts of Hurricane Harvey. *Nature Communications*, *13*(1), 1–10. https://doi.org/10.1038/s41467-022-31056-2

Smith, M. R., Mueller, N. D., Springmann, M., Sulser, T. B., Garibaldi, L. A., Gerber, J., Wiebe, K., & Myers, S. S. (2022). The lost opportunity from insufficient pollinators for global food supplies and human health. *The Lancet Planetary Health*, *6*, 1. https://doi.org/10.1016/S2542-5196(22)00265-0

Smith, S. M., Geden, O., Nemet, G. F., Gidden, M. J., Lamb, W. F., Powis, C., Bellamy, R., Callaghan, M. W., Cowie, A., Cox, E., Fuss, S., Gasser, T., Grassi, G., Greene, J., Lück, S., Mohan, A., Müller-Hansen, F., Peters, G. P., Pratama, Y., … Minx, J. C. (2023). *The State of Carbon Dioxide Removal—1st Edition*. The State of Carbon Dioxide Removal. https://doi.org/10.17605/OSF.IO/W3B4Z

Sovacool, B. K., Baum, C. M., & Low, S. (2023). Reviewing the sociotechnical dynamics of carbon removal. *Joule*, *7*(1), 57–82. https://doi.org/10.1016/j.joule.2022.11.008

Steckel, J. C., & Jakob, M. (2022). To end coal, adapt to regional realities. *Nature*, *607*(7917), 29–31. https://doi.org/10.1038/d41586-022-01828-3

Stevens, N., Bond, W., Feurdean, A., & Lehmann, C. E. R. (2022). Grassy Ecosystems in the Anthropocene. *Annual Review of Environment and Resources*, *47*(1), 261–289. https://doi.org/10.1146/annurev-environ-112420-015211

Stoddard, I., Anderson, K., Capstick, S., Carton, W., Depledge, J., Facer, K., Gough, C., Hache, F., Hoolohan, C., Hultman, M., Hällström, N., Kartha, S., Klinsky, S., Kuchler, M., Lövbrand, E., Nasiritousi, N., Newell, P., Peters, G. P., Sokona, Y., … Williams, M. (2021). Three Decades of Climate Mitigation: Why Haven't We Bent the Global Emissions Curve? *Annual Review of Environment and Resources*, *46*(1), 653–689. https://doi.org/10.1146/annurev-environ-012220-011104

Taylor, C., Robinson, T. R., Dunning, S., Carr, J. R., & Westoby, M. (2023). Glacial lake outburst floods threaten millions globally. *Nature Communications*, *14*(1). https://doi.org/10.1038/s41467-023-36033-x

Temmerman, S., Horstman, E. M., Krauss, K. W., Mullarney, J. C., Pelckmans, I., & Schoutens, K. (2023). Marshes and Mangroves as Nature-Based Coastal Storm Buffers. *Annual Review of Marine Science*, *15*(1), 95–118. https://doi.org/10.1146/annurev-marine-040422-092951

Terlouw, T., Bauer, C., Rosa, L., & Mazzotti, M. (2021). Life cycle assessment of carbon dioxide removal technologies: A critical review. *Energy & Environmental Science*, *14*(4), 1701–1721. https://doi.org/10.1039/D0EE03757E

Thalheimer, L., Choquette-Levy, N., & Garip, F. (2022). Compound impacts from droughts and structural vulnerability on human mobility. *iScience*, *25*(12), 105491. https://doi.org/10.1016/j.isci.2022.105491

Thornton, F., Serraglio, D. A., & Thornton, A. (2023). Trapped or staying put: Governing immobility in the context of climate change. *Frontiers in Climate*, *5*, 1–8. https://doi.org/10.3389/fclim.2023.1092264

Tienhaara, K., Thrasher, R., Simmons, B. A., & Gallagher, K. P. (2022). Investor-state disputes threaten the global green energy transition. *Science*, *376*(6594), 701–703. https://doi.org/10.1126/science.abo4637

Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., Qin, Y., & Davis, S. J. (2019). Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. *Nature*, *572*(7769), 373–377. https://doi.org/10.1038/s41586-019-1364-3

Trencher, G., Rinscheid, A., Florentine, K., Truong, N., & Temocin, P. (2023). The evolution of "phase-out" as a bridging concept for sustainability: From pollution to climate change. *One Earth*, *in press*.

Trencher, G., Rinscheid, A., Rosenbloom, D., & Truong, N. (2022). The rise of phase-out as a critical decarbonisation approach: A systematic review. *Environmental Research Letters*, *17*(12), 1–28. https://doi.org/10.1088/1748-9326/ac9fe3

Tribaldos, T., & Kortetmäki, T. (2022). Just transition principles and criteria for food systems and beyond. *Environmental Innovation and Societal Transitions*, *43*, 244–256. https://doi.org/10.1016/j.eist.2022.04.005

Trout, K., Muttitt, G., Lafleur, D., Van de Graaf, T., Mendelevitch, R., Mei, L., & Meinshausen, M. (2022). Existing fossil fuel extraction would warm the world beyond 1.5 °C. *Environmental Research Letters*, *17*(6), 1–12. https://doi.org/10.1088/1748-9326/ac6228

Tschersich, J., & Kok, K. P. W. (2022). Deepening democracy for the governance toward just transitions in agri-food systems. *Environmental Innovation and Societal Transitions*, *43*, 358–374. https://doi.org/10.1016/j.eist.2022.04.012

Tschumi, E., Lienert, S., Bastos, A., Ciais, P., Gregor, K., Joos, F., Knauer, J., Papastefanou, P., Rammig, A., van der Wiel, K., Williams, K., Xu, Y., Zaehle, S., & Zscheischler, J. (2023). Large Variability in Simulated Response of Vegetation Composition and Carbon Dynamics to Variations in Drought-Heat Occurrence. *Journal of Geophysical Research: Biogeosciences*, *128*(4), 1–24. https://doi.org/10.1029/2022JG007332

Turnhout, E., Duncan, J., Candel, J., Maas, T. Y., Roodhof, A. M., DeClerck, F., & Watson, R. T. (2021). Do we need a new science-policy interface for food systems? *Science*, *373*(6559), 1093–1095. https://doi.org/10.1126/science.abj5263

Ulibarri, N., Ajibade, I., Galappaththi, E. K., Joe, E. T., Lesnikowski, A., Mach, K. J., Musah-Surugu, J. I., Nagle Alverio, G., Segnon, A. C., Siders, A. R., Sotnik, G., Campbell, D., Chalastani, V. I., Jagannathan, K., Khavhagali, V., Reckien, D., Shang, Y., Singh, C., & Zommers, Z. (2022). A global assessment of policy tools to support climate adaptation. *Climate Policy*, *22*(1), 77–96. https://doi.org/10.1080/14693062.2021.2002251

UN Press. (2023, March 30). *Secretary-General Calls on States to Tackle Climate Change 'Time Bomb' through New Solidarity Pact, Acceleration Agenda, at Launch of Intergovernmental Panel Report.* United Nations. Meetings Coverage and Press Releases. https://press.un.org/en/2023/sgsm21730.doc.htm

UNEP. (2022a). *Adaptation Gap Report 2022: Too Little, Too Slow – Climate adaptation failure puts world at risk*. United Nations Environment Programme: Nairobi.

UNEP. (2022b). *Emissions Gap Report 2022: The Closing Window—Climate crisis calls for rapid transformation of societies*. United Nations Environment Programme: Nairobi.

UNEP. (2023). *Adaptation Gap Report*. The UNEP Adaptation Gap Report (AGR) Series. http://www.unep.org/resources/adaptation-gap-report

UNFCCC. (2022). *Nationally determined contributions under the Paris Agreement* [Synthesis report by the secretariat]. https://unfccc.int/documents/619180

United in Science. (2022). *United In Science 2022*. World Meteorological Organization, Global Carbon Project, UN Environment Programme, Met Office, Urban Climate Change Research Network, UN Office for Disaster Risk Reduction, World Climate Research Programme, Intergovernmental Panel on Climate Change.

van Asselt, H., & Newell, P. (2022). Pathways to an International Agreement to Leave Fossil Fuels in the Ground. *Global Environmental Politics* 2022; 22 (4): 28–47. doi: https://doi.org/10.1162/glep_a_00674

van der Geest, K., de Sherbinin, A., Gemenne, F., & Warner, K. (2023). Climate migration research and policy connections: Progress since the Foresight Report. *Frontiers in Climate*, 5, 1231679.

van den Hurk, B. J. J. M., White, C. J., Ramos, A. M., Ward, P. J., Martius, O., Olbert, I., Roscoe, K., Goulart, H. M. D., & Zscheischler, J. (2023). Consideration of compound drivers and impacts in the disaster risk reduction cycle. *IScience*, *26*(3), 106030. https://doi.org/10.1016/j.isci.2023.106030

van der Ven, D. J. van de, Mittal, S., Gambhir, A., Lamboll, R. D., Doukas, H., Giarola, S., Hawkes, A., Koasidis, K., Köberle, A. C., McJeon, H., Perdana, S., Peters, G. P., Rogelj, J., Sognnaes, I., Vielle, M., & Nikas, A. (2023). A multimodel analysis of post-Glasgow climate targets and feasibility challenges. *Nature Climate Change*, *13*, 570–578. https://doi.org/10.1038/s41558-023-01661-0

Vasiliev, D., & Greenwood, S. (2021). *The role of climate change in pollinator decline across the Northern Hemisphere is underestimated*. *775*. https://doi.org/10.1016/j.scitotenv.2021.145788

Vautard, R., van Oldenborgh, G. J., Bonnet, R., Li, S., Robin, Y., Kew, S., Philip, S., Soubeyroux, J.-M., Dubuisson, B., Viovy, N., Reichstein, M., Otto, F., & Garcia de Cortazar-Atauri, I. (2023). Human influence on growing-period frosts like in early April 2021 in central France. *Natural Hazards and Earth System Sciences*, *23*(3), 1045–1058. https://doi.org/10.5194/nhess-23-1045-2023

Veh, G., Lützow, N., Tamm, J., Luna, L. V., Hugonnet, R., Vogel, K., Geertsema, M., Clague, J. J., & Korup, O. (2023). Less extreme and earlier outbursts of ice-dammed lakes since 1900. *Nature*, *614*(7949), 701–707. https://doi.org/10.1038/s41586-022-05642-9

Veldman, J. W., Aleman, J. C., Alvarado, S. T., Anderson, T. M., Archibald, S., Bond, W. J., Boutton, T. W., Buchmann, N., Buisson, E., Canadell, J. G., Dechoum, M. de S., Diaz-Toribio, M. H., Durigan, G., Ewel, J. J., Fernandes, G. W., Fidelis, A., Fleischman, F., Good, S. P., Griffith, D. M., … Zaloumis, N. P. (2019). Comment on “The global tree restoration potential.” *Science*, *366*(6463), eaay7976. https://doi.org/10.1126/science.aay7976

Walton, M. A. (2022). Energy security and the energy transition. In *Handbook on the Water-Energy-Food Nexus* (pp. 81–95). Edward Elgar Publishing. https://www.elgaronline.com/display/book/9781839100550/book-part-9781839100550-11.xml

Wentz, J., Merner, D., Franta, B., Lehmen, A., & Frumhoff, P. C. (2023). Research Priorities for Climate Litigation. *Earth’s Future*, *11*(1), 1–15. https://doi.org/10.1029/2022EF002928

Whyte, K. P. (2021). Indigenous peoples, climate change loss and damage, and the responsibilities of states. In *Research Handbook on Climate Change Law and Loss & Damage* (pp. 224–244). Edward Elgar Publishing. https://china.elgaronline.com/display/edcoll/9781788974011/9781788974011.00019.xm

Wiegel, H., Warner, J., Boas, I., & Lamers, M. (2021). Safe from what? Understanding environmental non-migration in Chilean Patagonia through ontological security and risk perceptions. *Regional Environmental Change*, 21. https://doi.org/10.1007/s10113-021-01765-3

Wiegel, H., Boas, I., & Warner, J. (2019). A mobilities perspective on migration in the context of environmental change. *WIREs Climate Change*, *10*(6), 1–9. https://doi.org/10.1002/wcc.610

Wilkes, M. A., Carrivick, J. L., Castella, E., Ilg, C., Cauvy-Fraunié, S., Fell, S. C., Füreder, L., Huss, M., James, W., Lencioni, V., Robinson, C., & Brown, L. E. (2023). Glacier retreat reorganizes river habitats leaving refugia for Alpine invertebrate biodiversity poorly protected. *Nature Ecology & Evolution*, *7*(6), 841–851. https://doi.org/10.1038/s41559-023-02061-5

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., De Vries, W., Majele Sibanda, L., … Murray, C. J. L. (2019). Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, *393*(10170), 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4

Williamson, P., & Gattuso, J.-P. (2022). Carbon Removal Using Coastal Blue Carbon Ecosystems Is Uncertain and Unreliable, With Questionable Climatic Cost-Effectiveness. *Frontiers in Climate*, *4,853666*. https://doi.org/10.3389/fclim.2022.853666

WMO. (2023a). *Global annual to decadal climate update*. World Meteorological Organization.

WMO. (2023b). *State of the Global Climate 2022*. World Meteorological Organization.

Wood, A., Queiroz, C., Deutsch, L., González-Mon, B., Jonell, M., Pereira, L., Sinare, H., Svedin, U., & Wassénius, E. (2023). Reframing the local–global food systems debate through a resilience lens. *Nature Food*, *4*(1), 22–29. https://doi.org/10.1038/s43016-022-00662-0

Woodhill, J., Kishore, A., Njuki, J., Jones, K., & Hasnain, S. (2022). Food systems and rural wellbeing: Challenges and opportunities. *Food Security*, *14*(5), 1099–1121. https://doi.org/10.1007/s12571-021-01217-0

Wunderling, N., Winkelmann, R., Rockström, J., Loriani, S., Armstrong McKay, D. I., Ritchie, P. D. L., Sakschewski, B., & Donges, J. F. (2023). Global warming overshoots increase risks of climate tipping cascades in a network model. *Nature Climate Change*, *13*(1), 75–82.

WWF. (2022). *Unlocking and Scaling Climate Solutions in Food Systems: An Assessment of Nationally Determined Contributions*. World Wildlife Fund. https://wwfint.awsassets.panda.org/downloads/unlocking_and_scaling_climate_solutions_in_food_systems___wwf_analysis_of_ndcs_2022.pdf

Yao, T., Bolch, T., Chen, D., Gao, J., Immerzeel, W., Piao, S., Su, F., Thompson, L., Wada, Y., Wang, L., Wang, T., Wu, G., Xu, B., Yang, W., Zhang, G., & Zhao, P. (2022). The imbalance of the Asian water tower. *Nature Reviews Earth & Environment*, *3*(10), 618–632. https://doi.org/10.1038/s43017-022-00299-4

Yasunaka, S., Manizza, M., Terhaar, J., Olsen, A., Yamaguchi, R., Landschützer, P., Watanabe, E., Carroll, D., Adiwara, H., Müller, J. D., & Hauck, J. (2023). *An assessment of CO_2 uptake in the Arctic Ocean from 1985 to 2018* [Accepted]

Yee, M., McNamara, K. E., Piggott-McKellar, A. E., & McMichael, C. (2022a). The role of Vanua in climate-related voluntary immobility in Fiji. *Frontiers in Climate*, *4*, 1–19. https://doi.org/10.3389/fclim.2022.1034765

Yee, M., Piggott-McKellar, A. E., McMichael, C., & McNamara, K. E. (2022b). Climate Change, Voluntary Immobility, and Place-Belongingness: Insights from Togoru, Fiji. *Climate*, *10*(3). https://doi.org/10.3390/cli10030046

Yin, J., Gentine, P., Slater, L., Gu, L., Pokhrel, Y., Hanasaki, N., Guo, S., Xiong, L., & Schlenker, W. (2023). Future socio-ecosystem productivity threatened by compound drought–heatwave events. *Nature Sustainability 6*, 1–14.

Zhang, G., Bolch, T., Yao, T., Rounce, D. R., Chen, W., Veh, G., King, O., Allen, S. K., Wang, M., & Wang, W. (2023). Underestimated mass loss from lake-terminating glaciers in the greater Himalaya. *Nature Geoscience*. https://doi.org/10.1038/s41561-023-01150-1

Zheng, G., Allen, S. K., Bao, A., Ballesteros-Cánovas, J. A., Huss, M., Zhang, G., Li, J., Yuan, Y., Jiang, L., Yu, T., Chen, W., & Stoffel, M. (2021). Increasing risk of glacial lake outburst floods from future Third Pole deglaciation. *Nature Climate Change*, *11*(5), 411–417. https://doi.org/10.1038/s41558-021-01028-3

Zheng, B., Ciais, P., Chevallier, F., Yang, H., Canadell, J. G., Chen, Y., van der Velde, I. R., Aben, I., Chuvieco, E., Davis, S. J., Deeter, M., Hong, C., Kong, Y., Li, H., Li, H., Lin, X., He, K., & Zhang, Q. (2023). Record-high CO_2 emissions from boreal fires in 2021. *Science*, *379*(6635), 912–917.

Zhu, Z., Duan, J., Dai, Z., Feng, Y., & Yang, G. (2023). Seeking sustainable solutions for human food systems. *Geography and Sustainability*, *4*(3), 183–187. https://doi.org/10.1016/j.geosus.2023.04.001

Zickfield, K., Azevedo, D., Mathesius, S., & Matthews, H.D. (2021). Asymmetry in the climate–carbon cycle response to positive and negative CO_2 emissions. *Nature Climate Change*, 11(7), 613–617, https://doi.org/10.1038/s41558-021-01061-2.

Zscheischler, J., & Lehner, F. (2022). Attributing Compound Events to Anthropogenic Climate Change. *Bulletin of the American Meteorological Society*, *103*(3), E936–E953. https://doi.org/10.1175/BAMS-D-21-0116.1

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R. M., van den Hurk, B., AghaKouchak, A., Jézéquel, A., Mahecha, M. D., Maraun, D., Ramos, A. M., Ridder, N. N., Thiery, W., & Vignotto, E. (2020). A typology of compound weather and climate events. *Nature Reviews Earth & Environment*, *1*(7). https://doi.org/10.1038/s43017-020-0060-z

Zscheischler, J., Westra, S., van den Hurk, B. J. J. M., Seneviratne, S. I., Ward, P. J., Pitman, A., AghaKouchak, A., Bresch, D. N., Leonard, M., Wahl, T., & Zhang, X. (2018). Future climate risk from compound events. *Nature Climate Change*, *8*(6). https://doi.org/10.1038/s41558-018-0156-3

Zurek, M., Hebinck, A., & Selomane, O. (2022). Climate change and the urgency to transform food systems. *Science*, *376*(6600), 1416–1421. https://doi.org/10.1126/science.abo2364