10 | NEW INSIGHTS IN CLIMATE SCIENCE

2023/2024

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Each year, Future Earth, the Earth League and the World Climate Research Programme gather leading scholars from around the world to review the most pressing findings in climate research. The result is the *10 New Insights in Climate Science*, delivered as two self-standing products: a peer-reviewed scientific article and this policy report providing a rich and valuable synthesis for policymakers and society at large. The scientific evidence underpinning this year's report was published between January 2022–June 2023.

For policymakers responding to the urgent challenge of the climate crisis, the *10 New Insights in Climate Science 2023/2024* offers credible guidance through 2024 and beyond.

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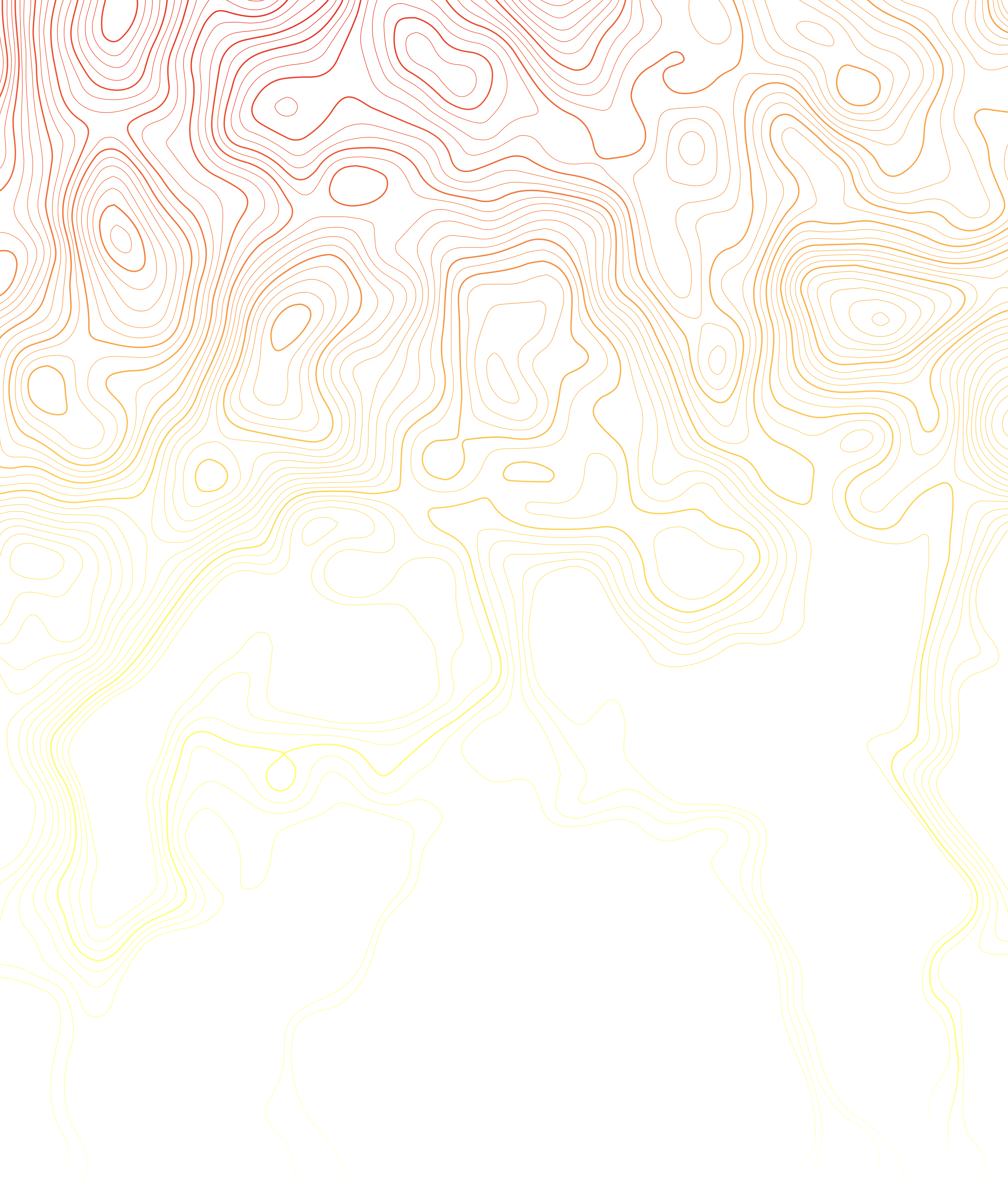

INSIGHTS AT A GLANCE

INSIGHTS AT A GLANCE

1. **Overshooting 1.5°C is fast becoming inevitable. Minimising the magnitude and duration of overshoot is essential.** Multiple lines of evidence indicate that, due to insufficient mitigation of greenhouse gases (GHGs), no pathway remains that avoids exceeding 1.5°C global warming for at least some decades, except for truly radical transformations. Minimising the magnitude and duration of the overshoot period is critical for reducing loss and damage and the risk of irreversible changes.

2. **A rapid and managed fossil fuel phase-out is required to stay within the Paris Agreement target range.** The fast-shrinking carbon budget means that governments and the private sector must stop enabling new fossil fuel projects, accelerate the early retirement of existing infrastructure, and rapidly increase the pace of renewable energy deployment. High-income countries must lead the transition and provide support for low-income countries. All countries should pursue an equitable and just transition, minimising socio-economic impacts on the most vulnerable segments of the population.

3. **Robust policies are critical to attain the scale needed for effective carbon dioxide removal (CDR).** While not a replacement for rapid and deep emissions reductions, CDR will be necessary to deal with hard-to-eliminate emissions and eventually to reduce the global temperature. Current CDR is predominantly forest-based, but rapid acceleration and deployment at scale of other CDR methods with permanent CO_2 removal is required, supported by stronger governance and better monitoring.

4. **Over-reliance on natural carbon sinks is a risky strategy: their future contribution is uncertain.** Until now, land and ocean carbon sinks have grown in tandem with increasing CO_2 emissions, but research is revealing uncertainty over how they will respond to additional climate change. Carbon sinks may well absorb less carbon in the future than has been presumed from existing assessments. Therefore, emission reduction efforts have immediate priority, with nature-based solutions (NbS) serving to increase carbon sinks in a complementary role to offset hard-to-abate emissions.

5. **Joint governance is necessary to address the interlinked climate and biodiversity emergencies.** The international conventions on climate change and biodiversity (United Nations Framework Convention on Climate Change and the Convention on Biological Diversity, respectively) must find better alignment. Ensuring that the allocation of climate finance has nature-positive safeguards, and strengthening concrete cross-convention collaboration, are examples of key actions in the right direction.

6. **Compound events amplify climate risks and increase their uncertainty.** “Compound events” refer to a combination of multiple drivers and/or hazards (simultaneous or sequential), and their impacts can be greater than the sum of individual events. Identifying and preparing for specific compound events is crucial for robust risk management and providing support in emergency situations.

7. **Mountain glacier loss is accelerating.** Deglaciation in response to climate change is even quicker in high mountain areas, including the Hindu Kush Himalayas and polar regions. This threatens populations downstream with water shortages in the longer term (approximately 2 billion worldwide), and exposes mountain dwellers to increased hazards, such as flash flooding.

8. **Human immobility in areas exposed to climate risks is increasing.** People facing climate risks may be unable or unwilling to relocate, and existing institutional frameworks do not account for immobility and are insufficient to anticipate or support the needs of these populations.

9. **New tools to operationalise justice enable more effective climate adaptation.** Monitoring the distinct dimensions of justice and incorporating them as part of strategic climate adaptation planning and evaluation can build resilience to climate change and decrease the risk of maladaptation.

10. **Reforming food systems contributes to just climate action.** Food systems have a key role to play in climate action, with viable mitigation options spanning from production to consumption. However, interventions should be designed with and for equity and justice as linked outcomes, and implementation of mitigation measures should be done inclusively with diverse stakeholders across multiple scales.

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INTRODUCTION

Decades of insufficient action for mitigating GHG emissions have set the world on the current trajectory to overshoot the internationally agreed target of limiting global warming to 1.5°C, enshrined in the Paris Agreement. National mitigation commitments are inadequate to even stay well below 2°C of global warming, creating unacceptable risks for human societies and ecosystems, with vast yet unequally distributed costs. This is a dangerous gamble that could lead to irreversible impacts for life on Earth, including devastating loss of biodiversity and a rising risk of triggering climate tipping points. So far in 2023, the world has witnessed devastating extreme weather events attributable to climate change, including the megafires in Canada, May–July, extreme rainfall and flooding as in Bulgaria, Greece, Libya, Spain and Turkey in September, and extreme heatwaves across Europe, Asia and the Americas.

This year, we explain the looming inevitability of overshooting 1.5°C global warming (Insight 1), a situation that will entail a significant increase in risks and uncertainty. We call attention to the fast-shrinking carbon budget and emphasise the inescapable need for a managed and equitable fossil fuel phase-out (Insight 2). Considering the significance of carbon dioxide removal (CDR) to achieve the long-term temperature goal,, we outline the challenges related to deployment at scale, accounting and governance (Insight 3). This is particularly pressing in the context of research revealing key uncertainties regarding the extent to which global warming negatively affects natural carbon sinks (Insight 4). This could complicate efforts towards temperature stabilisation and reversal, further adding to the urgency for decarbonising the global economy and being clear-sighted about the realistic role of CDR methods.

The research highlighted in this review points to the impending overshoot of 1.5°C in the short term (barring truly radical transformations). The risks we outline are an emphatic call to *minimise* overshoot, in both magnitude (by how much) and duration (for how long), while still acting to avoid it. New projects to expand fossil fuel infrastructure, including the so-called carbon bombs, while clearly incompatible with the Paris Agreement, are still being approved by parties to the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement. The expectations for COP28 will revolve around fossil fuel phase-out, a goal incorporated in the mandates of several governments and championed by the UN Secretary-General as part of the Acceleration Agenda at the Climate Ambition Summit 2023. To be successful, these negotiations must deliver on climate financing in support of just transitions in low- and middle-income countries.

In this report we stress the interwoven nature of biodiversity loss and climate change, requiring effective institutional cooperation for realising synergistic solutions (Insight 5). With climate impacts and vulnerabilities on the rise, this year's report features advances on the scientific understanding of "compound events" (Insight 6) and the acceleration of mountain glacier loss (Insight 7); both of which we highlight as priority issues for adaptation planning, especially due to their impacts on food and water security. The urgency for mitigation is reinforced by the urgency for adaptation, especially for the most vulnerable regions and segments of society. Yet this urgency does not justify impositions on local communities.

We devote one Insight to immobility in the face of climate risks (Insight 8), aiming to shed light on an often overlooked dimension of the complex relationship between human mobility and climate change. We dedicate the last two Insights to the need for climate action to be deeply reflective of the myriad interlinked sources and impacts of climate change, as well as potential co-benefits: incorporating, operationalising and centring justice in climate adaptation planning, emphasising the key role of locally led adaptation (LLA) efforts (Insight 9), and transforming food systems to reduce GHG emissions, while also increasing food security and biodiversity conservation, which can only happen with justice placed front and centre (Insight 10).

The Global Stocktake, while recognising the concerning trends resulting from insufficient climate action so far, should reinforce the international commitment to mitigation to avoid long-lasting overshoot and keep peak warming as close to 1.5°C as possible.

We hope that this year's *10 New Insights in Climate Science* will be reflected in the outcomes at COP28:

1. Taking unambiguous steps towards clear commitments for a managed phase-out of all fossil fuels, recognising the risks of prolonged overshoot, the uncertainties over the future of natural carbon sinks, and the remaining challenges for realising the complementary role of CDR.

2. Strengthening the international support for adaptation and preparedness plans, in the face of emerging risks resulting from current and committed levels of global warming.

3. Stressing the importance of food systems transformation as a key engine of climate action and climate justice.

4. Advancing the integration of climate change and biodiversity in international policy agendas, and further promoting a holistic and equitable systems transformation premised on the interconnectedness of the challenges facing life on Earth.

All statements in this report are based on the following article and the references provided therein: Bustamante, M., Roy, J., Ospina, D., et al. (2023). Ten New Insights in Climate Science 2023/2024. *Global Sustainability*.

10 NEW INSIGHTS IN CLIMATE SCIENCE

THE INSIGHTS

1 Overshooting 1.5°C is fast becoming inevitable. Minimising the magnitude and duration of overshoot is essential

KEY POINTS

- During overshoot of 1.5°C warming, risks become increasingly severe with every increment of global warming. Impacts for humans and ecosystems worsen in relation to the magnitude and duration of overshoot period (i.e. by how much and for how long temperatures exceed 1.5°C). Impacts include loss and damage due to heatwave exposure and other extreme events, especially in tropical countries, as well as accelerated loss of biodiversity.

- Minimising the magnitude and duration of overshoot is crucial. An overshoot of multiple decades holds significant risks of irreversible changes in regional climate. There is also considerable risk that a long period above 1.5°C could trigger self-perpetuating feedbacks, destabilising the Greenland or West Antarctic ice sheets, which would result in their almost complete and irreversible loss over multiple millennia and several metres of sea-level rise.

- Keeping global mean temperature rise within 1.5°C is only possible in the near term with immediate, transformative action that rapidly decarbonises the economy, energy and land-use systems, cutting emissions by 43% by 2030 relative to 2019 levels. Mitigation efforts will also have to be complemented with carefully selected CDR methods at scale (Insight 3).

INSIGHT EXPLAINED

Recent evidence shows that we are not on track to keep global warming below or at 1.5°C, implying an overshoot of the pathway to comply with the Paris Agreement. Continuing to emit GHGs at the current rate will use up our carbon budget for 1.5°C warming in the next six to seven years. Current policies, if fully implemented, take global temperatures well above 2°C by the end of this century. Even fulfilling all national short- and long-term climate pledges would almost certainly exceed warming of 1.5°C.

The peak level of global warming depends directly on cumulative CO_2 emissions, and this relationship determines the remaining carbon budget for the Paris Agreement temperature limits. The extent to which cumulative CO_2 emissions exceed the carbon budget consistent with 1.5°C warming determines the magnitude of the overshoot. The duration of the overshoot period is determined by how long it takes to achieve net-negative CO_2 emissions and thereby reduce CO_2 concentrations in the atmosphere (see In Focus box). Both the magnitude and duration of the overshoot will determine the extent of climate impacts, during the overshoot period and afterwards.

Governments, corporations and other actors must now focus on minimising the magnitude and duration overshoot, while still acting to avoid it. Although the implementation of strong mitigation measures this

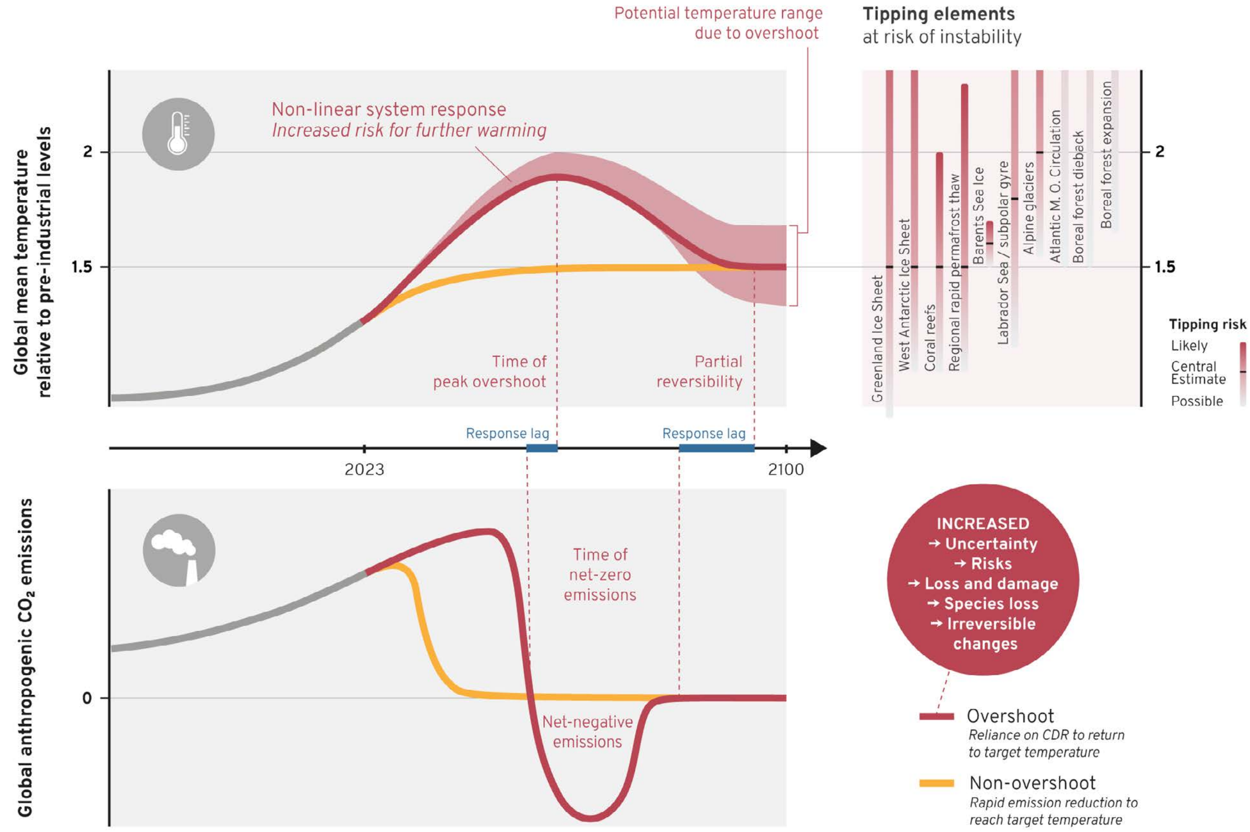

Figure 1. Stylised illustration of a temperature overshoot scenario (red line) and its risks in comparison with a non-overshoot scenario (yellow line) stabilising at 1.5°C through rapid emissions reductions and reaching net-zero emissions. The temperature of the overshoot pathway may not return to 1.5°C on reaching the same cumulative emissions as the non-overshoot scenario due to feedbacks and response lags in the Earth system components. Note that the tipping elements at risk of instability in the upper panel[1] only correspond to the global warming levels, not to the time axis.

decade to minimise the overshoot presents near-term challenges, postponing decisive action beyond 2030 raises feasibility concerns due to volatility and uncertainty caused by higher climate impacts (especially in low-income countries). Bringing temperatures down from peak overshoot will require every tonne of CO_2 exceeding the carbon budget for 1.5°C to be removed from the atmosphere through CDR technologies, which may be unfeasible due to high costs, or unacceptable at scale due to their social and ecological impacts (see Insight 3).

Widespread and potentially irreversible impacts worsen with higher magnitude and longer duration of overshoot. Exposure to extreme events, such as heatwaves, will exacerbate biodiversity loss and economic damage, particularly in tropical countries. Irreversible impacts are especially likely for marine biodiversity, with species facing the added pressure of prolonged ocean acidification after overshoot. An overshoot period of multiple decades would have a long-lasting legacy on the Earth system. This is because some key Earth system components respond slowly to temperature changes. In some regions, surface air temperature and precipitation may not return to pre-overshoot values for several hundred years. Other irreversible changes (timescales of centuries or more) include permafrost carbon loss, sea-level rise from ocean thermal expansion, melting of ice sheets, and changes in ocean acidity, oxygenation and temperature.

Furthermore, a long period above 2°C of warming carries a considerable risk of triggering self-perpetuating feedbacks leading to instabilities of the Greenland or West Antarctic ice sheets or mountain glaciers, largely irreversible even on timescales of centuries to millennia. The impacts could 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.

[1] Data for the tipping element risk assessment: Armstrong McKay et al. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*, 377(6611), eabn7950. doi: 10.1126/science.abn7950

IN FOCUS: REACHING NET-ZERO CO_2 EMISSIONS IS CRUCIAL FOR CONTAINING THE PEAK WARMING LEVEL

The world's ability to bring temperature down after exceeding 1.5°C warming, relative to the pre-Industrial era, depends on removing more CO_2 from the atmosphere than is emitted, or net-negative CO_2 emissions. There are significant unresolved questions regarding the feasibility, risks and effectiveness of CDR at scale, so achieving net-negative emissions is far from a given. If achieved, there will still be a delay of several years before the climate cools, due to lags in the carbon cycle and thermal response.

Moreover, there is a risk that during overshoot the release of GHGs from natural carbon sinks could be triggered in ways not yet clearly anticipated. Already now, elevated tree mortality events following droughts and heatwaves are being observed worldwide (see Insight 4). This could prolong the overshoot and increase the risk of irreversible impacts, and their potential magnitude.

POLICY IMPLICATIONS

If 1.5°C is exceeded, as is now likely based on past and current actions, decision-makers should continue to strive to limit warming as close to 1.5°C as possible. Arresting further rise is crucial: every fraction of a degree matters.

- Governments should urgently work to close the emission gap consistent with the Paris Agreement climate goals by implementing concrete measures in their existing nationally determined contributions (NDCs) – with sector-specific details for driving down emissions in the near term. But it is important to prepare for the impacts of overshooting 1.5°C, which will be geographically uneven and, in some cases, irreversible.

- Governments should urgently implement policies to catalyse systemic mitigation action, chiefly the phase-out of fossil fuels (see Insight 2), and transformations in other sectors (see Insight 10) to limit the degree of overshoot and its harmful impacts.

- Global collective action towards net-zero will determine the world's peak warming level and the associated costs and climate impacts. High-income countries should take the lead on setting net-negative targets and implementing measures accordingly. This will be essential to bring temperatures down and limit the duration of overshoot and its accumulating risks.

2 A rapid and managed fossil fuel phase-out is required to stay within the Paris Agreement target range

KEY POINTS

- The committed CO_2 emissions expected from existing fossil fuel infrastructure exceed the remaining carbon budget consistent with the Paris Agreement target temperature range. Yet governments, companies and investors continue expanding infrastructure for production and consumption of fossil fuels.
- Such investments risk creating stranded assets worth trillions of dollars and undermine decarbonisation efforts.
- Governments should implement a managed and equitable phase-out of fossil fuel production and consumption, promoting policy coherence and ensuring an accelerated and just energy transition as we scale up renewable energy systems.
- Further delaying action would require even more ambitious efforts later, increasing the cost and disruptiveness of the unavoidable energy transition.

INSIGHT EXPLAINED

Past climate mitigation efforts have been insufficient in phasing out fossil fuels from our energy systems and replacing them with clean energy sources at the speed required to stop dangerous planetary heating. Fossil-CO_2 emissions reached record highs in 2021–2022, as did government subsidies for fossil fuels. The CO_2 emissions expected over the lifetime of existing infrastructure for fossil fuel production and consumption already exceed the remaining carbon budget for a 50% chance of limiting long-term warming to 1.5°C (see Figure 2). But governments and companies worldwide still plan to extract vastly more fossil fuels than would be consistent with limiting warming to 1.5°C, with many also expanding their fossil fuel infrastructure. The development of any new long-lived fossil fuel infrastructure is wholly inconsistent with limiting warming to 1.5°C, and risks creating trillions of dollars of stranded assets (see In Focus box).

Potential asset stranding in the oil and gas extraction sector is estimated at over USD 1 trillion. Governments are directly exposed to this risk through state-owned companies, taxes and royalties, and indirectly via potential bailouts for stabilising the financial system. Consequently, governments and financial institutions need to actively plan for and implement a fossil fuel phase-out while accelerating the phase-in of renewable energy, aiming for a comprehensive and coordinated energy transition.

The challenges of a global fossil fuel phase-out are complicated especially by:

- Geopolitical considerations related to energy security.
- Energy poverty, especially in lower-income countries, and insufficient international support to diversify or leapfrog to clean energy systems and alternative development pathways.

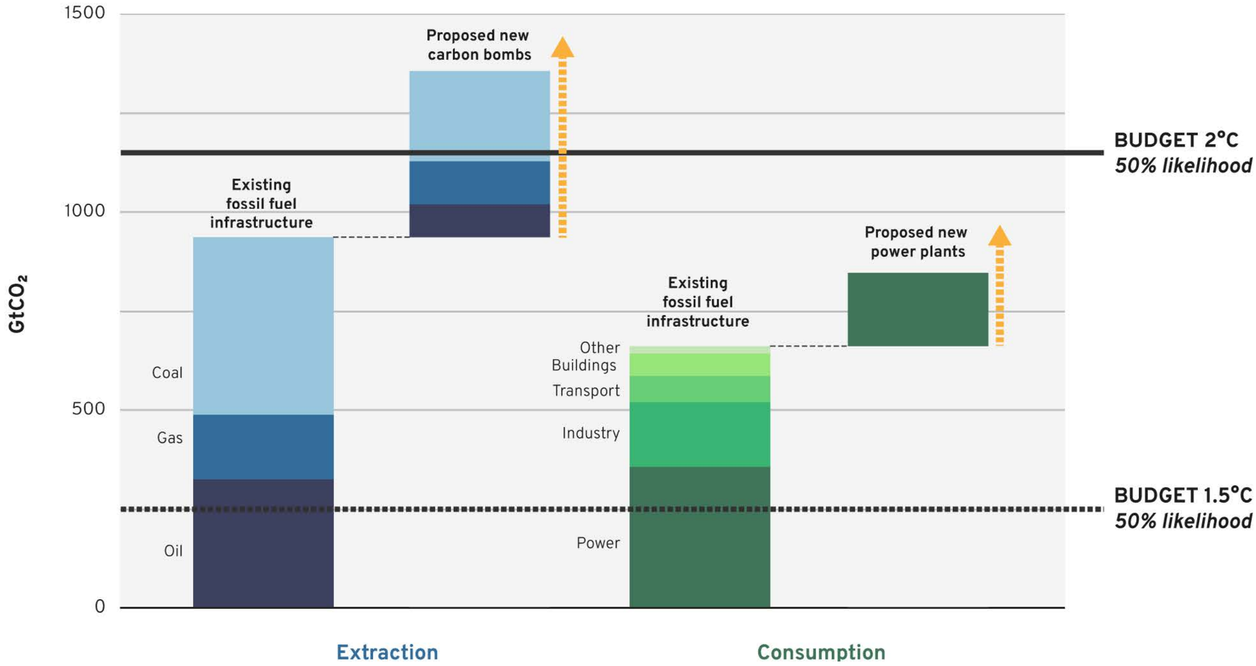

Figure 2. Committed CO_2 emissions from fossil fuel infrastructure compared with carbon budgets reflecting the Paris Agreement target range. The bars show future emissions arising from full-lifetime operation of fossil fuel-extracting infrastructure[2] and of fossil fuel-consuming infrastructure,[3] also showing proposed "carbon bombs",[4] defined as fossil fuel extraction projects whose lifetime emissions exceed 1 $GtCO_2$. These are compared with the remaining carbon budget as of early 2023.[5] Dotted yellow lines reflect uncertainty regarding the possibility that some new infrastructure projects may be cancelled.

- Heavy dependence on fossil fuel revenues in many countries.
- Fossil fuel interests that continue to undermine, delay and block climate action through lobbying, greenwashing and disinformation campaigns.

In recent years, several governments and international institutions have committed to phasing out fossil fuel production and consumption, and related investments. Examples include the Powering Past Coal Alliance, Beyond Oil & Gas Alliance, Fossil Fuel Non-Proliferation Treaty Initiative, and Clean Energy Transition Partnership ("Glasgow Statement"). However, many of the world's largest coal, oil or gas producers and consumers have yet to join such initiatives.

Another positive development is that several governments have recently withdrawn from the Energy Charter Treaty. This is an important step in preventing fossil fuel companies from using the treaties' investor-state dispute settlement to protect their investments by suing governments that act decisively to reduce emissions from this sector. Estimates suggest that governments could be subject to up to USD 340 billion in claims from oil and gas investors through such mechanisms.

Renewables are now the cheapest form of power in most parts of the world, and ample research charts pathways to achieve a clean, resilient and inclusive energy system globally. Governments must therefore direct all efforts towards phasing out all fossil fuels and scaling up renewable energy. Efforts should ensure energy access and affordability, and minimise impacts for communities and workers who are dependent on fossil fuels. An equitable global transition should also recognise countries' differentiated responsibilities and capabilities.

[2] Data from: Trout et al. (2022). Existing fossil fuel extraction would warm the world beyond 1.5 °C. *Environmental Research Letters*, 17(6), 1–12. doi:10.1088/1748-9326/ac6228

[3] Data from: Tong et al. (2019). Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. *Nature*, 572(7769), 373–377. doi:10.1038/s41586-019-1364-3

[4] Data from: Kühne et al. (2022). "Carbon Bombs"—Mapping key fossil fuel projects. *Energy Policy*, 166, 1–10. doi:10.1016/j.enpol.2022.112950

[5] Following: Forster et al. (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.

IN FOCUS: ASSET STRANDING, FINANCIAL RISKS AND LOCK-IN

A key problem for a rapid fossil fuel phase-out is the long operational lifetimes of many fossil fuel assets, up to 60 years for some infrastructure. Asset stranding occurs when the firm faces early retirement or substantially lower revenues than anticipated at the time of the initial investment. Financial assets that depend on physical fossil fuel assets, such as shares in a fossil fuel company, can also become stranded. This can precede physical asset stranding due to expectations, and might happen abruptly if many investors adjust their expectations of future returns downward at the same time. Such a "green swan" event substantially devalues stocks, which in turn risks affecting macro-financial stability through contagion to other financial assets and spillovers from the financial world to the real economy. Due to the inherent financial interest of incumbent firms and their shareholders to avoid asset stranding, among other sources of system inertia, fossil fuel investments tend to create infrastructural, technological and institutional "carbon lock-in".

POLICY IMPLICATIONS

Governments should commit to a phase-out of all fossil fuels at COP28 and beyond, following through by:

- Stopping approval of new investments in fossil fuel infrastructure for extraction and consumption now, especially in high-income countries.
- Accelerating the retirement of existing fossil fuel infrastructure.
- Withdrawing from international investment treaties that pose litigation liability risks from fossil fuel companies via investor–state dispute settlements.
- Redirecting fossil fuel subsidies and investments to clean energy.
- Managing the phase-out by setting near- and long-term targets to reduce fossil fuel production and use in coordination with a phase-in of renewable energy and storage systems to avoid energy shortages, price spikes and inflation.
- Reporting on plans and progress towards fossil fuel phase-out in the NDCs.

International cooperation will be necessary to foster a coordinated, transparent and just transition away from fossil fuels across countries and sectors:

- Governments from high-income countries with greater capacity to transition should agree to move faster towards phase-out.
- Governments from high-income countries should provide financial, technological and capacity-building support for lower-income countries to diversify or leapfrog their economies and energy needs away from fossil fuels.

3 Robust policies are critical to attain the scale needed for effective carbon dioxide removal

KEY POINTS

- Emissions must be reduced rapidly and deeply; CDR can only complement this effort, not replace it.
- Both new (often engineered) and more traditional (often forest-based) types of CDR need to be scaled up.
- Robust monitoring, reporting and verifying (MRV) is critical for the success of further CDR deployment.
- The different time frames and types of CDR must be aligned with the specific type of emissions they are supposed to neutralise (a “like-for-like” approach).
- New, multi-level governance and policy instruments are required to support CDR innovation.

INSIGHT EXPLAINED

Meeting the Paris Agreement’s targets will require scaling up CDR from a current level of about 2 billion tonnes of CO_2 to at least 5 billion tonnes or more by 2050. Today, virtually all CDR consists of afforestation, reforestation and management of existing forests. Only 0.1% of current removals come from the rest of deployed methods, such as direct air capture and storage, bioenergy with carbon capture and storage, biochar, enhanced weathering, and ocean-based methods. However, almost all scenarios that limit warming to 1.5°C or 2°C rely on large-scale deployment of these CDR methods.

While many of these CDR methods have great potential, current estimates predict a substantial shortfall compared with what is necessary to cover the hard-to-abate emissions to achieve net-zero. That shortfall also means that these methods would be unlikely to compensate for initial exceedance of the carbon budget for a 1.5°C warming limit. The extent of efforts to develop what are currently small-scale (or even untested) CDR methods over the next decade will determine whether sufficient carbon removal capacity will be available at the scale necessary and in time to reach net-zero CO_2 emissions by the early 2050s, and for achieving net-negative CO_2 emissions afterwards.

A wide variety of CDR options exists, with different levels of technological readiness and sequestration or storage duration (Figure 3). All of these methods have uncertainties regarding their feasibility, life-cycle assessment, and monitoring, reporting and verification (MRV) (see In Focus box). For example, estimates of CO_2 removal by forests are hampered by indeterminate effects from environmental changes (see Insight 4) and inconsistent definitions. Large

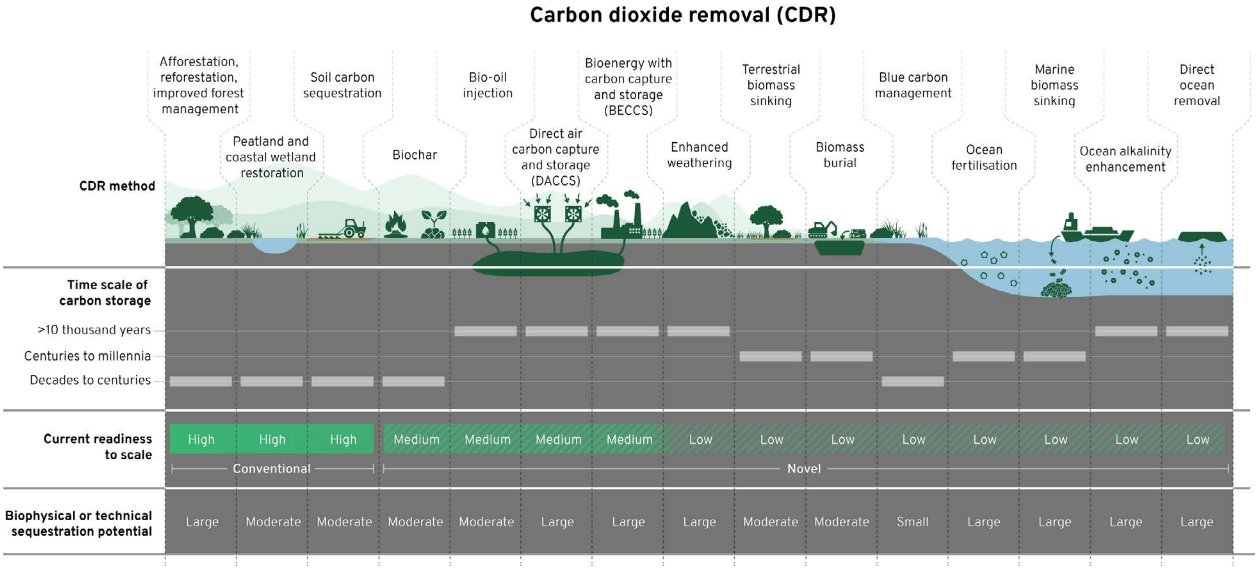

Figure 3. Taxonomy of carbon dioxide removal options. CDR methods characterised in terms of: Timescale of carbon storage: expected durability of the carbon storage (second row); Current readiness to scale: maturity level for deployment at scale (third row); and Biophysical or technical sequestration potential (fourth row), reflecting current understanding (based largely on IPCC 2022, AR6-WG3:Ch12.3).

uncertainties exist in the carbon storage rates for enhanced rock weathering, as well as the evolution of the air-sea gas exchange for direct ocean removal or ocean alkalinity enhancement. Direct air carbon capture and storage, on the one hand, has enormous potential to scale with relatively small land-use impacts, yet the viability of doing it at a feasible energy intensity is still unknown. The use of carbon capture and storage to enhance fossil fuel recovery presents a particular dilemma (see Insight 2, In Focus box).

Increasingly, the scientific community and standard-setting bodies are emphasising a “like-for-like” approach to CDR neutralisation claims. This means that fossil CO_2 emissions should be neutralised through CDR that durably sequesters CO_2, while forestry (and other land-use-based) CDR should only neutralise land-use-related CO_2 emissions. This would address the concern about CO_2 sequestered in vegetation and soils being at risk due to increased prevalence of wildfires, droughts and pests (see Insight 4).

The level of CDR deployment needed will require significant multi-level policy and governance. In some cases, policies can be built on experience from existing CDR methods, emissions reduction measures and, to a limited degree, from carbon capture and storage deployment. But many aspects of CDR policy instruments will require governance innovation. Political commitment and robust MRV systems are necessary.

IN FOCUS: THE CDR MIX WILL EVOLVE

Currently, the vast majority of CDR happens through “conventional” methods, such as afforestation/reforestation. But forests in many regions are threatened by climate-driven disturbances such as droughts, heatwaves, fires, storms and pests (see Insight 4). Less-established CDR options, such as bioenergy with carbon capture and storage, direct air carbon capture and storage, enhanced weathering, biochar and ocean alkalinisation, play only a minor role, so far. The Intergovernmental Panel on Climate Change (IPCC) scenarios (AR6-WG3:Ch3) that stay below a 2°C warming assign a very large role to land-use and forestry-related CDR, as well as to bioenergy with carbon capture and storage, and partly also to direct air capture with storage. But the weight of these CDR options in the IPCC scenarios (and others) does not actually reflect a judgement of their feasibility. Many research and demonstration programmes, as well as policy strategies, consider a broader range of CDR options.

POLICY IMPLICATIONS

- CDR is not a substitute for deep and sustained emissions reductions.
- For CDR to become available on time and at the scale required to meet national net-zero targets, policies must be put in place in the near term to support deployment of new forms of CDR. These policies should responsibly incentivise research, development and demonstration, and targeted deployment.
- Relying on forest-based CDR, the main method of carbon removal today, is risky given major uncertainties due to the impacts of climate change (see Insight 4).
- Given the limited potential of each CDR method and the associated risks at scale (see In Focus box), a portfolio of CDR options should be planned for, the composition of which will adjust over time to account for technological progress, risk assessment and changing environmental, societal, economic and political requirements.

Specific proposals for policy action include:

- Set clear and separate targets for emission reductions and for carbon removal. For example, mandatory separation of reductions and removals in NDCs, specifically the Information to facilitate Clarity, Transparency and Understanding (ICTU) tables.
- Set separate targets based on removal processes that match the timescales of carbon removal permanence with the timescales of emissions permanence (like-for-like approach). For example, the separate setting of targets should be part of frameworks for CDR credits (as has currently been proposed by the European Commission).
- Develop common, robust and transparent MRV frameworks for CDR. For example, by improving existing and developing new inventory guidance through the IPCC's Task Force for National GHG Inventories and ensuring consistency between project-level and country-level reporting.
- Create structured exchanges for mutual learning. This would be relevant not only for knowledge exchange and capacity building, but also in the context of establishing international carbon trading under the Paris Agreement's Article 6.4 mechanism.

4 Over-reliance on natural carbon sinks is a risky strategy: their future contribution is uncertain

KEY POINTS

- There is a high level of uncertainty regarding how natural carbon sinks will respond to human-induced environmental changes, including climate change.
- Natural carbon sinks may absorb less carbon in the future than we are expecting now.
- If natural sinks are indeed weaker than expected, then warming will be stronger than expected in IPCC scenarios. Hence, even more ambitious efforts on emissions reduction will be required.

INSIGHT EXPLAINED

The remaining carbon budget for staying within the Paris Agreement target range for global warming substantially depends on the future contribution of natural carbon sinks on land and in the ocean. Despite rising CO_2 emissions, a relatively constant fraction of about 44% (on average) of these emissions have remained in the atmosphere over the past 50 years. That means that the natural sinks on land and in the ocean have increased their carbon uptake along with the increases in atmospheric CO_2.

However, recent data suggests that the increasing land sink trend may have slowed down. This could just be due to natural variability, but it could also be signalling the start of a “saturation point” in the Earth system. The relative importance of these two factors is highly uncertain. The latter would imply that rising temperatures, altered rainfall patterns and weather extremes, along with other human-induced disturbances, are reducing the buffering capacity of the land sinks, or could even lead to their destabilisation. There is sparse but strong evidence indicating that some land sinks are changing faster than expected. For example, most models do not reproduce the increasing sensitivity of the carbon cycle to tropical droughts, witnessed in the past decades. In boreal forests, drought-induced increase in tree mortality corresponds to a decrease in carbon sink capacity. Events of elevated tree mortality following heat and drought are now being observed worldwide, in places where this had not been expected earlier.

The increase in the ocean sink stalled in the 1990s, but has recovered since. The main driver for the increasing sink is the rising CO_2 content in the atmosphere, pushing anthropogenic carbon into the ocean. But the natural processes of the carbon cycle can modify the sinks, increasing or decreasing carbon storage beyond what is expected solely from CO_2 content in the atmosphere. For example, the warming of the ocean tends to push natural CO_2 out of the ocean, reducing net CO_2 uptake. In the Southern Ocean, changes in wind patterns have exposed more carbon-rich deep waters to the air-sea interface, inducing a loss of natural carbon. The Arctic Ocean, on the other hand, is currently the only large-scale region where the carbon sink is strengthening, as melting sea ice exposes more ocean surface, which can then absorb more CO_2.

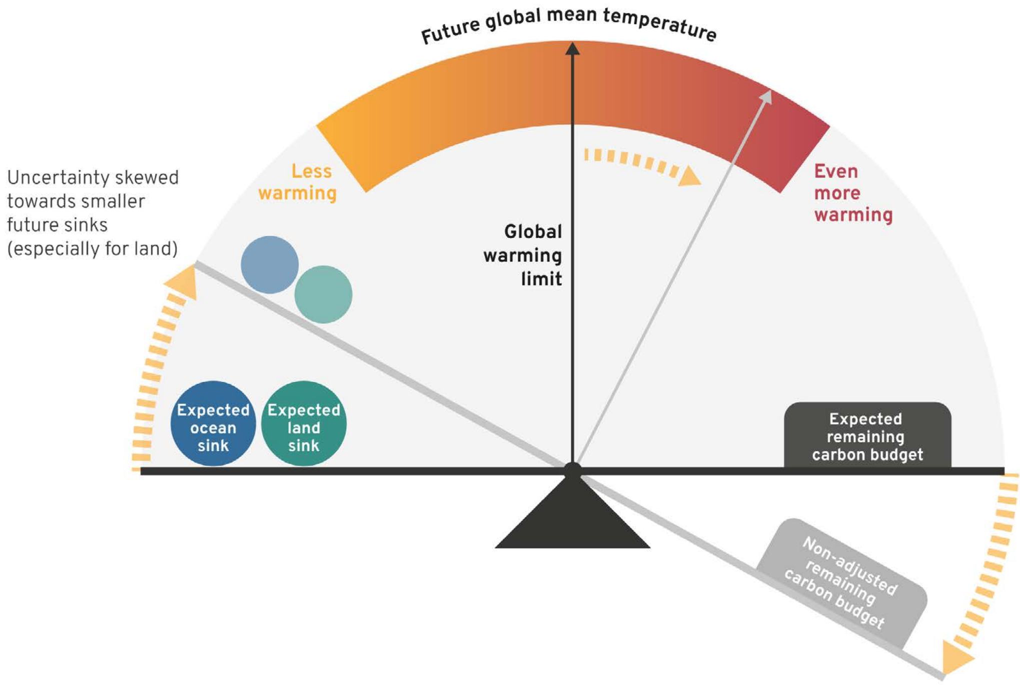

Figure 4. The remaining carbon budget depends on expectations about the future carbon sinks. If sinks are smaller than expected, and mitigation action is not adjusted accordingly, then there will be even more warming than expected.

Overall, the uncertainties regarding natural carbon sinks are concerning. Scientists and policymakers need to be alert to a potential problem: plans to avoid exceeding the Paris Agreement limits on global warming rely on current model projections of sink capacity. If the models are overestimating the sinks, then the true carbon budget might actually be even smaller, and current pathways for achieving net-zero emissions would be insufficient to meet the targets. To reduce uncertainties and avoid over-reliance on natural carbon sinks (or solutions based on them, see In Focus box and Insight 3), we need reliable and robust quantifications of the sinks.

IN FOCUS: A REALITY CHECK ON NATURE-BASED SOLUTIONS (NBS)

Nature-based solutions rely on land and ocean carbon sinks, but over-relying on the future strength of these carbon sinks is a risky strategy, as explained above.

- In the case of land sinks, the problem is well-illustrated with the example of fire: while it is a key driver of change that will increase in the future, fire processes (along with other natural disturbances) are not fully incorporated in current assessments of the future carbon sequestration potential of forests.
- Similarly, the carbon absorption gains of re/afforestation in some regions would be largely offset by counteracting albedo effects, especially in the short term. Yet forest conservation and re/afforestation are prominent in the NDCs of many countries, constituting virtually all currently deployed CDR (see Insight 3).
- For the ocean, an area of great uncertainty is the accounting of the carbon flows between coastal ecosystems, sea shelves and beyond. The rapidly rising frequency and intensity of marine heatwaves, as well as extremes in oxygen loss and acidification, has the potential to also impact the ocean carbon sink, but this is not well understood.
- While acknowledging the importance of NbS in maintaining the integrity of natural carbon sinks (the protection of ecosystems that comes through well-conceived and implemented NbS), for the reasons outlined in this section, mitigation plans should not over-rely on them.

POLICY IMPLICATIONS

Mitigation strategies must not over-rely on natural carbon sinks. Given the growing scientific concern about the future of natural carbon sinks, it is essential to strengthen emissions reductions to account for this uncertainty.

To inform future planning and decision-making it is important to:

- Coordinate and mobilise sustainable funding for a fit-for-purpose ocean and land carbon observation system.
- Perform comprehensive vulnerability assessments of carbon sinks (especially those on land) as part of robust MRV systems for CDR (see Insight 3), in order to make solutions effective and permanent.

5 Joint governance is necessary to address the interlinked climate and biodiversity emergencies

KEY POINTS

- **Climate and biodiversity are deeply intertwined; processes and institutions for managing and governing them must also become interlinked.**
- **The rates of change in both global mean temperature and biodiversity loss are higher than ever before during human history, and continue to rise.**
- **We are increasingly certain of the risks and amplification of harms due to their interdependencies.**

INSIGHT EXPLAINED

The climate and biodiversity crises are intertwined, yet we have been addressing them separately. In 2019–2021, for the first time, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the IPCC together gathered international experts for a joint report on climate and biodiversity actions. More broadly, the Sustainable Development Goals (SDGs) express the need for joint action across all goals, setting out the ambition of all 193 UN member states to guide decision-making for synergistic and effective action.

Biodiversity loss and climate change both result from the dominant economic development and socio-political systems of modern societies, the drivers of which have promoted and incentivised environmentally damaging production and consumption models. Though these drivers manifest in a broad range of pressures and their expression varies locally, some impact both climate and biodiversity, such as deforestation and intensive agriculture.

Climate change drives environmental shifts that control biological processes from intracellular to ecosystem levels. At large scales we tend to see linear, smooth responses or declines, but individual species and ecosystems often show abrupt and unexpected declines on timescales shorter than any feasible reversal of global warming. Furthermore, climate-induced changes in species and ecosystems may amplify feedbacks reinforcing climate changes.

Climate impacts on society that are mediated by biodiversity occur through shifts in nature's contributions to people. For example, changes in weather patterns, the length of growing seasons and the occurrence and intensity of extreme weather events affect pollinator diversity, in turn affecting food production. Coastal ecosystems such as mangroves and salt marshes are natural solutions to climate change mitigation by sequestering carbon, while also supporting adaptation to climate change impacts by absorbing wave energy during storms. These benefits are at risk due to their vulnerability to sea-level rise, flooding and climate warming.

Nature-based solutions can reduce climate change impacts and help restore biodiversity and the resilience of nature's contributions to people, yet these contributions are less certain than often assumed (see Insight 4, Box 4). Hasty implementation, however, such as large-scale tree planting for carbon sequestration, can miss synergistic opportunities and cause harm to other aspects of nature. Safeguards are needed to ensure well-designed NbS deliver multiple benefits for people and nature. For example, synergies and trade-offs between biodiversity protection, climate mitigation and food production show that moderate ambition across all targets may achieve balance (see Insight 10), but that focusing on high ambition for just one target comes at the price of lower achievement in others.

IN FOCUS: CORAL REEFS THREATENED BY CLIMATE AND BIODIVERSITY THREATS

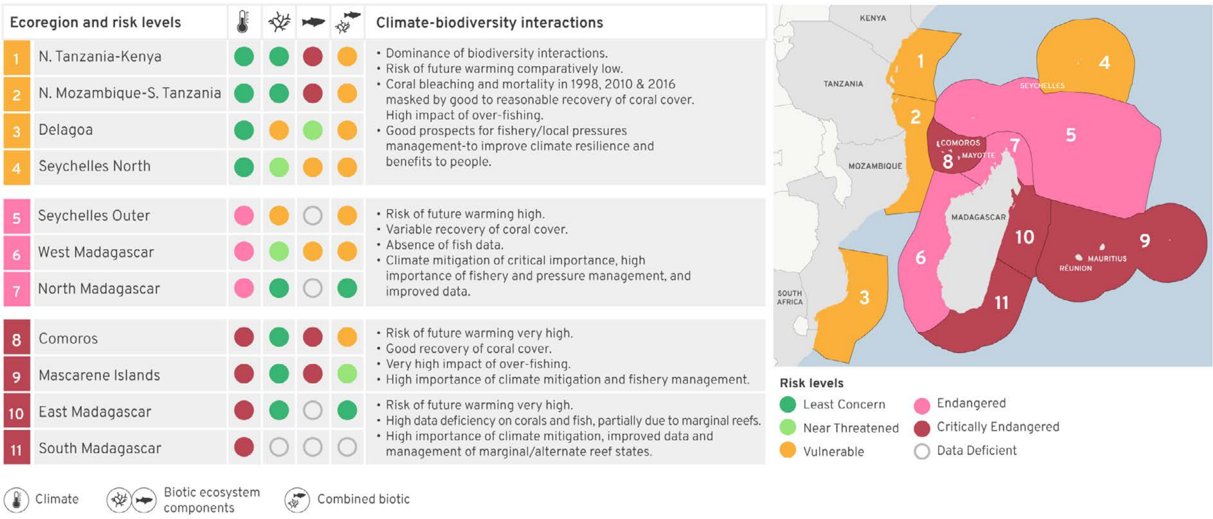

Figure 5. Ecoregions of the Western Indian Ocean showing their risk of coral reef collapse in the IUCN Red List of Ecosystems.[6] Risk levels for climate (thermometer icon) and biotic (coral and fish icons) ecosystem components are shown with their individual levels of risk. The combined biotic risk 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, prospects for management and benefits for people.

Coral reefs are among the first ecosystems being driven to collapse across multiple regions, e.g. the Caribbean, the Great Barrier Reef and the Eastern Tropical Pacific, potentially aggregating to global collapse. Western Indian Ocean coral reefs have been assessed as vulnerable to collapse, comprising four critically endangered ecoregions, three endangered ecoregions and four vulnerable ecoregions (Figure 5). Biodiversity–climate interactions underpin their risk of collapse – island reefs are typically at higher risk from increasing temperatures in the next three to four decades, while continental reefs have better climate futures but are at a higher risk 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 some or all reef ecoregions crossing their point of collapse. 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.

[6] Redrawn from: Obura et al. (2021). Vulnerability to collapse of coral reef ecosystems in the Western Indian Ocean. *Nature Sustainability*, 5(2), 104–113. doi:10.1038/s41893-021-00817-0

Understanding and managing the joint impacts of climate and biodiversity change on society is challenging. Human risks from both climate change and biodiversity loss are less studied but growing evidence shows they are higher in low- and middle-income countries, where vulnerability and impacts of loss are also higher. For example, tropical regions have contributed the least to climate forcing yet face the highest potential for cascades and tipping dynamics. Data and dominant approaches for biodiversity conservation, climate information-gathering, and setting relevant local decisions and global policies are still strongly biased towards wealthier nations. Our ability to model and anticipate risks and shifts induced by biodiversity–climate changes is insufficient to incorporate them in policy responses, and their complexity challenges implementation.

POLICY IMPLICATIONS

The intricate links between climate change mitigation and adaptation, biodiversity conservation actions and broader societal needs will require transformative change in how we govern social-ecological systems at all scales.

- Biodiversity and climate goals must be pursued jointly, and policies should coherently reflect the intertwined nature of these crises. To this end, the UNFCCC and CBD need to be better aligned and cross-convention collaborations enhanced. Some goals, such as for food production, may be achieved in isolation but at a cost to other goals, such as those related to biodiversity and climate. By contrast, well-aligned ambition across multiple goals can lead to success for all goals and maximise opportunities for co-benefits and synergies.

- The USD 100 billion climate finance commitment proposed as part of the UNFCCC process must be implemented with nature-positive safeguards and outcomes. High-income countries, starting with the G7, should dedicate 30% of their international climate finance towards socially just NbS to simultaneously achieve climate and biodiversity outcomes.

- The Green Climate Fund, the Adaptation Fund and other climate funds (multilateral and bilateral) should strengthen their selection criteria for positive biodiversity protection effects, and incentivise project designs that maximise multiple benefits.

- Decision-makers at all levels – international, national and local – must:

    - ensure that conservation and climate actions are designed to include safeguards for people and nature (to avoid harmful financial incentives and risks from complex interactions) and aim for positive economic and social effects;

    - re-appraise targets and indicators of economic and social development to transform systems that drive climate change and biodiversity loss. This includes addressing deeper socio-cultural factors, such as world views, attitudes and values, that underpin entrenched institutions that drive environmentally damaging production and consumption.

6 Compound events amplify climate risks and increase their uncertainty

KEY POINTS

- The impacts of compound event can be greater than the sum effects of individual events.
- New data and modelling highlight the challenges associated with compound events. Some effects of compound events are cumulative and may lead to new equilibrium states of the impacted systems.
- Risk-management planning should account for compound events, especially through integrated assessments to reveal natural or human-induced linkages among seemingly disparate risk factors.

INSIGHT EXPLAINED

Compound events are defined as events that occur when a combination of drivers and/or hazards contribute to environmental or societal risks (Figure 6). These phenomena span scales and interaction types, including phenomena that enable others, those involving multiple variables and those that occur in sequence and across different spaces. Examples include the heavy rain, extreme wind and storm surge from Hurricane Sandy in 2012, and the sequential storms in California's winter 2023 where metres of snow entrapped some residents for weeks.

Physical science research on compound events mostly began with atmospheric and bivariate events, such as drought–heatwave interactions. Researchers have since adapted the concept to other domains, including terrestrial ecosystems, the ocean and inter-domain linkages. An array of methodological approaches, such as large ensembles and extreme event attribution, are confirming the relevance of compound events to a wide range of potential areas of impact. For example, compound events pose critical risks to food security and ecosystem services, complicate disaster risk management, interfere with adaptation strategies and affect human migration patterns.

Crops are particularly sensitive to the simultaneous occurrence of extreme hot and dry conditions. Variability, such as an early spring followed by a late frost, can also harm crops. Given that a large proportion of crops are grown in just a few breadbasket regions, low yields in the same harvest in more than one region could threaten global food security.

Ecosystems are threatened by compounding impacts. Plant recovery usually lags after extreme events, which in turn increases vulnerability to

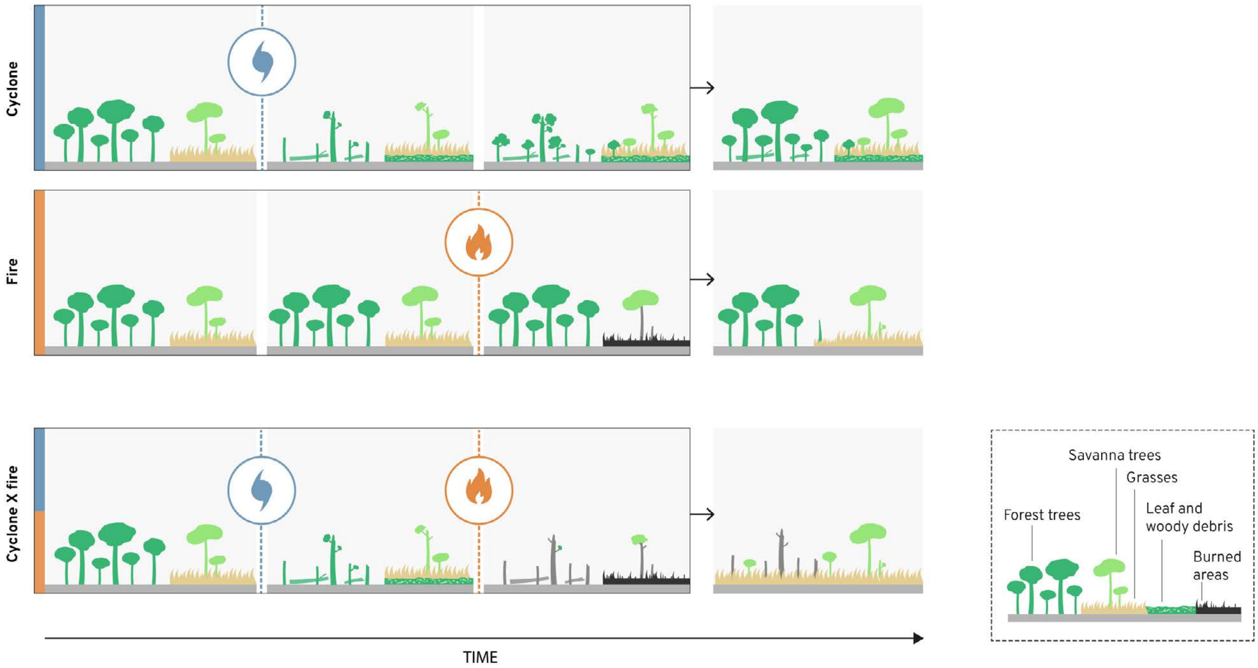

Figure 6. A compound event. The illustration shows how a cyclone (blue icon) followed shortly afterwards by a wildfire (orange icon) can create a much larger impact than either event on its own. On the bottom right is a visualisation of the severity of cyclone and wildfire hazards, causing a potential impact that gets exponentially worse towards the upper right as indicated by the different equilibrium state in the "cyclone X fire" case.[7]

another (compound) event, as well as, among other consequences, limiting vegetation's capacity to act as a carbon sink (see Insight 4). The interaction of effects from separate events, such as cyclones and fires, can alter equilibrium ecological states. Compound ocean events, such as marine heatwaves, changes in oxygen concentration, ocean acidity and/or net primary production, can impact marine ecosystems at individual, population and community levels. Compound events across the land–ocean continuum, such as severe droughts in South America and marine heatwaves in the South Atlantic in 2013/14 led to water shortages in Brazil and impacted food supply globally.

"Compound event thinking" improves early warning, emergency response, infrastructure management, long-term planning and capacity-building. So far, however, few adaptation efforts sufficiently consider compound events. This is often due to a lack of knowledge about the physical system that forms compound events, the difficulty in translating existing knowledge into action as well as the fact that most adaptation and early warning systems are structured around single hazards.

Identifying and quantifying compound events will require understanding how discrete climate hazards interact with and intensify each other. Improved models and statistical methods are revealing that the impacts from compound events are likely to exacerbate each other, in part because of longer recovery timescales. This interconnectedness implies the need for cooperation at the scales of compound event impacts, which are often larger and longer than what the existing decision-making frameworks encompass. Local preconditions appear to shape compound event impacts, whether societal (e.g. migration, poverty, conflict) or environmental (e.g. scarce resources, overfishing, denuded landscape), making those context features of crucial importance to assess and incorporate.

[7] Based on: (1) Ibanez et al. (2022). Altered cyclone–fire interactions are changing ecosystems. *Trends in Plant Science*, 27(12), 1218–1230. doi:10.1016/j.tplants.2022.08.005; (2) Zscheischler et al. (2020). A typology of compound weather and climate events. *Nature Reviews Earth & Environment*, 1(7), 333–347. doi:10.1038/s43017-020-0060-z

IN FOCUS: EXTREME FACTORS CAN AMPLIFY EACH OTHER

The last few years have seen exceptional climatic and extreme weather events far outside the previous local historical range, with severe socio-ecological impacts. Events are being connected to combinations of antecedent and/or simultaneous drivers that only together were able to achieve the observed conditions. For example, researchers now interpret the heatwaves in western North America in June 2021 as the integrated outcome of multi-scale processes including atmospheric ridging, low soil moisture and latent heating from upwind precipitation. Even when occurring in a single region, these exceptional events can be compounded by the heightening of multiple types of impacts simultaneously: e.g. simultaneous heat stress, wildfire risk and air pollution, or heat-drought and heat-flood linkages.

The same can also happen at sea. Some of the devastating impacts of the North-East Pacific 2013–2015 marine heatwave and accompanying extreme high sea surface temperature – 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 events including ocean acidity, low oxygen, and crop failures in several major agricultural regions simultaneously leading to price shocks and food shortages. Increasingly, these types of ocean-based events are also co-occurring with land events, multiplying the impacts.

POLICY IMPLICATIONS

- Adaptation planning and risk management at any scale should incorporate an assessment of the likelihood and consequences of discrete events becoming compound events. To this end, the perspectives of people who have previously been affected by natural hazards should inform the development of targeted intervention points and anticipatory action, including early warning systems.

- Anticipatory action and risk management of compound events should not only encompass but transcend the geographical and temporal scales at which these events often occur. For example, through development of international and intersectoral climate finance mechanisms or cooperation agreements for sharing supplies and personnel, ideally among regions or sectors with a comparatively small risk of simultaneous disaster.

- Emergency preparedness and risk-management planning should always (a) account for local preconditions (social and environmental); (b) Recognise that global attention to and the distribution of data on compound events is not representative; (c) erect institutional infrastructure for decision-makers to prepare for future compound or multi-hazard events with appropriate response mechanisms.

- Allocation of adaptation investments should reflect the geographically unequal distribution of the impacts of compound events. For example, investment cost/benefit analyses based on single events in isolation (e.g. a severe storm affecting a province) should also consider additional emergent risks in case of multiple such events in close proximity. Relative to single events, the impacts of compound events tend to more heavily interact with underlying infrastructure and socio-economic systems, creating a special need for well-coordinated anticipatory and response actions (ensuring, for example, that flood risk reduction efforts in one area do not increase flood risk in a neighbouring area).

7 Mountain glacier loss is accelerating

KEY POINTS

- Mountain glaciers respond to changes in atmospheric forcing over shorter temporal scales than ice sheets, and have caused almost one quarter of sea-level rise so far.
- Glacial melting puts the growing populations living downstream at risk of flash-floods and water shortages.
- As these glaciers retreat, biodiversity in high-alpine catchments may strongly decrease, compromising ecosystem functions.

INSIGHT EXPLAINED

Mountain glaciers are highly sensitive indicators of climate change. Improved satellite observations and modelling have enhanced our ability to measure the response of glaciers to climate change and project their evolution, while Indigenous and local knowledge have extended the time depth and spatial resolution of our understanding. In comparison with 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. However, since mountain glaciers are melting much faster than ice sheets, their mass loss explains almost one quarter of current sea-level rise. Glaciers contribute to healthy mountain environments. During dry periods, glacier meltwater is vital for maintaining river flows that support mountain and downstream regions, recharging aquifers, providing freshwater for human consumption and irrigation, and sustaining ecosystems and biodiversity, as well as fisheries and shipping. Additionally, glaciers have considerable spiritual, cultural and touristic value.

Present-day observations of glacier change reveal a loss of 267±16 Gt yr^{-1} with a clear acceleration over the last two decades. Globally, glacial mass loss is potentially around 12% greater than previously reported, due to ice melt occurring below the water surface that is unaccounted for by available estimates. As these glaciers retreat, high-alpine catchments may lose species and ecosystem function.

New global glacier projections estimate that glaciers will lose between 26% (at +1.5°C) and 41% (at +4°C) of their current volume by 2100 (Figure 7). Relative mass loss varies greatly at regional scales, with mid-latitude regions such as Western Canada, Central Europe and Caucasus expected to experience widespread deglaciation if warming goes beyond 3°C. Limiting the temperature increase by reducing GHG emissions is thus critical for preserving these glacial regions and limiting their contribution to sea-level rise.

The impact of climate change on mountain environments is diverse. Glacier loss poses immediate flooding risks to the surrounding communities, and when compounded by the thawing of permafrost, it causes cascading hazards such as landslides and debris flows. Glacier loss also poses medium-term risks of water shortages, including areas with very large populations in the Hindu-Kush Himalayas. In all cases, additional in situ observations are key and will help reduce uncertainties in glacier change projections. Improving these projections will benefit from incorporating high-resolution models to ensure projections are provided at the correct scale for disaster risk management, and implementing programmes that build trust and collaboration between governments and Indigenous and local peoples to ensure the success of adaptation measures.

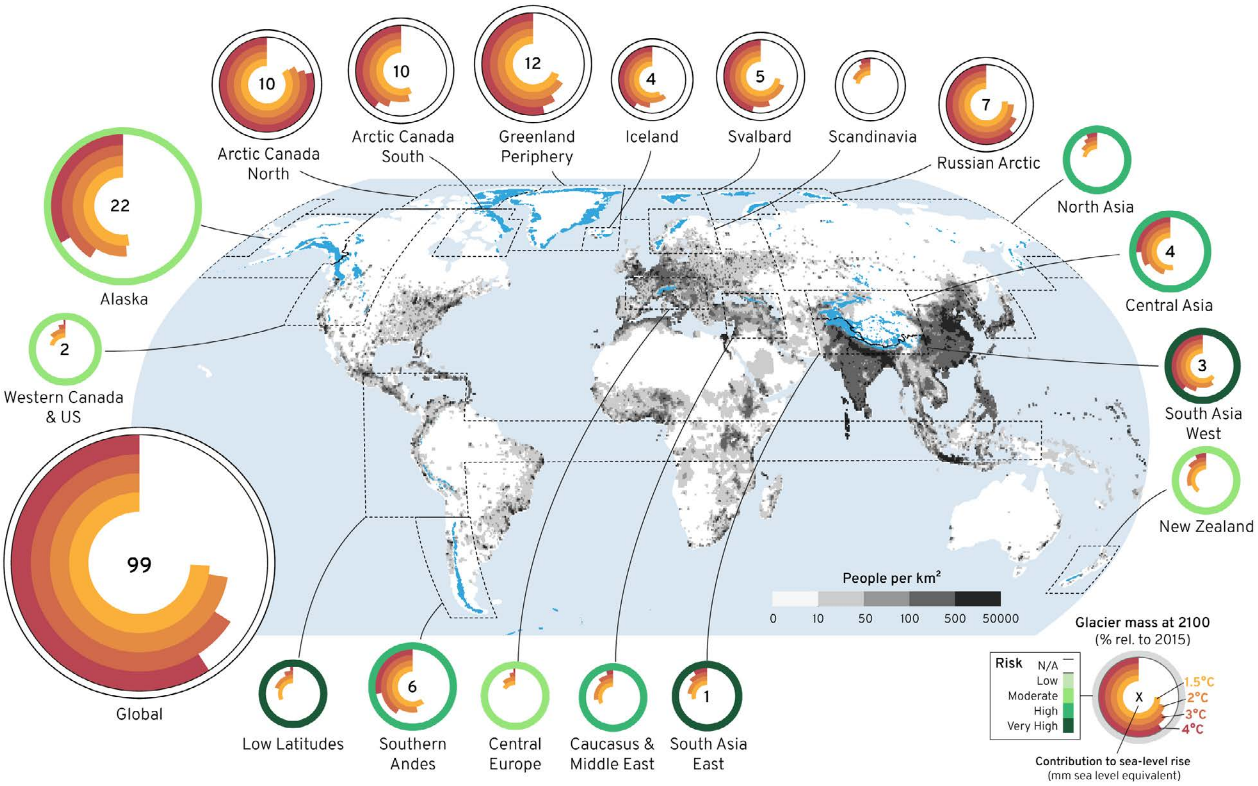

Figure 7. Glacier loss and sea-level rise from 2015–2100.[8] Discs show global and regional projections of glacier mass remaining by 2100 (relative to 2015) for global mean temperature change scenarios. The size of each disc is based on the region's contribution to global mean sea-level rise from 2015–2100 for the +2°C scenario. 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 for the +2°C scenario are in the centre of each disc. The colour of the outer circle refers to the risk to livelihoods and the economy from changing mountain water resources, for global warming between 1.5–2°C (IPCC, 2022, AR6-WG2:CCP5.3). The map shows population density (people per km^2) in grey, and glaciers in blue.

IN FOCUS: MORE PEOPLE THAN EVER LIVE IN THE WATERSHEDS OF THE HIGHEST MOUNTAINS

Increasingly large numbers of people are affected by mountain glacier loss. Mountainous regions with high population densities, such as the Himalayas, are particularly vulnerable (Figure 7). Approximately 1.65 billion people downstream of the Himalayas currently rely on mountain water sources, compared with 0.6 billion worldwide in the 1960s. Central Asia, South Asia and tropical and subtropical western South America are predicted to experience the most significant impacts from changing water availability this century. Variable timings of glacier and snow melt affect water availability and may lead to conflict over resources. Downstream mountain populations are also growing. Today, there are roughly 15 million people worldwide exposed to glacial lake outburst floods. Rapid GHG emissions reductions will 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.

[8] Modified from: Rounce et al. (2023). Global glacier change in the 21st century: Every increase in temperature matters. *Science*, 379(6627), 78–83. doi: 10.1126/science.abo1324

POLICY IMPLICATIONS

Adaptation strategies would benefit from more stakeholder cooperation to ensure effective implementation and management. The agreement at COP27 to establish a Loss and Damage Fund highlights the need for disaster risk reduction and more support for vulnerable populations. Still, too few risk control measures have been implemented to address the impacts of global climate change in mountain regions.

In order to prioritise comprehensive climate adaptation policies for immediate- and medium-term challenges, climate negotiators and decision-makers at all levels should:

- Invest in climate-resilient and adaptable infrastructure, and urban planning considering rapid- and slow-onset challenges (e.g. glacial flooding, freshwater scarcity).
- Enhance early warning systems and emergency preparedness in vulnerable communities for glacial flooding.
- Prioritise water resource management, investing in water-efficient technologies, promotion of sustainable land management practices, and diversifying water sources whenever possible.
- Develop robust procedures for assessing and consulting on the possibility of relocation of vulnerable communities from high glacial melt flood risk zones (always through participatory processes with the affected communities, see Insight 8).
- Safeguard and restore wetlands and other ecosystems that help to mitigate the impacts of glacial loss, reducing the risks of flooding and erosion.
- Foster collaborative efforts between researchers, governments and local communities among wealthier and poorer parts of the world, which are crucial for filling data gaps and improving modelling accuracy.
- Seek regional collaborations for effective resource allocation and risk reduction.
- Support glacier protection laws, which have emerged in the last decade.

8 Human immobility in areas exposed to climate risks is increasing

KEY POINTS

- Climate change can increase barriers to mobility, leading to a rise in involuntary immobility particularly among the poorest populations.
- Policies addressing climate change and human mobility predominantly focus on managing mobility, but overlook immobility.
- Recent research highlights the multi-faceted nature of decision-making related to (im)mobility. Despite climate risks, some individuals and communities opt to stay.
- People who are immobile require institutional support to effectively cope with the challenges posed by climate hazards.
- Human-centred policies for migrants and non-migrants require participatory, inclusive and community-led approaches.
- Top-down approaches to adaptation and planned relocation may be ineffective and maladaptive, and be met with community resistance.

INSIGHT EXPLAINED

People who are unable or unwilling to relocate from high-risk areas may face even greater challenges than those who do move away. Some climate-impacted communities face economic, political, socio-cultural and physical constraints to mobility. Differences in ability to move can create gendered and other inequities at the household level. Demographic factors and access to information about safe accommodation, safe migration opportunities and labour markets influence (im)mobility outcomes.

Recent studies show an increase in involuntary immobility particularly among the poorest populations. Climate change may decrease emigration rates by over 10% among the lowest-income groups by 2100, under medium development and climate scenarios, compared with no climate change, and up to 35% in more pessimistic scenarios. Studies also show that mobility is facilitated in wealthier regions and inhibited in the poorest.

Mobility and immobility outcomes in climate hazard contexts can result from a rational decision-making process shaped by intersecting community- and individual-level factors (Figure 8). Community-level factors, place attachment, individual/household characteristics and risk perception and tolerance shape perceived capacity to withstand or respond to climate impacts and risks, which, in turn, affects an individual's capability and aspiration to migrate.

However, not all immobility is involuntary. Some populations express a strong desire to stay, sometimes in opposition to planned relocation. These communities possess valuable local knowledge of habitability and profound place attachment, and they prioritise safeguarding cultural identity and political agency. The risks they associate with relocation, including threats to livelihood, social connection, personal safety and access to services, outweigh the risks perceived from climate change. While relocation programmes can contribute to

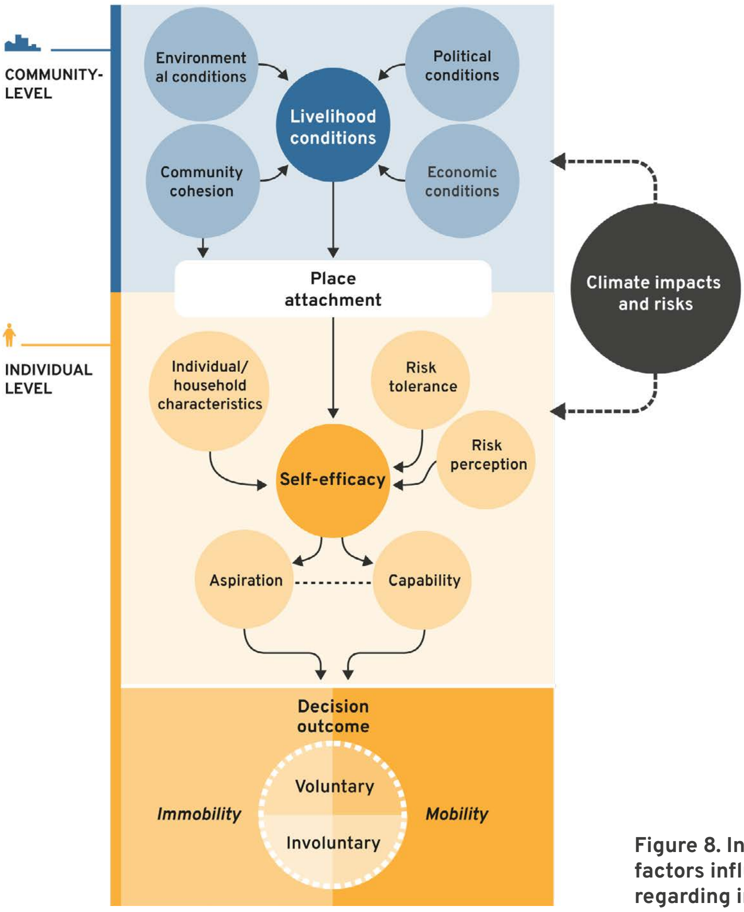

Figure 8. Intersecting community- and individual-level factors influencing individual decision-making processes regarding immobility in climate-risk contexts.[9]

adaptation, the desire of some communities to stay might rise in reaction to solutions they perceive as maladaptive or as threatening established rights. 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. Immobility can thus be a political act of resistance and defiance of future displacement. These findings contest the dominant policy and media discourse on mass migration caused by climate change by demonstrating that despite environmental degradation and climate risks, some people may decide to stay.

IN FOCUS: TUVALU'S STANCE ON CLIMATE-INDUCED RELOCATION

In the face of climate risk and its significant implications for the island nation of Tuvalu, the government asserts its commitment to self-determination and emphasises the right of the population to thrive in its own land:

"Tuvalu stands against relocation as a solution to the climate crisis because Tuvalu is a sovereign country, and its population has the right to live, develop, and prosper on its own land. Relocating populations affected by climate change provides a 'quick fix' while failing to address the root causes of the climate crisis. At the same time, Tuvalu seeks to realistically address land-loss and land-degradation issues and how they affect the security of the nation. Tuvalu further supports all people who have been displaced by or have migrated because of climate change. Human mobility has been practised in various forms in the Pacific region, and Tuvalu respects the decisions of Pacific nations that may choose relocation as an option." (Te Sikulagi: Te Ataeao Nei – Tuvalu Foreign Policy 2020: Future Now Project.)

[9] Adapted from: Mallick et al. (2023). How do migration decisions and drivers differ against extreme environmental events? *Environmental Hazards*, 22(5), 475–497. doi: 10.1080/17477891.2023.2195152

POLICY IMPLICATIONS

Recommendations for climate negotiators and decision-makers at different scales.

Regionally or internationally:

- Include immobility (risks and costs) in deliberations on adaptation and loss and damage, including related to the Global Goal on Adaptation and the Loss and Damage Fund, to address situations where immobility may not sufficiently be addressed through adaptation strategies. Further research into the costs of immobility is needed to develop adaptation measures with a particular focus on marginalised groups to mitigate overall risk.

- Develop comprehensive policies and prioritise anticipatory approaches that reduce the need to move, improve mobility options, and safeguard the rights of those considering relocation, those opting to stay and those resisting relocation. For instance, measures to improve agricultural resilience, establish insurance schemes for crops, livestock and shelter, and promote temporary and circular internal and international livelihood migration, as outlined in Bangladesh's Action Plan to implement its National Strategy on Internal Displacement 2022-2042.

- Eliminate institutional barriers to safe, orderly and regular migration at the national, regional and international levels to enable individuals to opt for migrating from high-risk climatic areas as an adaptation strategy.

Nationally:

- Revisit and revise existing policies on adaptation, mitigation, disaster risk reduction, and resilience building to explicitly address climate immobility. Policymakers often overlook immobility compared with climate-induced migration, disaster displacement and international security; only a minority of national adaptation plans (NAPs) and NDCs integrate considerations for populations unable or unwilling to move.

- Recognise immobility (including temporary immobility and symbolic resistance) as a component of local climate risk responses to inform nuanced, human-centred policies for both migrants' and non-migrants' needs within specific temporal and political contexts. For example:

    - Bangladesh's National Strategy on Internal Displacement Management (2021) upholds that "The Displaced Persons should in principle be able to choose where to live while being displaced and to voluntarily reassess such decisions once the reasons for their displacement or barriers to their voluntary return have ceased to exist."

    - The Solomon Islands Planned Relocation Guidelines outline a specific category of "People Who Choose Not to Participate in Planned Relocation" to capture those "who are eligible to take part in a Planned Relocation (for example, they are part of the Relocating Community) but who choose not to do so."

- Prioritise participatory, inclusive and community-led approaches in migratory policymaking, and avoid top-down approaches that may be ineffective, maladaptive and may even incite resistance. The Solomon Islands Planned Relocation Guidelines are illustrative in this regard, providing that "successful relocation may require consultations over generations", and that "all communities have a central role in outlining their future needs and aspirations with respect to relocation, climate adaptation and sustainable development, and are able to direct the relocation process before, during and after the relocation itself".

9 New tools to operationalise justice enable more effective climate adaptation

KEY POINTS

- Implementing adaptation equitably benefits everyone and helps avoid maladaptation, yet most adaptation planning neglects justice dimensions.
- An adaptation justice index proposes long-term collaborative adaptation planning across social scales and timescales.
- Adaptation rationales articulate the values and practicalities of an adaptation plan.
- Locally led adaptation (LLA) emphasises that when projects are designed and implemented and funds are managed at the local level, the resulting outcome is a more just form of adaptation.

INSIGHT EXPLAINED

Adaptation in response to climate change is uneven in large part due to unjust design, funding and implementation. The United Nations Environment Programme Adaptation Gap Reports have increasingly mentioned justice concerns. Adaptation is recognised as being most effective when it centres on justice, yet adaptation planning and implementation still neglect conceptualisations of adaptation justice and the most vulnerable and marginalised people – who are also the most heavily impacted by climate change. Globally, because of limited monitoring, evaluation and learning, there is limited evidence of the extent of justice within outcomes from adaptation strategies and plans. There is also a lack of consideration of social divisions, such as poverty, gender and ethnicity. An intersectional approach that might better capture the ways in which vulnerability and risk take shape is rarely taken.

While acknowledging the importance of physical processes, recent adaptation justice research emphasises the socio-economic structures that drive climate vulnerability and make adaptation unavailable to many – and destructive to some. Adaptation plans perceived as unjust may face resistance. Examples include forced relocation (see Insight 8), imposition of food crops and technocratic practices (see Insight 10), lack of participation in drafting plans, or applying labels such as "climate refugee".

The factors that produce unjust outcomes operate at different scales. At the international scale, insufficient funding and structural biases in funding mechanisms reflect the lack of recognitional and procedural justice (see Figure 9 for how we operationalise these concepts). This gap prevents funds from reaching those who need them most, in turn hampering distributive and restorative justice

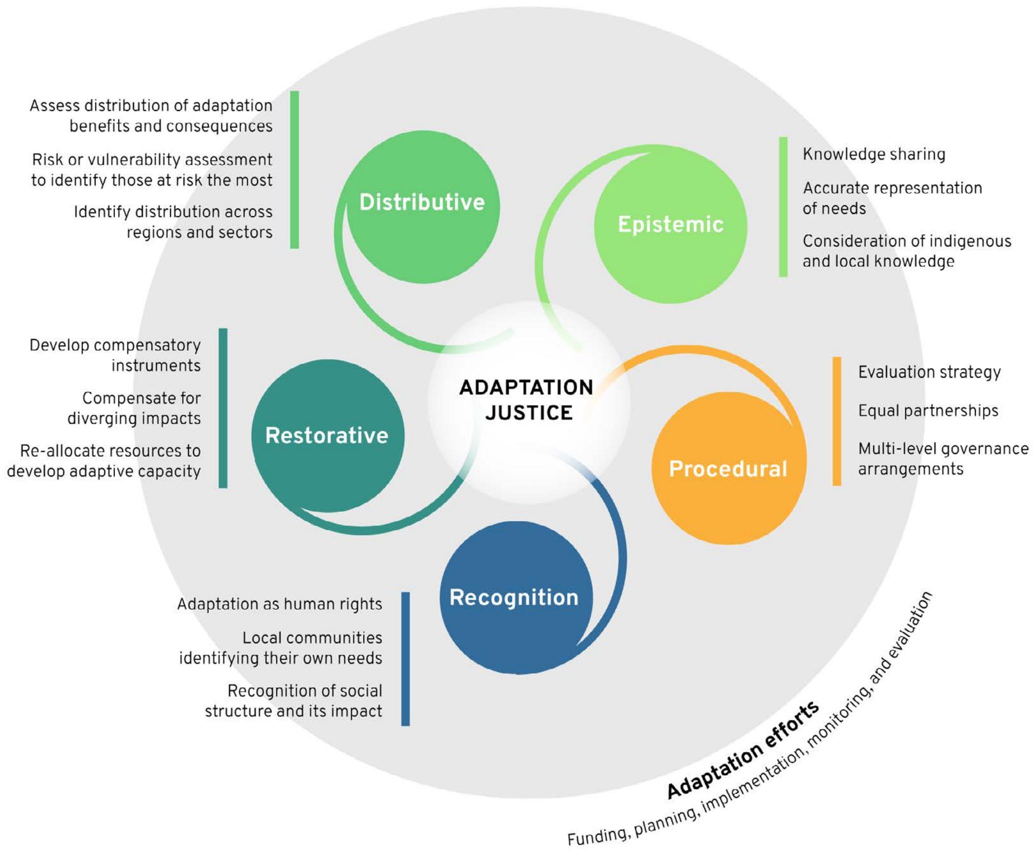

Figure 9. A perspective on the components of adaptation justice and implications in adaptation planning and processes.[10]

mechanisms such as compensation for loss and damage. Many communities cannot fulfil the burdensome reporting requirements attached to most sources of funding. Similarly, funds to address loss and damage should be easily accessible by communities in need via grants.

Here, we highlight three recent conceptual advances for adaptation justice in practice: the adaptation justice index, adaptation rationales and LLA.

The adaptation justice index proposes a shift from a narrow model of stakeholder engagement to full and long-term co-produced collaborative partnerships for procedural and distributive justice. It operates across scales of social organisation and accounts for short- and long-term implications of adaptation actions. It aligns with recent work that examines adaptation and maladaptation as poles of a continuum, rather than distinct types of action.

Adaptation rationales are pathways that guide priorities, actions and outcomes. They are not focused on technical adaptation fixes alone and can incorporate solutions to improve livelihoods and sustainable development. Good rationales promote equality and reduce vulnerability. Many adaptation projects lack explicit adaptation rationales, reflecting gaps in procedural and epistemic justice. Transparent, well-constructed adaptation rationales with well-articulated benefits help minimise uneven distribution of those benefits. To achieve justice, we must plan for a broad set of adaptation benefits framed around reduced exposure, reduced sensitivity and increased adaptive capacity. Moreover, strong adaptation rationales enable the effective monitoring, evaluation and learning of the different components of justice.

LLA can foster bottom-up initiatives and respect community autonomy while sharing knowledge and building capacity. This approach was recently shown to promote more just outcomes in adaptation planning and implementation.

[10] Based on: (1) Juhola et al. (2022). Connecting climate justice and adaptation planning: An adaptation justice index. *Environmental Science and Policy*, 136, 609–619. doi: 10.1016/j.envsci.2022.07.024; (2) Orlove et al. (2023). Placing diverse knowledge systems at the core of transformative climate research. *Ambio*, 52, 1431–1447. doi: 10.1007/s13280-023-01857-w

IN FOCUS: INCREASES IN RESILIENCE CAN BE SECURED IN ALL REGIONS AND COMMUNITIES BY ADDRESSING ADAPTATION JUSTICE IN ADAPTATION PLANS

People are responding to new climate realities everywhere, but deliberative planning processes can have better, more just outcomes. Communities with more participatory processes are more likely to design adaptation plans that are just and values-aligned.

Drawing on Indigenous knowledge and scientific information, villagers in Fiji planned their own relocation of coastal villages impacted by coastal erosion and saltwater intrusion. The decision was made possible thanks to land-use laws enabling relocation, which served to support livelihoods by expanding access to terrestrial and marine resources, and maintained cultural values and connections to ritual sites.

Hurricane Harvey in Harris County, Texas (United States) revealed inadequacies of adaptation planning as low-income neighbourhoods were especially impacted, particularly those residing outside of floodplains. These communities received no warning, because they were not considered to be at high risk.

POLICY IMPLICATIONS

Recommendations for climate negotiators and decision-makers at different scales.

In international settings:

- Increase and improve access to funds to promote procedural justice. For example, the Loss and Damage Fund should be easily accessible to communities in need through grants.
- Request explicit, clear analysis of justice implications (short- and long-term) of proposed adaptation projects supported with multilateral and bilateral climate funds such as the Adaptation Fund and Green Climate Fund.
- Move towards fair collaborative partnerships with inclusion of marginalised voices in decision-making processes, equal access to resources, and operating across scales of social organisation.
- Promote a mechanism for learning from ongoing adaptation initiatives:
    - Monitor, evaluate and learn from adaptation actions, with attention to specific impacts across gender and ethnicity, in adaptation strategies and plans.
    - Emphasise ‘learning loops’ and ensure that lessons drawn from evaluations are built back into future adaptation strategy design.
    - Make positive and reproducible case studies around the world available for learning.

In national settings:

- Recognise and break down detrimental power differences among all stakeholders in the adaptation planning and implementation process to ensure equitable representation and participation.
- Increase adaptive capacity through appropriate (de)regulation, including monitoring, evaluation

and learning of the different components of justice.

  - Promote the use of new tools to operationalise justice in adaptation plans, to:
  - Support the development of clear and explicit 'adaptation rationales' by local communities that protects the community by reducing exposure and vulnerability.
  - Ensure (re)development plans are evaluated with an 'adaptation justice index'.

In local settings:

- Ensure that outside actors do not interfere with the decision-making process so that local communities can discuss and assess a full range of appropriate and desirable adaptation options.
- Take particular care to support the participation of the most vulnerable and marginalised in adaptation efforts.
- Report adaptation efforts as part of monitoring and evaluation procedures to other communities and to national and international organisations, including lessons learned to work with alternative options when they arise.

10 Reforming food systems contributes to just climate action

KEY POINTS

- There has been insufficient consideration of historical and persistent injustices, socio-economic conditions, regional disparities in geography, culture and technological readiness, and power imbalances in food systems governance.
- Acknowledging and addressing injustices and how they are reinforced in contemporary food systems is a prerequisite for realising the mitigation potential of food systems transformations.
- Policies must be co-designed with all key actors, with a plurality of solutions across different scales that reflect diverse regional contexts.

INSIGHT EXPLAINED

On their own, food systems are responsible for 31% of global GHG emissions and are capable of pushing global warming towards 2°C by 2100 barring significant changes to the status quo. At the same time, over 700 million people face hunger, and marginalised groups such as women and girls, racial, ethnic and caste minority groups, Indigenous peoples, and small-scale farmers are disproportionately affected by food insecurity and climate change.

Though agreement across scientific disciplines is widespread that food systems transformation for climate mitigation is urgently needed, current dialogues and decision-making processes on food systems governance remain siloed, polarised (for example, on the debate of local vs. global solutions) and exclusive (often the most vulnerable stakeholders are not actively engaged or are overpowered by dominating actors). As a result, current governance systems are ill-equipped to recognise or wilfully neglect social vulnerabilities, regional disparities in geography, culture and socio-economic conditions, technological readiness, vested interests and power imbalances. The agrifood industry constitutes a set of structures that contributes to and reinforces unsustainability and injustices worldwide. Scholars fear that acting urgently in pursuit of low-carbon food futures, without the governance infrastructure and capacity to acknowledge and address these injustices in contemporary food systems, will hamper transformations towards secure, just and sustainable food systems.

Broader participatory platforms to integrate marginalised communities and diverse cultures, designed for safe, inclusive and candid dialogue, must be established for moving towards just transitions for sustainable and equitable food systems. Continuous transdisciplinary engagement with stakeholders starting from the stage of problem defining, evidence gathering, impact monitoring, all the way to solution implementation, creates co-ownership of policy processes, minimises the potential for negative externalities, and yields unique solutions appropriate for the particularities of the context. A food systems governance regime characterised by justice and sustainability is built to manage trade-offs equitably, aligning incentives with action and compensating for losses, and produces diverse solutions across scales. Strategies for low-emission diets and production practices and for food waste elimination, among others, cannot be one-size fits all and must account for regional, social and ecological heterogeneity, dietary preferences, the needs of small-scale producers, inequalities in food access and waste, land tenure and technological readiness. Hence, a plurality of solutions should be explored to address the diverse narratives and needs.

Strategies to curb corporate influence, such as competition policies that account for the impacts of excessive market concentration, and measures to strengthen transparency and deprioritise profit-making over the right to food, are also important. Scholars also argue for the importance of regrounding food systems in regional circuits of production and consumption. Others call for recognising social innovations such as informal community gardening, as well as food system precarity and trade dependencies, to ensure food security.

Sustainability transformations research shows that fundamental food systems change might take decades, so action cannot be delayed any further. Sufficiency, regeneration, distribution, commons and care are guiding principles to steer the restructuring of food systems.

Successful climate action requires justice-centred transformation of food systems

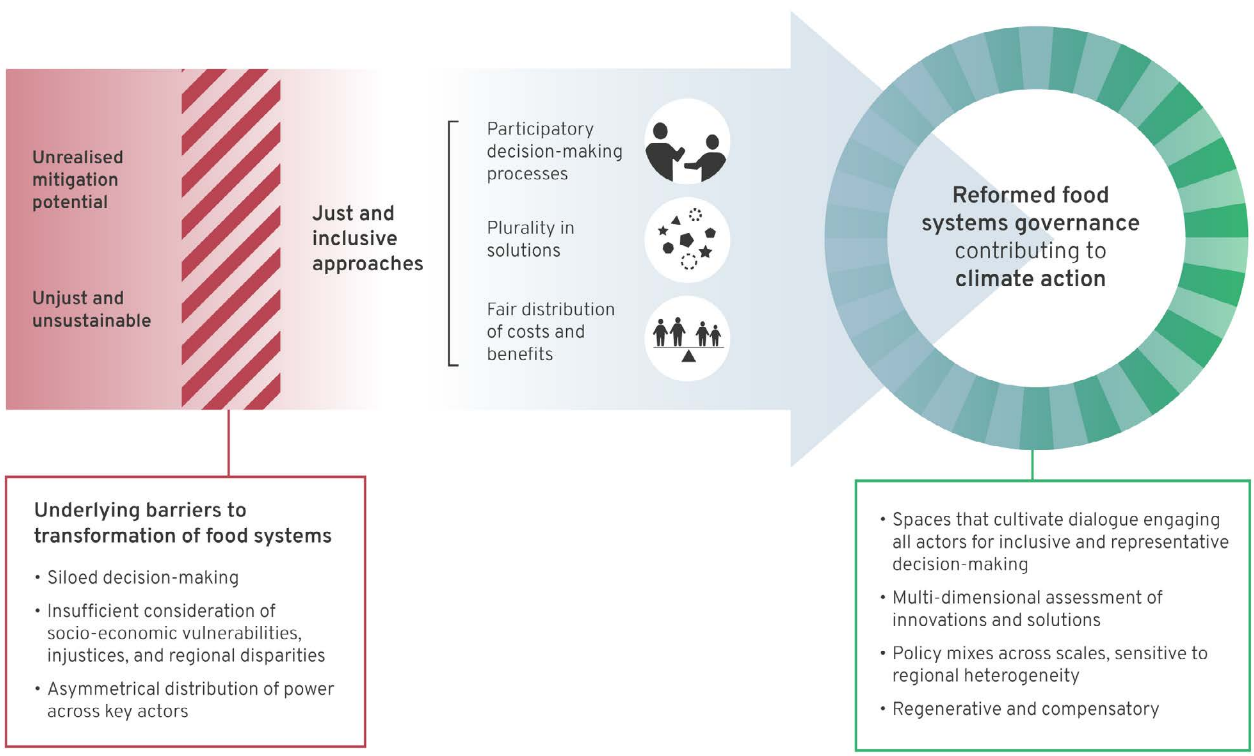

Figure 10. Just climate solutions for food systems transformations. Current food systems transformations for climate action are constrained due to siloed decision-making, insufficient consideration of regional disparities in geographies, innovation, socio-economic factors and power asymmetries across key actors, all of which act as barriers to effective climate action and result in unjust and unsustainable 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.

IN FOCUS: A CHECKLIST TOWARDS POLICYMAKING FOR JUST FOOD SYSTEMS

A Analyse current food system governance mechanisms in the region to identify existing injustices, including institutional mechanisms that perpetuate them.

B. Reform entrenched power dynamics that serve to reinforce endemic injustices, and create spaces for previously unheard voices to engage in policymaking and dialogues.

C. Establish and utilise decision-making regimes to foster the co-design of policies and solutions, beginning with the initial steps of problem definition and information gathering, together with smallholder farmers, marginalised communities, diverse cultures, and public and private sectors.

D. Reflect regional dietary preferences, socio-ecological context, technological readiness, small-scale producer needs and societal challenges.

E. Design diverse policy mixes with multiple solutions at different scales.

F. Acknowledge trade-offs and compensate for losses.

This list is not exhaustive, but is a starting point to help move towards more just food systems transformations.

POLICY IMPLICATIONS

- International platforms should centre justice in approaches to and governance of food systems transformation by facilitating global dialogues and providing guidelines and recommendations for policy [see In Focus box: A, E].
    - For example, a working group on just transitions has been proposed for the Sharm el-Sheikh joint work on implementation of climate action on agriculture and food security. Such emphasis can be made at other platforms and dialogues such as the Food, Agriculture and Water theme day at COP28, the United Nations Food Systems Coordination Hub and the Agriculture Innovation Mission for Climate.
    - Global platforms should also highlight lessons learnt from agro-ecological farming practices that prioritise both land health and farmer well-being. For example, the Andhra Pradesh Community-Managed Natural Farming initiative, which engages over 6 million farmers who practise organic farming and traditional methods of cultivation across 8 million hectares.
- International negotiators and decision-makers should include food systems and agriculture within the Loss and Damage fund. For instance, the fund can support stakeholders affected by climate change and food systems policy change through anticipatory mechanisms by acting as a financial safety net [In Focus: F].
    - For example, farmers who received financial support in anticipation of a flood event in Bangladesh in 2020 from the Central Emergency Response Fund were more inclined to move their livestock and have more financial stability following the disaster.

- National-level policymakers must prioritise the engagement of marginalised populations and incorporate a justice lens into food systems and agricultural commitments within national policies such as the NDCs, NAPs and National Biodiversity Strategies and Action Plans [In Focus: C, D].
    - Although there was an increase in food systems measures across the updated NDCs, fewer than 50% of them mention smallholder farmers, Indigenous peoples and local communities in these measures.
    - An example of an updated NDC referring to these actors is Egypt. The nation's updated NDC includes topography-specific risk assessments and participatory approaches engaging farmers, civil society groups and cooperatives to advise on climate-resilient farming practices across the country.
- Local and regional policymakers should pursue alternative approaches to food systems governance, such as food policy councils that can act as convening spaces for stakeholders across different sectors and disciplines for open dialogues and consultations [In Focus: A, B, C].

Abbreviations

CBD
Convention on Biological Diversity

CDR
carbon dioxide removal

COP
Conference of the Parties of the UNFCCC

GHG
greenhouse gas emissions

Gt
gigatonnes – unit of mass measuring 1 billion metric tons

IPCC
Intergovernmental Panel on Climate Change of the United Nations

MRV
monitoring, reporting and verification

NAPs
national adaptation plans

NbS
nature-based solutions

NDCs
nationally determined contributions

UNFCCC
United Nations Framework Convention on Climate Change

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