10 NEW INSIGHTS IN CLIMATE SCIENCE

2025/2026

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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 change research. The result is the *10 New Insights in Climate Science*, delivered as two self-standing products: a peer-reviewed academic article and this science-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 2024 and June 2025.

For policymakers responding to the urgent challenge of the climate crisis, the *10 New Insights in Climate Science 2025/2026* offers credible guidance throughout 2026 and beyond.

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INSIGHTS AT A GLANCE

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1. **Evidence, uncertainty, and questions around record warm years 2023/2024.** While the transition to El Niño conditions helped amplify recent temperature records, these climate fluctuations alone are insufficient to explain the anomalies. The notable rise in Earth's energy imbalance in recent years suggests that global warming may be accelerating. This reinforces the urgency of narrowing the widening gaps in both emissions reductions and adaptation investments.

2. **Accelerating sea surface warming and intensifying marine heatwaves.** The unprecedented pace of ocean surface warming and the intensification of marine heatwaves are driving severe ecological losses, eroding coastal livelihoods, and compounding risks from extreme weather, while also weakening the ocean's role as a carbon sink. The evidence increasingly points to a dual urgency: accelerate adaptation investments and strengthen global mitigation to prevent further ocean and climate destabilisation.

3. **Global land carbon sink under strain.** A marked drop in the global land carbon sink in 2023 raises concerns about a more permanent increase in atmospheric carbon transfer from land and a shrinking 'remaining carbon budget'. In particular, Northern Hemisphere ecosystems, once considered more stable, are increasingly affected by wildfires and permafrost thawing. The possibility that natural sinks are weakening at the current level of warming underscores the urgent need to accelerate both emissions reductions and carbon removal.

4. **Climate change and biodiversity loss amplify each other.** Mounting evidence shows that climate change and biodiversity loss reinforce each other, creating a destabilising feedback loop that threatens both carbon storage and ecosystem resilience. Coordinated action across the Rio Conventions offers a pathway to maximise co-benefits and avoid policy fragmentation by prioritising the protection and restoration of biodiverse ecosystems and safeguarding natural carbon sinks.

5. **Climate change is accelerating groundwater depletion.** The global pace of groundwater depletion is rising compared to previous decades, with climate change disrupting aquifer recharge and amplifying socioeconomic demands. The environmental and socioeconomic risks include threats to agriculture and food security, as well as land subsidence and seawater intrusion.

6. **Observed and projected climate-driven increase in dengue.** Dengue has surged to its largest global outbreak on record. Climate-driven shifts in temperature have expanded mosquito habitats and lengthened transmission periods, compounding the effects of urbanisation, global connectivity, and inadequate waste management. Health systems are already strained under current outbreaks, but projections point to steeper increases this century.

7. **Climate change–related labour productivity and income loss.** Heat stress driven by climate change threatens global labour productivity and incomes. While direct losses are greatest in developing countries, the economic impacts will be felt globally, amplified through supply chains and international trade. Projected annual gross domestic product losses are substantially lower in low-emission scenarios, underscoring the urgency for more ambitious mitigation action.

8. **Safe scale-up of carbon dioxide removal is needed to tackle hard-to-abate emissions and climate risks.** The scale-up of carbon dioxide removal (CDR) is necessary to complement — not substitute — rapid emissions cuts. The development of strong international guidelines and support for research and innovation is essential to close the 'CDR gap' and support both near-term targets and longer-term climate stability, while ensuring environmental and social safeguards.

9. **Carbon credit markets – integrity challenges and emergent responses.** The rapid expansion of carbon credit markets has come with serious integrity challenges due to systematic flaws, with many projects overstating carbon sequestration and lacking additionality. Heavy reliance on low-quality credits risks delaying direct decarbonisation. Recent progress developing stronger benchmarks, transparency, and market standards, alongside a shift toward viewing credits as contributions rather than substitutes for direct emissions reductions, suggest a path towards more credible and constructive markets.

10. **Policy mixes outperform stand-alone measures in advancing emissions reductions.** Carefully designed policy mixes, especially those including carbon pricing, tend to deliver greater emissions reductions than individual measures. Policy mixes that include carbon pricing or reduced fossil fuel subsidies are especially effective; however, policy design must be tailored to the country context. Coordinated cross-sectoral approaches and harmonised reporting can help maximise learning and impact.

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Global climate indicators continue to signal increasing cause for concern. In early 2025, the World Meteorological Organization (WMO) confirmed that 2024 was the warmest year on record, with average temperatures reaching 1.55°C (± 0.13°C) above pre-industrial levels.[1] While this is not yet a breach of the Paris Agreement goal to keep long-term global warming below +1.5°C, it is a stark indication of just how close the world is to getting there. This exceptional warming was accompanied by record-breaking ocean heat content and sea level rise, dramatic glacier mass loss, and the second-lowest Antarctic sea ice extent observed.[1,2] The ongoing rise in global temperatures has fueled more frequent and intense extreme weather, including heatwaves, droughts, wildfires, storms, and floods, causing substantial human and economic losses.[3]

Despite these escalating risks, anthropogenic greenhouse gas (GHG) emissions have continued to increase through 2023 and 2024,[4] further driving the steady rise in atmospheric greenhouse gas concentrations.[2,5] Current global mitigation efforts remain insufficient. If fully implemented, the latest round of Nationally Determined Contributions (NDCs) would cut global emissions by just 5.9% (range: 3.2–8.6%) by 2030 compared to 2019 levels — far short of the 28% reduction needed to keep warming below 2°C, or the 42% necessary for 1.5°C by the end of the century.[6] The urgency to bridge the gaps in both ambition and implementation is heightened in the context of repeated delays by most parties to submit the updated NDCs. By early October 2025, only 62 countries, covering just 31% of all GHG emissions, had submitted updated NDCs.[7] Several major emitters, including China, India, and the European Union are yet to submit theirs. The lack of momentum on ambition and implementation presents one of the most pressing challenges for COP30 in Belém, Brazil.

With the Paris Agreement's rulebook now largely complete and mounting scientific evidence about the urgency of accelerating climate action, COP30 is widely seen as an "implementation COP": a pivotal moment in climate diplomacy to interrogate and overcome the persistent barriers holding back real-world progress on mitigation and adaptation. Parties must agree on ways to turn the outcomes of the Global Stocktake[8] (COP28, Dubai), especially the transition away from fossil fuels, into concrete actions for course correction. To this end, discussions about how to reform the COP process for the "post-negotiation phase" will continue to gather momentum. Climate finance remains a contentious unresolved issue, fundamental for enabling collective action. Following the decision of a New Collective Quantified Goal of USD 300 billion/yr (COP29, Baku), widely recognised as inadequate,[9] the Baku-Belém Roadmap was set up to find ways to reach the aspirational goal of USD 1.3 trillion/yr by 2035. While the geopolitical context is particularly challenging, these priorities require reinvigorating multilateralism and multilevel governance.

Science has a critical role in informing governance for the implementation of climate commitments at international, national, and subnational levels. The Intergovernmental Panel on Climate Change (IPCC) is the primary scientific body informing the United Nations Framework Convention on Climate Change (UNFCCC) process. However, given their comprehensiveness and procedural demands, each Assessment Report from the IPCC has a multi-year production cycle. The *10 New Insights in Climate Science* initiative is an annual collaborative effort, to curate and

1 WMO. *State of the Global Climate 2024.* World Meteorological Organization (2025).

2 C3S. Global Climate Highlights. *Copernicus Climate Change Service - EU Observation Programme* (2025).

3 Otto, F. et al. When Risks Become Reality: Extreme Weather in 2024. *World Weather Attribution* (2024).

4 Friedlingstein, P. *et al.* Global Carbon Budget 2024. *Earth Syst. Sci. Data* 17, 965–1039 (2025).
Forster, P. M. *et al.* Indicators of Global Climate Change 2024: Annual update of key indicators of the state of the climate system and human influence. *Earth Syst. Sci. Data* 17, 2641–2680 (2025).

5 NOAA-GML. *Trends in CO_2, CH_4, N_2O, SF_6.* Global Monitoring Laboratory of the National Oceanic & Atmospheric Administration (2025).

6 UNEP. *Emissions Gap Report 2024.* United Nations Environment Programme: Nairobi (2024).

7 Climate Watch. *Nationally Determined Contributions (NDC) Tracker.* World Resources Institute (2025).

8 UNFCCC. *Outcome of the First Global Stocktake. FCCC/PA/CMA/2023/16/Add.1 Decision 1/CMA.5.* (2023).

9 Bhattacharya, et al. *Raising Ambition and Accelerating Delivery of Climate Finance. Grantham Research Institute on Climate Change and the Environment, LSE: London.* (2024).

synthesise key messages across diverse fields of climate change research, based on the latest relevant peer-reviewed literature. This year, the synthesis is built on the collective effort of over 70 researchers, based on input from more than 150 experts across the world. The ultimate aim is to support the timely uptake of new scientific evidence in policy processes and international governance spaces.

The first four insights of this year's report revolve around Earth system processes and highlight the concerning possibility that global warming is accelerating. Recent analyses of global climate indicators in 2023 and 2024 point to an elevated Earth energy imbalance (Insight 1), a significant surge in ocean heat uptake and marine heatwaves (Insight 2), and a sharp drop of the global land carbon sink (Insight 3). These geophysical developments underscore the narrowing window available to minimise temperature overshoot and stabilise the climate within the Paris Agreement temperature range. Furthermore, new analyses show biodiversity loss in itself can exacerbate climate change, as it underpins ecosystem functions of carbon uptake and storage (Insight 4). This first cluster of insights reinforce the urgency for ambitious mitigation plans and effective implementation.

Next, three insights focus on impacts of climate change on water security, human health, and livelihoods and productivity: acceleration of groundwater decline (Insight 5), the ongoing and future expansion of dengue (Insight 6), and increasing heat-induced losses in labour productivity and global income (Insight 7). These impacts are already affecting populations in different regions, but risks are significantly larger at higher levels of temperature overshoot. Adaptation efforts must be rapidly scaled up to reduce the increasing socioeconomic consequences. However, there are limits to adaptation, and in the absence of ambitious mitigation, healthcare systems could be overwhelmed and economies severely weakened.

The third and final cluster of insights focuses on key aspects for enhancing mitigation. Two mitigation approaches that have a vital but complementary role to direct GHG emissions reductions are carbon dioxide removal (CDR) and carbon credit markets. Responsibly scaling CDR is a necessity for stabilising the climate, especially in the context of temperature overshoot, but deployment remains far below the levels needed (Insight 8). With voluntary carbon markets (VCM), the pervasiveness of low-quality credits stands out as a key problem, which might contribute to further delaying direct decarbonisation (Insight 9). Closing the 'CDR gap' and addressing the systemic integrity flaws in VCMs require comprehensive policy frameworks. Fortunately, there is now a wealth of knowledge on effective climate policies that builds on four decades of policy experimentation and recent systematic reviews. A key lesson is that carefully tailored policy mixes, especially those including carbon pricing, tend to achieve greater and more robust emissions cuts (Insight 10).

We hope that the *10 New Insights in Climate Science 2025/2026* will reach Party and Observer delegations to the UNFCCC, help inform their positions and arguments, and ultimately be reflected in the outcomes of COP30 in Belém, Brazil, and beyond. In particular:

- Strengthening the operationalisation of Global Stocktake outcomes through enhanced NDC transparency and accountability mechanisms that embed science-based emission reduction pathways consistent with the Paris Agreement goals – specifically by establishing standardised progress indicators and reporting frameworks that track countries' progress transitioning away from fossil fuels.

- Promoting the integration and coordination between the UNFCCC and CBD to strengthen forest conservation and restoration to safeguard biodiversity and land carbon sinks. Specifically, by advancing the operationalisation of the CBD COP16 decision on biodiversity-climate coordination.

- Finalising and formally adopting the list of 100 adaptation indicators proposed under the UAE-Belém Work Programme, providing the necessary political guidance to resolve outstanding divergences regarding shared definitions and overarching conceptual issues regarding the indicators related to 'means of implementation'.

- Formally recognising distinct roles of CDR in climate mitigation, specifically to counterbalance hard-to-abate residual emissions and, eventually, to enable net-negative emissions. To avoid delaying or deterring direct decarbonisation, separate targets and accounting are required for emissions reductions versus carbon removals to ensure transparent reporting in NDCs and Article 6 transactions.

- Adopting stringent quality standards for both voluntary and compliance mechanisms as part of the operationalisation of high-integrity carbon markets under Article 6. This requires robust measurement, reporting, and verification systems; and safeguards for permanence of stored carbon and for risks of reversibility; and testing of additionality and prevention of double-counting.

- Establishing an official knowledge-sharing platform that systematically consolidates and synthesises evidence on effective climate mitigation policies and policy combinations.

The science underpinning each of the insights presented in this report is described in more detail and with all the supporting references in:

Ospina, D., Mirazo, P., Allan, R.P., Basnett, S., Bastos, A., Bhattarai, N., Broadgate, W., Broekhoff, D.J., Bustamante, M., Chen, D., Choi, Y., Cox, P., Domeignoz-Horta, L.A., Ebi, K.L., Friedlingstein, P., Frölicher, T.L., Fuss, S., Goessling, H.F., Gruber, N., He, Q., Hebden, S., Hedrich, N., Heilemann, A., Hirota, M., Hodnebrog, Ø., Hugelius, G., Izquierdo-Tort, S., Juhola, S., Kasuga, F., Ke, P., Kelley, D.I., Kilkiş, Ş., Kotz, M., Kumarasinghe, N., Lamb, W.F., Lee, S., Liu, J., Maesano, C.N., Martin, M.A., Mazzochini, G.G., Merchant, C.J., Mishra, V., Mori, A.S., Morris, J., Persson, Å., Pörtner, H., Probst, B.S., Ramage, J., Razanatsoa, E., Redman, A., Rockström, J., Rodrigues, R.R., Ruehr, S., Ryan, S.J., Sanchez-Rodriguez, R., Schleussner, C., Schlosser, P., Scott, W.A., Semenza, J.C., Seybold, H., Shindell, D.T., Sioen, G.B., Smith, K.E., Sokona, Y., Stechemesser, A.H., Stocker, T., Su, S.H.L., Thiam, D., Trencher, G.P., Virkkala, A., Warszawski, L., Weiskopf, S.R., Wu, H.C., Zhu, S. (under review) Ten New Insights in Climate Science 2025. *Global Sustainability*. doi: 10.5281/zenodo.17457864

10 NEW INSIGHTS IN CLIMATE SCIENCE

THE INSIGHTS

1 Evidence, uncertainty, and questions around record warm years 2023/2024

KEY MESSAGES

- The years 2023/2024 saw record warmth. The unprecedented magnitude of warming, as well as a significantly elevated Earth energy imbalance (EEI), suggest an acceleration of global warming.
- The recent temperature surge cannot be fully explained based on the long-term warming trend and typical year-to-year fluctuations, even though the transition from La Niña to El Niño in 2023/2024 made it more likely. This suggests other factors are at play.
- The elevated EEI is driven by rising greenhouse gas levels, and exacerbated by the reduced reflection of sunlight from the planet, associated with fewer and less reflective clouds over the oceans (linked to declining aerosol emissions), as well as less ice cover.

Since 2023, global surface temperatures have shattered previous records. While the shift from La Niña to El Niño was expected to warm the planet, the intensity, extent, and persistence of the heat have been unprecedented, and temperatures remain elevated into 2025. This coincides with an elevated Earth energy imbalance (EEI): the difference between energy input from absorbed sunlight (shortwave radiation) and output in the form of infrared (longwave) radiation to space. Since 2000, the increasing in EEI has largely been due to the reduction in the sunlight being reflected from the planet (planetary albedo), resulting in a greater heating rate and so an acceleration of global warming. The role that feedback, declining aerosol particulate pollution, internal ocean variability, and other factors play in warming remain debated. Here, we assess how unusual the 2023/2024 level of warmth was in the context of climate variability, the role of elevated EEI in explaining this warmth, and the factors that may explain the elevated EEI, all of which have implications for the rate of climate change over the coming decades.

A large jump in global temperatures in this period was more likely thanks to the transition from a prolonged La Niña phase to an El Niño in 2023/2024. However, the recent surge does not entirely reconcile with the long-term warming trend combined with internal variability, particularly given that the 2023/2024 El Niño was not as strong as previous ones. This emphasises a need to investigate other contributing factors and to scrutinise changes in Earth's energy budget.

Physically, the substantial warming from 2022 to 2023 was a consequence of how much heat was absorbed by Earth's surface layers. The EEI during mid-2022 to mid-2023 more than doubled the 2006–2020 average and is at the upper level of what models predicted. Around 15–20% of this contributed to atmospheric and land warming and, to a lesser extent, the melting of ice, while the remainder heated the ocean. This heating is not sufficient to explain the magnitude of sea surface warming, unless it was concentrated in the shallow, upper-most ocean layers or additional heat from beneath the ocean surface was released during the transition to El Niño in 2023 and this added to the larger EEI heating from above (see Insight 2).

EEI increases since 2000 are mainly the result of the greater absorption of sunlight, which is primarily

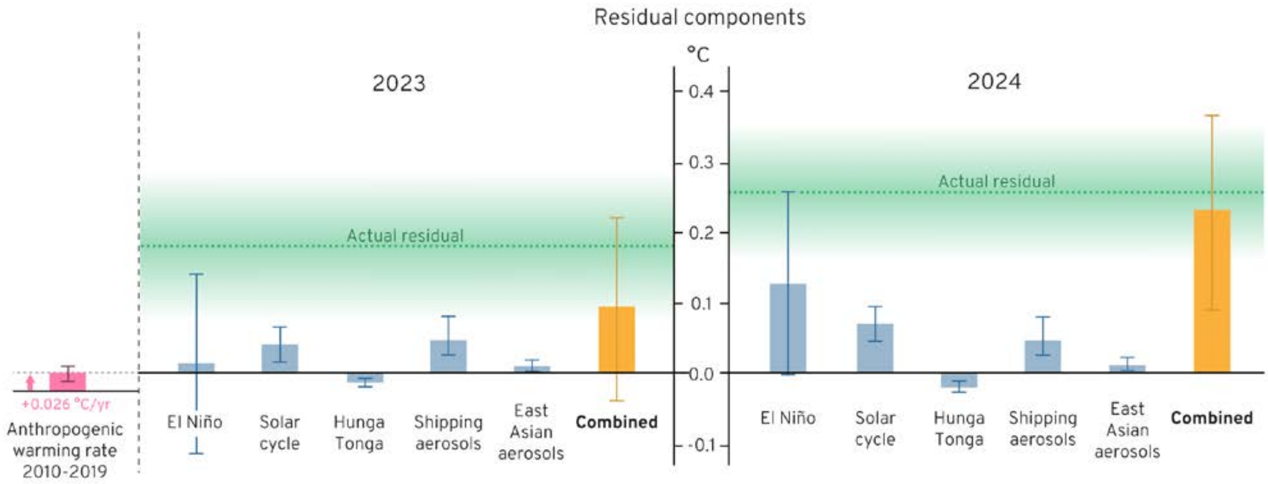

Figure 1. Estimates of contributing factors to the anomalous global mean temperatures in 2023 and 2024 adding to the annual warming effect. The actual residual (green dashed line; fading indicates uncertainty) is the difference between the annual 2023/2024 global mean temperature and a 20-year trend (pink bar), while individual components (blue vertical bars) are contributions to the residuals for each of the two years (uncertainty bars nominally represent the 95% confidence level). The data displayed are from WMO (2025), and Figure 12 especially (cf. Forster et al. 2025 for a similar analysis, with slightly different values). It is important to note that the data shown are only indicative and represent preliminary estimates.

associated with reduced reflectivity over cloudy regions of the ocean. A moderate additional heating from the 11-year solar cycle also contributed to the warming (Figure 1). Effects from volcanoes, wildfires, and reduced Sahara dust in June 2023 are considered small at the global scale. A considerable factor in the elevated EEI and associated warming from 2001–2019 is reductions in sulphate aerosol pollution (Figure 1). Regulations implemented in 2020 reduced sulphur emissions from international shipping by ~80% creating a heating effect as less sunlight was reflected because of sulphate aerosol effects on clouds. This is mostly estimated to have a moderate effect on global surface warming, though there is a potentially large regional change over mid-latitude oceans in the Northern Hemisphere (Figure 1). Land-based anthropogenic aerosol emissions have also declined in recent decades. Aerosol emissions peaked over East Asia in the early 2000s and have since rapidly decreased, significantly contributing to global warming during 2010–2023 as well as to record high sea surface temperatures in the Northeast Pacific. While extra absorbed sunlight associated with declining East Asian aerosol is linked with long-term warming, their contribution to the 2023/2024 level is less obvious (Figure 1). It is thought that reducing aerosol emissions where pollution has already been mitigated somewhat, such as in East Asia or over the still moderately pristine open ocean, will have a larger effect on making clouds reflect less sunlight.

Uncertainties remain around the causes and implications of the record heat since 2023. Aerosol-cloud interactions and cloud feedbacks are difficult to model with precision, and coarse-resolution global models cannot adequately represent ship tracks, adding to the uncertainty of the impact of reduced sulphur emissions from shipping. A more robust quantification of the cloud feedback, including how the shrinking of cloud zones contributes to reduced planetary albedo, can inform to what extent global warming is accelerating because of these effects. EEI observations from the Clouds and the Earth's Radiant Energy System (CERES) since 2000 are essential for improving models but are at risk as satellites age.

In summary, new insights add to the evidence that a combination of cloud feedback responses to global warming and reduced reflection of sunlight by clouds as aerosol emissions decline have plausibly contributed to the long-term increase in the absorption of sunlight by the planet since 2000. The exact relative importance of these drivers and the role of internal ocean variability in growing EEI have not been established. These are essential for reducing the range in climate sensitivity estimates, but existing analyses already indicate that very low estimates are unlikely. Extra planetary heating and a transition from an extended La Niña to El Niño in 2023 were instrumental in explaining the record global warmth in 2023/2024. Current levels of global temperature are consistent with a continued acceleration of global warming, and surpassing the 1.5°C threshold above pre-industrial conditions seems inevitable. Once again, the evidence underscores how essential rapid and massive cuts in greenhouse gas emissions are for limiting further warming and associated impacts on societies and ecosystems.

POLICY IMPLICATIONS

- The acceleration of global warming implies that current gaps in both emissions reductions and adaptation investments are even wider than currently estimated. Closing these gaps requires:
    - Above all else, greater ambition and effective implementation of new Nationally Determined Contributions (NDCs), including economy-wide targets, sector-specific measures, and coverage of all major GHGs.
    - Strengthening adaptation components in new NDCs in alignment with National Adaptation Plans (NAPs).
    - Scaling up carbon dioxide removal (CDR), which gains further importance, given the insufficient mitigation effort thus far. Yet, CDR targets are seldom considered explicitly in current NDCs (see Insight 8).
    - Advancing sectoral transformation towards Global Stocktake benchmarks by 2030: transitioning away from fossil fuels across energy systems, tripling renewable energy capacity, doubling the rate of energy efficiency improvements, and halting or reversing deforestation.
    - Faster and deeper mitigation by G20 countries in line with fair-share and cost-effective emission reduction pathways, as outlined by the UNEP Emissions Gap Report (2024).
    - Scaling up adaptation finance and enhancing capacity-building and technology transfer.
- The geophysical changes underpinning the observations from 2023–2024 suggest that large ensemble model projections informing the UNFCCC policy process may be increasingly underestimating the pace and magnitude of global warming. Reducing uncertainties and refining models, especially concerning the role of aerosols and clouds in the Earth's energy budget, should therefore be a scientific priority. This requires sustained funding and protection of scientific research.
- Observations of the Earth energy imbalance (EEI), along with improved cloud and aerosol diagnostics, are crucial for improving models and estimates. Parties need to protect and fund global climate monitoring capabilities and ensure the continuity of data.
    - In this regard, the NASA mission CERES (Clouds and the Earth's Radiant Energy System) has been essential, but is now at risk due to aging satellites. Initiatives like the WMO's Global Climate Observing System and the Systematic Observations Financing Facility should receive further support to maintain and improve EEI observational infrastructure.

2 Accelerating sea surface warming and intensifying marine heatwaves

KEY MESSAGES

- **Ocean warming is accelerating. Global mean sea surface temperature records were continuously broken from April 2023 to June 2024. Marine heatwaves (MHWs) have become more frequent, intense, and persistent globally over the past four decades.**
- **Exceptional sea surface temperatures tend to strengthen extreme weather events (e.g., heatwaves, cyclones) and increase the likelihood of intensifying hurricanes (Atlantic, Caribbean, and Pacific).**
- **MHWs are causing severe, widespread, and in some cases likely irreversible ecological impacts, affecting biodiversity and coastal livelihoods, such as fisheries, tourism, and coastal protection.**
- **The ocean is a critical carbon sink, but its capacity to uptake carbon dioxide from the atmosphere is reduced as its surface warms.**

The global average temperature of the ocean surface serves as a key indicator of climate change, and in April 2023, it reached record-breaking levels. For the following 13 consecutive months, new records were set for global sea surface temperature: May 2023 exceeded all previous Mays, June 2023 all previous Junes, and so on. As the largest sink for Earth's accumulating heat, the ocean sets the pace for global warming, and that pace is accelerating. Impacts on ocean life are widespread, often severe, and in some cases probably irreversible.

Mean global sea surface temperature for 2024 was 0.6°C warmer than the average between 1981–2019, slightly warmer than 2023, and about 0.9°C warmer than pre-industrial levels. Between April 2023 and March 2024, temperatures exceeded previous records set in 2015–2016 by an average of 0.25°C. While it is not unexpected that El Niño years break records, the 2023–2024 El Niño was not particularly intense and the magnitude of exceedance is large: one study showed that the acceleration of the underlying warming trend, driven by the Earth's energy accumulation over the past decade (see Insight 1), is physically plausible and now statistically detectable. Furthermore, the acceleration of global mean sea surface temperature is consistent with the well-established accelerations in ocean heat content and sea level rise.

The rise in global ocean temperature is accompanied by an increasing incidence of marine heatwaves (MHWs), which last days to months and exert catastrophic ecological and socio-economic impacts. The persistence of MHWs detected, based on a fixed baseline (Box 1), has increased. They last a week longer on average than they did four decades ago. The intensity and persistence of MHWs, detected based on a fixed baseline (Box 1), has increased. Annual MHW days have risen by 54% in the past four decades, from 20–30 days long in the 1980s to 40–50 days during 2000–2016. These changes are in part driven by the weakening interaction between the upper and the deeper ocean, as the upper waters warm faster and become relatively more buoyant (less dense and therefore strengthening stratifica-

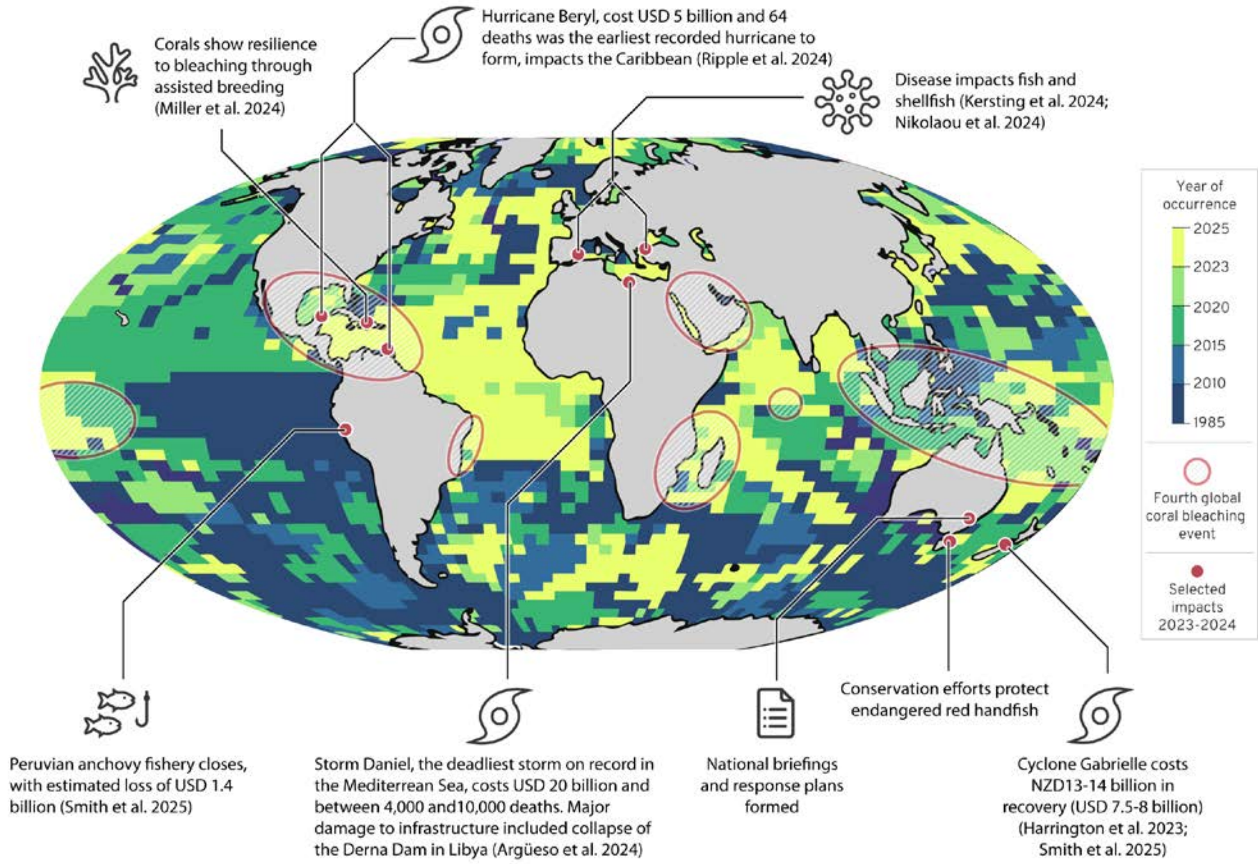

Figure 2. The impacts of the exceptional marine heatwaves in 2023–2024, which was also the period of occurrence of the warmest sea surface temperature (relative to the seasonal normal) in the satellite record since 1985. Dataset: ESA Climate Change Initiative Sea Surface Temperature v3 (Embury et al. 2024).

tion). Climate models consistently project further increases in both the frequency and intensity of MHWs under continued global warming.

MHWs also occur in the subsurface ocean, where the majority of fish live and diurnally migrate. Heatwaves in this layer can be more intense than their surface counterparts and most of them do not co-occur with surface ones. They are often caused by ocean eddies and are intensifying more rapidly (0.1–1°C per decade) than the rise in mean temperature (around 0.1°C per decade). Despite a growing recognition of the ecological importance of subsurface MHWs, there is a scarcity of observations, making it difficult to fully understand their dynamics and impacts.

Oceanic warming has consequences beyond the oceans themselves: the weather and seasons experienced by human populations are strongly determined by the warmth of the ocean. Exceptional sea surface temperatures tend to strengthen European heatwaves and increase the likelihood for intensification of Atlantic, Caribbean, and Pacific hurricanes. Several studies also link MHWs to extreme weather events like hurricanes, cyclones, flooding and atmospheric heatwaves, which have vast economic costs. The recovery from Cyclone Gabrielle, which was fuelled by an MHW, for example, cost USD 7.5–8.5 billion; the closure of the Peruvian anchovy fishery following a shift in species range (Figure 2) led to a USD 1.4 billion loss; and closures or reduced quotas in North American fisheries often follow MHWs. A warmer ocean surface also reduces the uptake of CO_2 from the atmosphere: recent estimates

BOX 1. DEFINITION OF MARINE HEATWAVES

Marine heatwaves (MHWs) are periods of abnormally high sea surface temperatures that persist for days to months or even longer and can extend across thousands of square kilometres. MHWs are commonly defined as seawater temperatures exceeding the 90th percentile relative to a baseline climate conditions for at least five consecutive days. These events can occur at the surface or subsurface and have wide-ranging ecological, biogeochemical, and socio-economic impacts.

point to a global net reduction of 8% during MHWs over 1990–2019, reducing the mitigation of human carbon emissions.

Declines in foundation species like macroalgae, seagrass and corals in many coastal ecosystems around the world are associated with MHWs, as highlighted in Figure 2. The fourth global coral bleaching event (a heat-stress response in which the algae that give corals their colour are lost) was declared in 2024. Even in the tropical Atlantic, where corals are considered more resilient to bleaching, massive bleaching events occurred in response to increases in frequency and intensity of MHWs over the last two decades. In the Mediterranean, MHWs worsened outbreaks of disease and increased mortality in fish and shellfish, and satellite observations identified shifts in the size and biomass of phytoplankton linked to MHWs in the Western Baltic Sea, South Atlantic, and eastern boundary upwelling systems.

The responses of marine species can vary and often depend on where within a species' geographic range the MHW occurs, complicating efforts to predict and interpret biological impacts. Trophic models, which show the flow of energy and nutrients through a food web or ecosystem, indicate that at the community scale, MHWs significantly reduce biomass across all consumer levels, with higher species most affected, altering ecosystem structure and function. Some "wins" are reported, with corals bred for heat tolerance demonstrating resistance to bleaching, and conservation efforts show some potential for preserving endangered species.

But the widespread impacts driven by MHWs are occurring more often and more intensely. Ultimately, to mitigate future ecological, economic, and societal losses, rapid measures to reduce greenhouse gas emissions and limit ocean warming are essential.

POLICY IMPLICATIONS

- Quantifying the economic toll of marine heatwaves (MHWs) on fisheries, aquaculture, and tourism highlights the need for climate-smart marine policies and early warning systems to support the resilience of "blue economies".

- The intensification of MHWs strengthens the case for incorporating marine-specific targets, especially for ocean-based livelihoods and biodiversity, as part of the Global Goal on Adaptation indicators.

- To enable proactive adaptation and ecosystem-based management, coastal and ocean governance frameworks such as Marine Spatial Planning and Marine Protected Areas should incorporate MHW risk projections.

- Existing initiatives, such as WMO's Early Warnings for All (EW4All), should expand coverage to MHWs and ocean hazards, particularly in the Global South, where ocean-dependent communities face disproportionate risks.

- At the multilateral level, coordination is necessary to enhance the exchange of best practices in coral reef restoration, adaptive fisheries policies, and nature-based ocean solutions. These efforts should be anchored to Article 7 of the Paris Agreement (on the Global Goal on Adaptation) and regional frameworks, such as the SAMOA Pathway or the Mediterranean Strategy for Sustainable Development.

- While the points above focus on adaptation, the unfolding impacts of MHWs add urgency to the call for accelerating global mitigation efforts. As listed above, meeting the Paris Agreement temperature goals requires phasing out fossil fuels across energy systems, tripling renewable energy capacity, doubling energy efficiency, and halting/reversing deforestation by 2030. The new Nationally Determined Contributions (NDCs), especially those of the G20 countries, will have to reflect greater ambition, including targets for sustainably scaling up carbon dioxide removal (CDR), as well as much more effective implementation.

3 Global land carbon sink under strain

KEY MESSAGES

- The global land carbon sink dropped sharply in 2023, deepening scientific concerns about the weakening of the processes through which terrestrial ecosystems absorb and store carbon. Wildfires, in particular, are increasingly impacting the global carbon cycle.
- Weaker land carbon sinks have been identified, not only in tropical ecosystems, but also in high latitude regions, which had been considered more stable carbon sinks. While the response in the tropics is mainly due to El Niño, the high latitude changes suggest longer-term shifts.
- There are indications that, over the past decade, carbon transfer to the atmosphere from Northern Hemisphere ecosystems is accelerating. If so, the overall land carbon sink would be smaller than currently anticipated, which would imply an even lower remaining carbon budget.

Natural land carbon sinks, including forests and soils, are under pressure. Increasing wildfires, droughts, heatwaves, and permafrost thaw are diminishing the ability of ecosystems to absorb and store carbon, in some cases turning them from carbon sinks into net sources. If this is the case, more of the carbon emitted by humans will end up in the atmosphere, with potentially drastic consequences for the pace of global warming. Here, we assess the evidence of short- and long-term changes in the global natural carbon sink on land, as well as new signs of vulnerability in northern land ecosystems.

The global land carbon sink doubled from 1.2 ± 0.5 gigatonnes of carbon per year (GtC/yr) in the 1960s to 3.1 ± 0.6 GtC/yr in the 2010s (Figure 3A). This was primarily driven by CO_2 fertilisation, which boosts photosynthesis, especially in tropical forests; nitrogen deposition; warming temperatures; and reduced cold limitations in the high latitudes, leading to increases in forest biomass. Yet in the near future, climate-driven disturbances and extreme weather threaten to overwhelm these benefits.

A drop in the global land carbon sink in 2023 (Figure 3A) coincided with record annual global temperatures in a year with strong El Niño conditions. This drop reflects terrestrial ecosystems responding negatively to extreme events. The Global Carbon Project estimates the land carbon sink in 2023 to have been 2.3 ± 1 GtC/yr, well below a La Niña–induced strong sink of 3.9 ± 1 GtC/yr in 2022 or the average of 3.2 ± 0.9 GtC/yr from 2014–2023. However, some uncertainty in the land carbon sink's magnitude persists across studies, with some including land use emissions of about 1± 0.7 GtC/yr in 2023 and thus a reduced sink. The weakening in the land carbon sink in 2023 is not wholly unusual (Figure 3A), and it recovered somewhat in early 2024: large drops have occurred in the past, usually in conjunction with El Niño years, and they subsequently recovered. Long-term decline may depend on whether the record warmth and widespread extremes of 2023–2024 reflect typical variability layered over long-term warming or mark a deeper shift in the climate system.

Above-average amounts of carbon were released into the atmosphere from multiple terrestrial biomes in 2023, all with different drivers and dynamics. Tropical ecosystems were a weaker carbon sink than in previous years (Figure 3B), declining by 58%

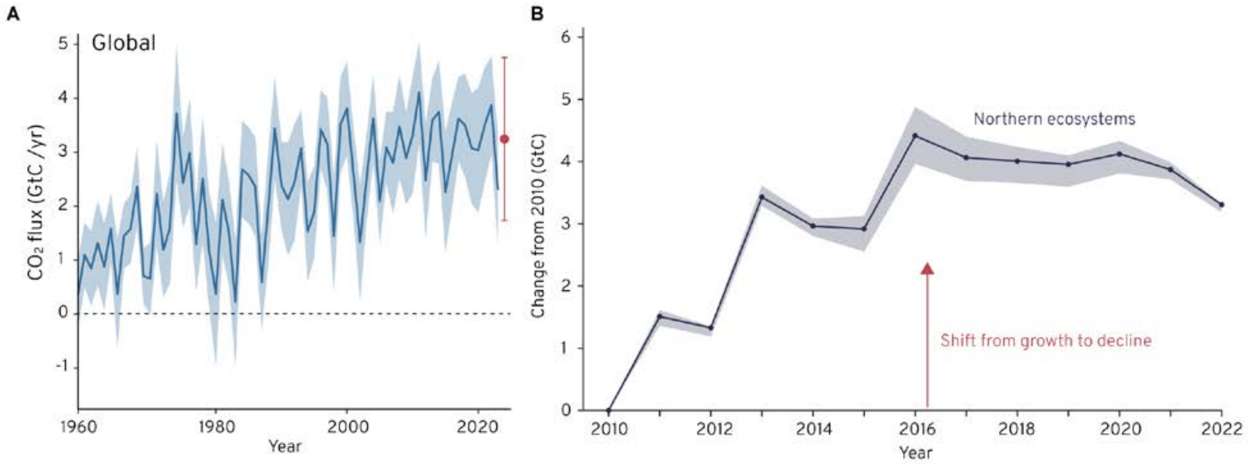

Figure 3. Temporal evolution of the global land carbon sink and associated uncertainties from 1960 to 2023 and recent changes in live biomass in northern ecosystems. Panel A: Global CO_2 flux (GtC/yr), where positive values indicate an increase in the land carbon sink. The dark line represents the annual mean net fluxes, with the shaded area denoting ±1 standard deviation uncertainty. The red dot shows the projected land carbon sink for 2024 with associated uncertainty (redrawn from Friedlingstein et al., 2025). Panel B: Annual variations in live biomass carbon stocks, expressed as the difference from 2010 values in northern ecosystems. The year 2016 marks a turning point after which biomass begins to decline (redrawn from Li et al. 2025).

from 2.8 GtC/yr in 2022 to 1.2 GtC/yr in 2023. El Niño–influenced warming and drying led to reduced vegetation productivity in the Sahel and southern Africa and decreased vegetation carbon uptake in the Amazon region. Wildfires in Canadian boreal forests released 0.65 ± 0.08 GtC – comparable to the European Union's annual fossil fuel emissions, offsetting several years of carbon uptake in these previously undisturbed forests.

The record-breaking fire emissions in boreal forests in 2023 are part of a broader shift. Once warming exceeded around 1°C globally, fire began to significantly impact global carbon storage. With burnt area projected to increase under global warming, emissions from wildfires further constrain the anthropogenic emissions limits to meet the 2°C target. The Canadian fires garnered significant attention, which is indicative of growing concern about the vulnerability of the northern extratropical land carbon sink. Emerging evidence also points to growing instability in northern land ecosystems, which have been considered more resilient to climate change. Although still a net carbon sink, recent studies using empirical and model-based approaches indicate a flattening or decline in the annual carbon sink in extra-tropical northern land ecosystems over recent decades. A shift from a growing to a decreasing trend in the live carbon biomass (a significant component of the land carbon sink) in northern ecosystems since 2016 (Figure 3B) may be a sign of accelerating carbon transfer from vegetation to the atmosphere.

Carbon uptake in boreal forests has declined significantly in recent decades for reasons beyond fires – for example, insect outbreaks, drought, and abnormal heat-induced mortality. Including emissions from land use change and management, average carbon stored in boreal forests decreased by 36% between 2010–2019 compared with the previous two decades, but increases in carbon sinks in tropical regrowth and temperate forests kept the global carbon sink stable on average over the past decade.

The permafrost region – including tundra and most of the boreal biome – is affected by profound, warming-induced changes, which make it less able to absorb and retain carbon. While the northern permafrost remains a net CO_2 sink, around a third of the Arctic-boreal land area has become a net source, and evidence suggests that the tundra biome is no longer a sink. When we include net greenhouse gas – not just CO_2, but also CH_4, and N_2O – emissions from inland waters, fires, and abrupt permafrost thaw, the region may already be a net source of carbon of 0.14 GtC/yr (−0.51, 0.83; 95% confidence interval).

Understanding the long-term impact of extreme events on the land carbon sink remains a challenge. Fires and droughts cause large, immediate carbon losses, but the amount of carbon remaining in the atmosphere (versus being reabsorbed by the land) depends strongly on the pace and extent of ecosystem recovery after disturbance. However, the rate and completeness of this recovery remains uncertain, making it difficult to predict the longer-term consequences for atmospheric carbon. Vegetation models do not represent forest regrowth well after fires, leading to a systematic ~1GtC underestimation of the northern land carbon sink, but lack of phosphorus limitation in vegetation models leads to overestimation of the tropical land carbon sink. Given the different drivers of dynamics in northern compared to tropical land ecosystems, the implications may be a smaller overall anthropogenic carbon budget for a given temperature target.

Because of these uncertainties, as global temperatures continue to rise, the capacity of land ecosystems to buffer climate change cannot be taken for granted. Strengthening knowledge is essential for credible climate policy.

POLICY IMPLICATIONS

- The weakening of the terrestrial carbon sink in the Northern Hemisphere implies a smaller "remaining carbon budget". This fundamentally affects current emissions accounting and target-setting under the Paris Agreement, requiring even faster GHG emission reductions and deployment of carbon removal.

- Climate projections used as a basis for mitigation pathways, targets, and national plans should incorporate the most updated scientific understanding on the state of natural carbon sinks and their stability under plausible emissions scenarios.

- Current NDCs systematically exclude permafrost emissions, despite the fact that the permafrost region holds the planet's largest soil carbon pool and may already be a net source of carbon. Therefore, it is urgent to establish mandatory reporting requirements for permafrost emissions.

- The Global Greenhouse Gas Watch (G3W), set up by the WMO to monitor, attribute, and forecast GHG fluxes (including those arising from land degradation and biosphere-climate feedbacks), has a fundamental role in integrating Earth system observations into national inventories and stocktake assessments. The new standardised permafrost monitoring guidelines are a particularly timely addition.

- Climate policy for mitigation and adaptation must be jointly addressed in landuse planning and ecosystem governance. Ecosystem resilience, recognised as a priority for the Global Goal for Adaptation (GGA), becomes increasingly relevant also for mitigation under these circumstances. Appropriate soil and land management techniques that build ecosystem resilience against intensified wildfires and permafrost thawing can therefore contribute to reducing the transfer of carbon to the atmosphere. Relatedly, the UN Decade on Ecosystem Restoration, Reducing Emissions from Deforestation and Forest Degradation (REDD+), and initiatives under the UN Forum on Forests could be recalibrated beyond the forest area to include resilience-building against fire, drought, and warming impacts on boreal and tropical sinks.

4 Climate change and biodiversity loss amplify each other's impacts

KEY MESSAGES

- **Climate change is impacting biodiversity from local to global scales, and growing evidence suggests that further loss of biodiversity can contribute to climate change, creating a destabilising feedback.**
- **Loss of plant diversity due to climate and land use change can weaken ecosystem functioning, leading to a decrease in biomass accumulation and reduced carbon storage.**
- **Natural climate solution initiatives that integrate aspects of ecosystem integrity and species composition, rather than focusing solely on land cover area, can more effectively safeguard the carbon sink function.**

Climate change and biodiversity loss are two of our most pressing and interlinked environmental challenges. Multiple studies demonstrate the potential impact of climate change on biodiversity at local to global scales: 3–6 million (or more) animal and plant species are threatened, even under intermediate climate change scenarios. There is also growing evidence that a loss of biodiversity contributes to destabilising feedback, directly impacting climate stability. Studies consistently find that higher plant diversity on land can increase ecosystem functioning, including carbon storage, and these effects grow stronger as time goes on (see Table 1 for the mechanisms).

Because higher plant diversity leads to greater biomass within a place over time, loss of plant diversity from climate and land use change can lead to decrease in biomass and reduced carbon storage. A recent study found that projected global plant-species loss could lead to the emission of 7–146 GtC in the coming decades (Figure 4). Although the

Table 1. Mechanisms behind the biodiversity-carbon storage relationship.

Mechanism	Description
Complementarity effect	In diverse communities, species differ in traits and resource use, allowing for more complete exploitation of available resources. This can enhance ecosystem functioning (e.g., primary productivity) through mechanisms such as niche partitioning and facilitation.
Selection effect	In more diverse communities, the likelihood of including particularly productive or competitively dominant species increases. These species may disproportionately contribute to biomass production and carbon storage, leading to higher overall ecosystem functioning.
Stability and insurance effects	Diverse ecosystems tend to exhibit greater temporal stability in functioning (e.g., carbon fluxes), as asynchronous responses among species to environmental variability buffer against losses in the overall function.

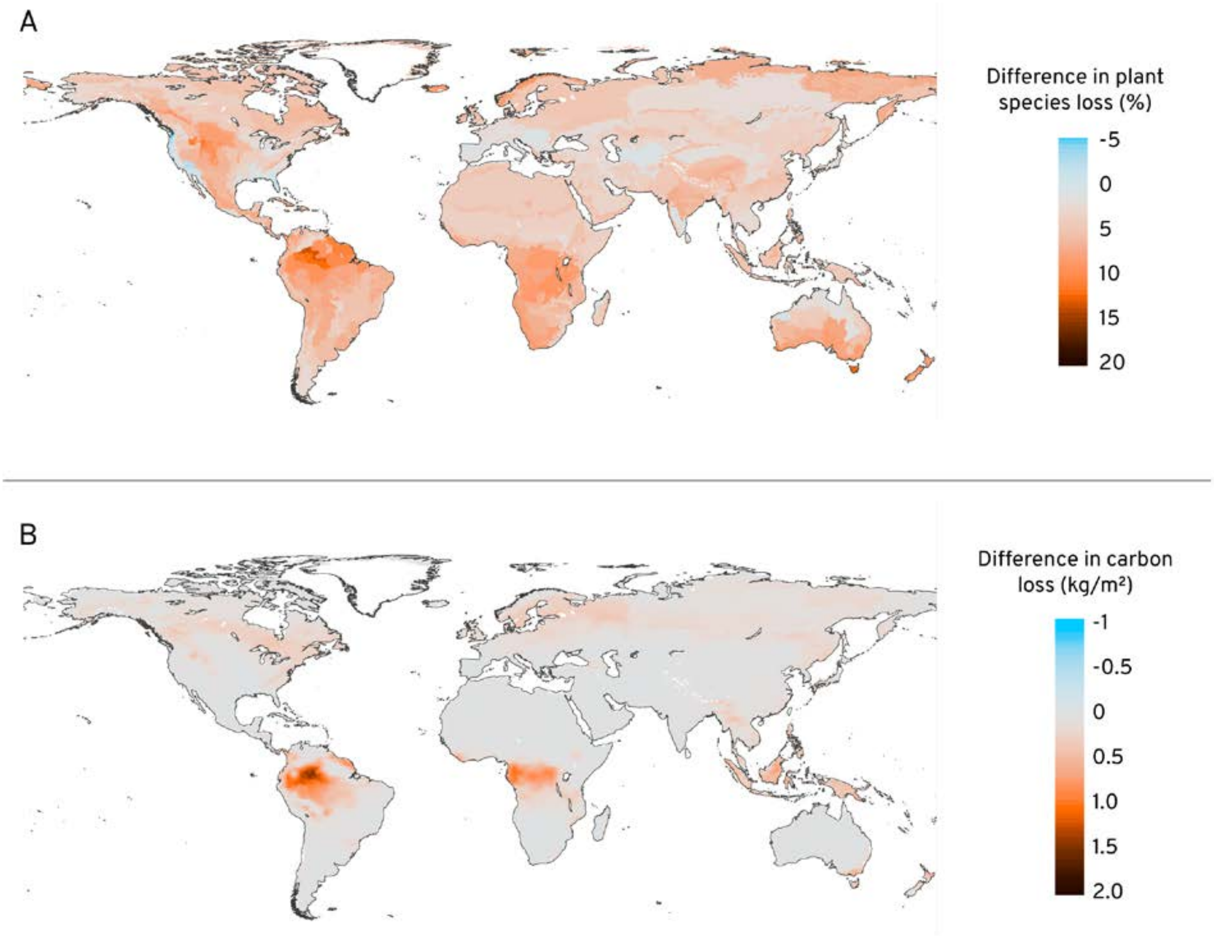

Figure 4. Additional plant diversity loss and resulting carbon loss, under a very high emissions scenario. Long-term loss of vascular plant species richness due to climate change and land use change, projected by 2050 (Panel A), shown as additional percentage of plants lost under a high emissions scenario (RCP8.5) relative to a low emissions scenario (RCP2.6). Reductions in vegetation carbon within the remaining habitat, attributable to plant biodiversity loss (Panel B), shown as additional carbon loss [kg/m^2] under high emissions scenario (RCP8.5) relative to a low emissions scenario (RCP2.6) (adapted from Weiskopf et al. 2024).

uncertainty range is large, the high-end estimates constitute a substantial portion of the remaining carbon budget before warming exceeds 1.5 or 2°C. Similarly, conserving tree diversity through climate change mitigation could correspond to 2–3 GtC/yr in reduced emissions.

While tree diversity can enhance carbon sequestration and retention in agroforestry systems, it remains less clear whether increasing plant diversity within cropland agroecosystems can have a similar effect. A large field trial that combined under-sown species with a cereal crop showed that increasing plant diversity within agroecosystems can increase the carbon retention potential in soils without compromising productivity. This confirms previous studies suggesting that manipulating plant diversity can enhance plant productivity and positively influence the associations between microorganisms, increasing microbial growth efficiency, which is considered a driver of soil carbon storage.

Though the role of plant diversity on ecosystem functioning is well established, the strength of the relationship can vary across biomes and environmental conditions. Large-scale analyses have shown stronger biodiversity-productivity relationships in less productive ecosystems. Similarly, studies have found that the effects of plant diversity on soil organic carbon storage were stronger at drier sites. To reduce uncertainties, research across distinct biomes, environmental gradients, and in different species is needed to clarify the ecological mechanisms underlying variations in the biodiversity–carbon storage relationship.

Plant-animal interactions, for instance through trophic chains, and ecosystem functions can potentially alter vegetation structure and plant species composition, which in turn can affect above- and belowground biomass. For example, studies show that elephants in African forests increase aboveground biomass, though in African savannas, fewer herbivores resulted in higher biomass. In tropical systems, human-induced reductions in animal species could reduce carbon storage by up to 26%, primarily through population declines in animal-dispersed tree species. In the

Brazilian Atlantic Forest, a study quantified that frugivores – who eat plant fruit, nuts, shoots, roots and seeds – can potentially enhance carbon recovery in fragmented forest landscapes when at least 40% forest cover remains. But these species may be disproportionately affected by climate change, especially in the tropics. Independent of these species interactions, evidence demonstrating the role of terrestrial animals as contributors to climate solutions is limited and remains contested.

Animals can also impact carbon storage in the oceans. Thanks to their large size, whales sequester carbon as biomass, which sinks to the ocean floor after their death. The recovery of baleen whale populations and their nutrient recycling services could enhance productivity and help restore ecosystem functions lost during 20th-century whaling, though the carbon benefits associated with this recovery are increasingly threatened by climate change.

Multidisciplinary and transdisciplinary approaches to understanding the social, ecological, and physical processes involving biodiversity loss and climate change through carbon uptake, release, and protection are critical in assessing destabilising feedback mechanisms. Because of this feedback, meeting the targets of the Kunming-Montreal Global Biodiversity Framework (KMGBF) can directly contribute to countries' Nationally Determined Contributions under the UNFCCC by reducing biodiversity-loss-driven carbon debt. Recognising and acting upon the interdependence between biodiversity conservation and restoration and effective climate mitigation are needed to effectively tackle climate and biodiversity policy targets. Despite the importance of biodiversity in carbon storage, many existing natural climate solution initiatives focus on ecosystem extent and cover, rather than on quality and composition, which impact the effectiveness of the carbon sink. Maintaining and restoring diverse ecosystems while considering Indigenous and traditional knowledge and livelihoods can be an effective step towards achieving sustainability in the face of multiple global crises and therefore towards contributing to both KMGBF and NDC agreements. Indigenous Peoples and local communities contribute location- and biome-specific knowledge that informs local policies and supports global goals.

POLICY IMPLICATIONS

- Meeting the targets of the Kunming-Montreal Global Biodiversity Framework (KMGBF) can directly contribute to mitigation efforts by reducing biodiversity-loss-driven carbon debt. This can be achieved by maintaining and restoring biodiverse ecosystems and by supporting biocultural practices rooted in Indigenous and traditional knowledge and livelihoods.

- Leveraging synergies between the three Rio environmental conventions (United Nations Framework Convention on Climate Change, United Nations Convention on Biological Diversity, United Nations Convention to Combat Desertification) through joint implementation and financing strategies at national and regional levels could help avoid fragmented action and deliver co-benefits across the climate, biodiversity, and land use agendas.

- Restoration programs that enhance both biodiversity and carbon storage capacity, such as those involving diverse native forests rather than monocultures, could be incentivised by adapting financing mechanisms to support these types of projects.

- Practices to protect biodiversity and ecosystem functions in agroecosystems to maintain productivity are potential nature climate solutions enhancing carbon sequestration and storage.

- National carbon accounting systems can be complemented by biodiversity and ecosystem integrity indicators, that enable monitoring, reporting, and verification of carbon stocks as well as the ecological functions that sustain them.

- Transdisciplinary knowledge integration – bridging ecology, climate modeling, and Indigenous and local knowledge – provides opportunities to co-design biodiversity-climate policies that are scientifically robust and context-specific.

5 Climate change is accelerating groundwater depletion

KEY MESSAGES

- The pace of global groundwater depletion is accelerating, relative to the 1980–2000 period, driven by compounding climate pressures and rising socioeconomic demands.
- Groundwater is a dynamic, climate-sensitive component of the global water cycle, and climate change is increasingly destabilising hydrological regimes by disrupting groundwater recharge. At the same time, global groundwater withdrawal rates have rapidly outpaced population growth, with future demands, especially from food production, expected to exacerbate this challenge.
- Groundwater is a critical buffer against climate change impacts on agriculture. However, increased groundwater withdrawal for irrigation to counteract warming temperatures is not a sustainable adaptation strategy.
- Beyond water scarcity, groundwater depletion carries major environmental and socioeconomic costs. These include land subsidence that damages agricultural and urban areas, and in coastal areas, saltwater intrusion can be further exacerbated as aquifers are depleted.

After polar ice, groundwater is our second largest freshwater source – supporting nearly half of humanity. It anchors water and food security for hundreds of millions, particularly in places with erratic rainfall patterns. In the early 20th century, global groundwater withdrawal increased roughly proportional to population, but since around 1960, rates have tripled from approximately 312 km^3/yr to over 1,000 km^3/yr, while global population has only increased by a factor of 2.6; factors beyond population growth, therefore, are at play. Most pumped groundwater is used for irrigation, and the United Nations' Food and Agriculture Organization (FAO) estimates there will be a 30% increase in irrigated agriculture in the coming decades, especially in developing countries, to feed a population of 10 billion by 2050. With drier summers predicted and less evenly distributed rainfall in many areas across the world, our reliance on groundwater as a stable resource will become even more important. And while climate change plays a significant role in altering irrigation needs, socio-economic drivers such as the intensification of agriculture and changes in dietary preferences are at least equally important in driving long-term groundwater depletion trends. Consequently, groundwater availability will be a major challenge for Earth's growing and increasingly prosperous population in the 21st century.

Groundwater is a critical buffer against the impacts of climate change on agriculture, as it enables the cultivation of water-demanding crops with multiple harvests per year, such as alfalfa or avocados, in arid regions like Arizona and Chile. But using groundwater as an adaptation strategy to counteract warming temperatures may lead to increased irrigation withdrawals, thereby accelerating depletion rates in already stressed groundwater zones like in India. The launch of the Gravity

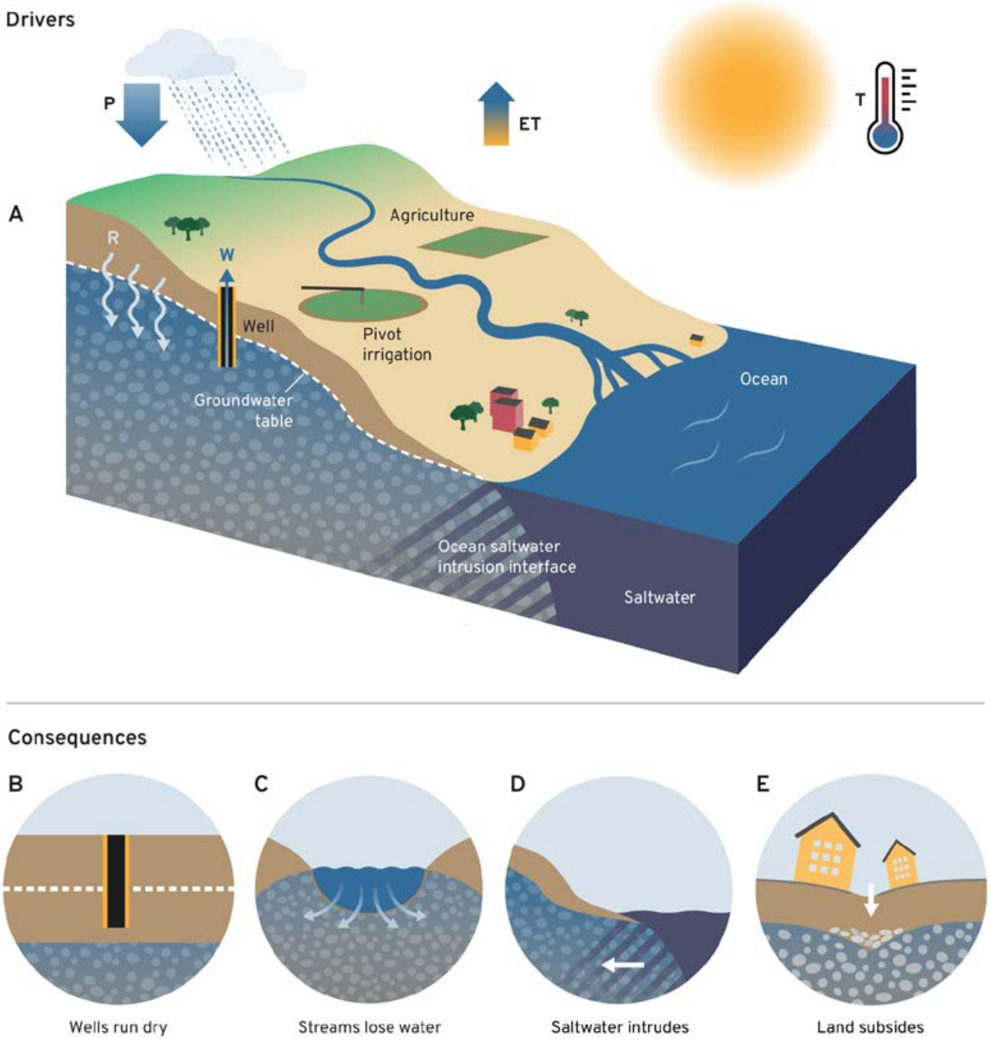

Figure 5. Drivers and consequences of groundwater depletion. Impact of climate change on terrestrial water fluxes (Panel A). Climate change directly and indirectly impacts groundwater resources: Precipitation (P) decreases in many regions around the world, while only a few will see a slight increase. Rising temperatures (T) under global warming affect evapotranspiration (ET), additionally reducing groundwater recharge (R). As a consequence, groundwater levels decline. Additionally, climate change puts pressure on agricultural food production, leading to higher withdrawal of groundwater for irrigation (W). Declining groundwater levels have severe consequences beyond water availability: Deeper water tables lead to increased extraction costs for drilling wells and ultimately for wells running dry (B); Streams lose water to their surrounding aquifer (C); Saltwater intrudes into coastal aquifers (D), and land subsides (E).

Recovery and Climate Experiment (GRACE) satellite mission in 2002 marked a turning point in global groundwater observations, enabling the visualisation of Groundwater Storage anomalies based on changes in Earth's gravitational pull. Until then, our understanding had been derived from drilled wells and inspection of geological records. GRACE revealed, with a monthly resolution, significant declines across key agricultural zones worldwide. It observed groundwater reductions of 0.26 cm/yr and 1 cm/yr between 2003 and 2024, in the Central Valley and the Southern High Plains of the USA, respectively. During the same period, notable declines of 0.66 cm/yr and 0.44 cm/yr were observed in Northwestern India and the North China Plain.

More recently, GRACE's limitations have been highlighted, including its coarse spatial resolution, the relatively short time period of 2002–2024 of collected data, and the difficulty distinguishing different water storage components (i.e., groundwater, soil moisture, and snow water storages). Bridging the gap between traditional local groundwater measurements and remote-sensing observations is crucial for actionable management, especially in vulnerable regions with limited well observations, like sub-Saharan Africa. There, groundwater supplies 75% of drinking water and faces climate-driven depletion. The International Groundwater Resources Assessment Centre was founded in 2003 by UNESCO and the World Meteorological Organization, to consolidate global information on groundwater. Two decades on, national data-sharing policies and varying data formats have made compiling a global well database challenging.

A global compilation of more than 170,000 groundwater-level time series from 40 countries, encompassing nearly 300 million observations, provides a dataset spanning four decades and enabling comparison of trends in 1,693 aquifers worldwide between 1980–2000 and 2000–2022. Beyond confirming that groundwater decline is indeed widespread, the analysis observed that in almost half of the declining aquifer systems worldwide, the pace at which groundwater levels drop accelerated in the most recent two decades. Over 80% of all aquifers experiencing accelerated declines are located in cultivated drylands where precipitation has declined and agricultural land use has intensified.

A recent study showed that groundwater is a dynamic, climate-sensitive component of the global water cycle. Under anthropogenic pressures, its behaviour has shifted in critical ways; global groundwater recharge, in which water moves downward from surface water to groundwater, is increasingly destabilised by climate change. Groundwater recharge dynamics are disrupted, particularly in snowmelt-dependent basins, where the earlier peak-flows that result from climate change, reduce infiltration, and exacerbate storage losses. Simultaneously, droughts diminish recharge rates, and intense rainfall often fails to percolate due to soil compaction or rapid runoff. Many arid regions are likely to experience significant declines in recharge due to decreased precipitation and higher evapotranspiration (Figure 5A).

Groundwater decline also leaves behind empty pore space (Figure 5E), into which the land above

BOX 2. SUCCESS STORIES OF INTEGRATED MANAGEMENT POLICIES AND STRATEGIES FOR WATER SECURITY

A. China's groundwater restoration efforts have achieved remarkable progress following the implementation of the *Regulations on Groundwater Management* (2021), the country's first specialised administrative regulation in this domain. Guided by this policy, the Ministry of Water Resources and the Ministry of Natural Resources conducted a nationwide reassessment of overexploited groundwater zones, analysing data from 34,929 monitoring wells with contributions from over 2,000 experts. Results reveal a 51% reduction (88,300 km^2) in severely overexploited areas compared to 2015, alongside a significant decrease in extraction volumes.

B. In Kansas, USA, the Local Enhanced Management Areas framework was established in 2012 to enable groundwater management districts (GMDs) to implement targeted water-use reductions in depleted zones of the Ogallala Aquifer. This approach has achieved withdrawal reductions of up to 35% in some areas while maintaining net farming profitability.

C. In California, USA, home to the critically depleted Central Valley aquifer, the Sustainable Groundwater Management Act was passed in 2014 to address groundwater overdrafts and promote sustainable irrigation practices. This legislation empowers local agencies to form Groundwater Sustainability Agencies tasked with developing Groundwater Sustainability Plans that balance extraction and recharge, prevent undesirable outcomes such as land subsidence and water quality degradation, and ensure long-term water reliability.

D. India’s participatory groundwater management program, Atal Bhujal Yojana, promotes community-driven conservation across highly depleted states through decentralised governance, incentivised participation, and collaboration between state and grassroots institutions. The program has demonstrated some promising outcomes, including strengthened institutional capacity at the local level, active youth engagement, and increased awareness of sustainable agricultural practices. In recent years, some notable cases of increased adoption of micro-irrigation techniques and crop diversification have also been observed, reflecting growing momentum towards efficient groundwater use in agriculture.

subsides, posing an imminent threat to agricultural land and urban communities in megacities such as Bangkok, Shanghai, Jakarta, or Manila. While this is by far the largest socio-economic threat associated with groundwater decline, coastal regions are additionally threatened by seawater intrusion into aquifers (Figure 5D). Small islands are particularly vulnerable, as freshwater floating above seawater can easily become salinised due to over-pumping, reduced recharge, and storm surges – all of which may intensify with climate change. Once an aquifer is contaminated, it can take decades to replenish it with clean freshwater.

Declining groundwater levels can often result from water wastage and unsustainable groundwater withdrawal, which can be mitigated through improved irrigation methods and better water management. Policies that address transboundary governance and Managed Aquifer Recharge, which currently offset less than 10% of global extraction, are also important. This approach acknowledges the interdependence of groundwater, surface water, and the ecosystems that rely on them. It will be crucial for mitigating cascading impacts on biodiversity and human water security in an era of accelerating climate change. Policies that operate across boundaries and involve stakeholders at all levels are considered more effective because of flexibility, adaptability, and ability to engage, at the same time they account for complex social-ecological systems interactions (Box 2).

In an increasingly water-stressed world, sustainable groundwater futures demand urgent action that balances human needs with ecosystem health. Successful sustainable groundwater management requires long-term monitoring and meaningful stakeholder involvement in planning and policy decisions. An analysis of 108 plans under California's Sustainable Groundwater Management Act revealed that most failed to comprehensively include stakeholders, leaving many unprotected from groundwater depletion. When stakeholders were engaged, their needs were better addressed, underscoring the importance of resource monitoring, inclusive policymaking, and the integration of diverse stakeholders for the long-term sustainability of groundwater.

POLICY IMPLICATIONS

- Parties could connect groundwater conservation efforts with sustainable agricultural practices to advance agrifood systems resilience and transformation, in alignment with the Sharm el-Sheikh Joint Work Programme on Agriculture and Food Security.

- Transboundary water cooperation should be incorporated as part of climate adaptation strategies. Countries could collaborate to align their initiatives under the Convention on the Protection and Use of Transboundary Watercourses and International Lake, or establish bilateral or regional adaptation frameworks that integrate transboundary water management. While some National Adaptation Plans (NAPs) mention transboundary water issues, these references are often limited and stop short of fully considering climate impacts in neighbouring countries that could threaten shared ecosystems and resources. A more deliberate approach is needed in NAPs to identify, assess, and address transboundary climate risks beyond national borders.

- The absence of global instruments for freshwater management, highlighted by the Global Commission on the Economics of Water, points to an important governance gap. Addressing groundwater as a global common good should be elevated in climate diplomacy. Relatedly, adaptation strategies should integrate sustainable groundwater use by promoting the inclusion of climate-resilient water management in NAPs and in discussions under the Global Goal on Adaptation.

- Supported by the UNFCCC's Technology Mechanism and the Capacity-Building Frameworks, enhanced South-South and North-South cooperation should be promoted to strengthen groundwater monitoring tools.

- Sustainable groundwater futures demand urgent action that balances human needs with ecosystem health in an increasingly water-stressed world. This calls for resource monitoring, inclusive policy making, and the integration of diverse stakeholders.

6 Observed and projected climate-driven increase in dengue

KEY MESSAGES

- **Dengue fever surged to the largest global outbreak ever recorded, with 14.2 million cases reported in 2024.**
- **Changing temperatures are expanding mosquito habitats and lengthening the transmission season, thus facilitating favourable conditions for them to breed and survive, which contributes to increased numbers of dengue cases.**
- **Urbanisation, unsanitary waste management, global trade and travel, along with climate change, further contribute to driving transmission into previously unaffected areas and overall increased in transmission intensity.**
- **Dengue outbreaks can already overwhelm healthcare systems and disrupt economies, and projections indicate even steeper increases under climate change by 2050 and 2100.**

Dengue fever surged over the past two years to 14.2 million reported cases in 2024, the largest global outbreak ever recorded according to the World Health Organization. It is caused by an RNA virus, from the genus *Flavivirus*, comprising four serotypes with limited cross-immunity, so people can get dengue up to four times. The official 2024 dengue burden figure is an underestimate of the true global burden: under-reporting is likely, as cases may be misclassified as malaria in countries where both are endemic; not all countries have monitoring systems to track widespread outbreaks accurately; and dengue may not be suspected in countries where dengue is not common. About half of the world's population is now at risk of dengue with an estimated 100–400 million infections occurring each year. While an estimated 75–80% of first-time dengue cases are mild or asymptomatic (and thus under-reported), subsequent dengue infections can take more severe forms, including dengue haemorrhagic fever, which can be fatal.

The most common mosquito-borne viral disease, dengue is on the increase because changing temperatures are expanding mosquito habitats and creating favourable conditions for them to breed and survive, though some areas project reductions in suitability. Appropriate climatic regions for the geographic transmission of dengue by *Aedes albopictus* and *Aedes aegypti* increased by 46.3% and 10.7% respectively, between 1951–1960 and 2014–2023 (Figure 6). The mosquitoes that carry and transmit dengue virus can also carry Zika, chikungunya, and yellow fever viruses, making these species important to control.

Dengue outbreaks are already capable of overwhelming healthcare systems and disrupting economies, and projections indicate steeper increases by mid- and late century. In the Americas, more than 13 million cases were reported in 2024, mostly in Brazil, where 17 cities declared states of emergency. In the USA, a health alert was announced, with local transmission in California, Florida, and Texas, while in Puerto Rico, a health emergency was declared. A recent study suggested climate change was responsible

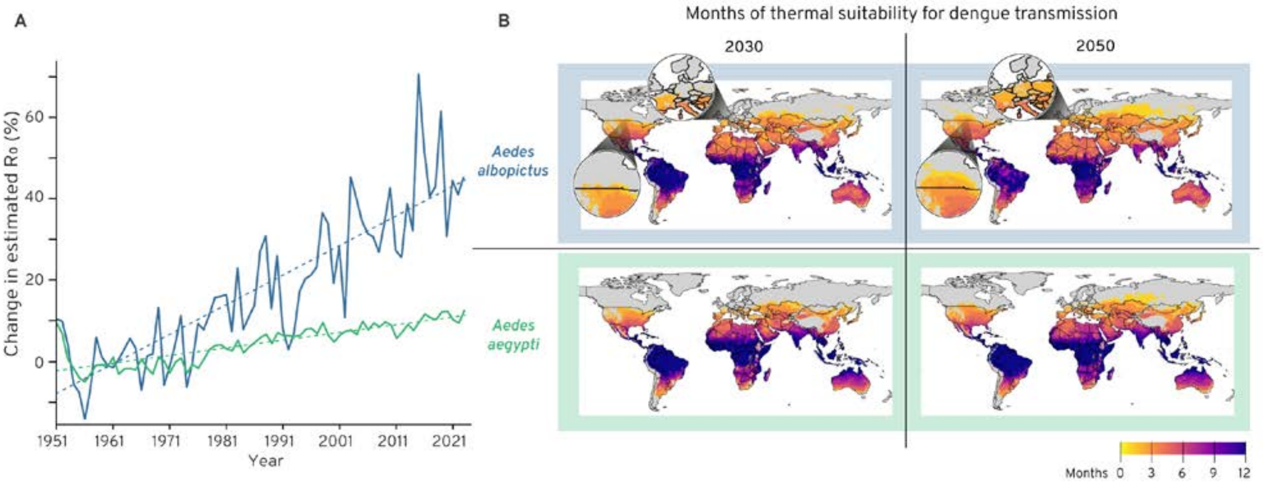

Figure 6. Climate suitability for dengue transmission and global redistribution of transmission risk. Change in the climate suitability for vectors of dengue (Panel A): R_0 (the basic reproduction) represents the average number of new infections in a completely susceptible population generated by a single new case (adapted from Romanello et al. 2024). Global expansion and redistribution of dengue transmission risk (number of months of thermal transmission suitability) by 2030 and 2025, under SSP2-4.5 (Panel B) (adapted and modified to CMIP6 projections from Ryan et al. 2019).

for up to 40% of dengue cases in some countries in the Americas. Climate change and human activity have driven the redistribution of mosquito vectors, altering habitats and facilitating the spread of disease into previously unaffected areas. Mosquitoes themselves have acquired a taste for humans above other species and there is greater evidence for this in urbanised areas. *A. aegypti*, the primary dengue vector in the Americas, thrives in hotter climates and has expanded through tropical and subtropical regions. It is well adapted to human environments, breeding even in small amounts of water, making it difficult to control. *A. albopictus*, the “Asian tiger mosquito,” has extended its range into temperate areas like Europe, aided by global trade and its ability to survive colder climates. It will bite during the daytime, becoming an issue in schoolyards. But the mere presence of these mosquitoes does not immediately lead to new dengue cases – there is often a lag between their introduction and sustained transmission, complicating public understanding and response efforts.

The number of cases in Africa was nine times higher in 2023 than in 2019. In several countries reporting increased cases, limited surveillance, monitoring, and control are further complicated by ongoing conflict, large numbers of displaced people, and climate factors. Elsewhere, dengue is present where it was not before. Nepal observed cases between March and November in 2023, indicating distributed peaks, with hotspots not limited to Kathmandu but across the country at different altitudes, which suggests ecological and climatic factors may no longer be effective barriers. In Europe, climate is the strongest predictor of outbreaks of viruses transmitted by mosquitoes, ticks, and sandflies, with longer, hotter summers significantly increasing risk, particularly in urban and semi-urban settings. The region has seen a steady rise in imported and local dengue cases, with record numbers in 2024: over 200 locally transmitted cases in Italy and 85 in France. Since 2000, Europe has recorded more than 45,000 dengue cases, both imported and locally transmitted, highlighting growing vulnerability.

While climate change creates conditions conducive to transmission, global travel and trade also play key roles in introducing both mosquitoes and the virus to new regions. Travellers can unknowingly transport dengue to areas with susceptible mosquito populations, fuelling outbreaks, as previously found in Florida, USA.

Dengue’s spread is not inevitable. A variety of vector control methods have proven effective. While mosquito control remains the cornerstone of intervention (notably Singapore’s measures to prevent mosquito larvae from growing), other approaches are being explored, including the use of specific bacteria to suppress dengue transmission in mosquitoes. These strategies carry risks; decreased exposure to dengue can make the population more susceptible and typically reduces investments in control strategies, raising questions about long-term reliability and creating tension between vector control and public health intervention strategies.

Vaccines have been developed but are not yet widespread or universally recommended, making surveillance and early warning systems key to prevention and intervention. Surveillance systems that track infections in travellers (e.g., phone apps leveraging traveller self-reporting) have become valuable early warning tools, especially for countries with weaker health monitoring. As the world faces the continued expansion of *Aedes*-transmitted diseases, reversing the trend will require a combination of robust public health interventions, innovative vector control strategies, and early warning systems with enhanced surveillance to stay ahead of this growing threat.

POLICY IMPLICATIONS

- The COP28 UAE Declaration on Climate and Health, the Baku COP Presidencies Continuity Coalition for Climate and Health, and the ongoing work to develop the Belém Health Action Plan reflect a growing momentum to mainstream health into the UNFCCC conversation. Operationalising the plan requires increased international collaboration to mobilise the necessary financial support to build climate-resilient health systems.
- The expansion of dengue transmission demands enhanced global health surveillance and early warning systems that integrate climate data with health monitoring systems and develop standardised protocols for climate-sensitive disease tracking across borders. The WHO Global Arbovirus Initiative's framework provides a foundation, but implementation must be accelerated.
- While dengue is broadly recognised as a priority climate-sensitive health risk, concrete adaptation actions should be reflected in national adaptation plans (NAPs). Planning requires intersectoral coordination mechanisms between health meteorological, and environmental agencies; improved surveillance and early warning systems; and vulnerability assessments at subnational levels to identify high-risk populations and areas.
- Given the potential for dengue outbreaks to overwhelm healthcare systems and disrupt economies, proactive resilience-building is essential:
    - Scaling up integrated vector management (IVM) strategies
    - Implementing “no regret” adaptation measures, including improved water storage systems and solid waste management, to reduce vector breeding sites
    - Strengthening health system preparedness, including improved case management capacity and enhanced laboratory diagnostic capabilities
- The health expert group in the UAE-Belém Work Programme on Indicators for the Global Goal on Adaptation to be concluded at COP30 recommends indicators related to vector-borne diseases be included to track progress towards the target of “attaining resilience against climate change–related health impacts, promoting climate-resilient health services, and significantly reducing climate-related morbidity and mortality, particularly in the most vulnerable communities”. These should be formally adopted by the Parties.

7 Climate change–related labour productivity and income loss

KEY MESSAGES

- The negative effects of heat stress on labour productivity are among the most clearly established channels by which climate change affects economies. Additional global warming of 1°C is expected to expose over 800 million people in tropical regions to unsafe levels of heat stress, potentially reducing working hours by as much as 50%.
- While direct impacts are concentrated in developing countries, the economic damages are amplified globally by supply chains and trade. Hence, global income losses are not limited to the regions where the heat stress occurs.
- In a low-emissions scenario, global annual GDP losses from labour impacts could be limited to 0.1%–0.8% compared to 1.4%–4.5% under high-emissions scenarios, providing a compelling economic justification for more ambitious climate action. While estimates of the aggregate economic costs vary depending on the methodological approach, there is consensus that global incomes will be negatively affected.

Estimates of the economic costs of climate change are crucial for informing decisions about mitigation and adaptation measures. They can reveal important channels through which climate change can impact the economy; identify risks across regions, sectors, and demographics; highlight issues related to justice and equity; and motivate emission mitigation.

One of the main ways climate change hurts the economy is in reducing worker productivity (Figures 7A & B), and there is consensus that large increases in future exposure to and impacts of unsafe heat stress will occur. Consistent definitions of heat stress that take into account variables beyond temperature, such as humidity, are a challenge. Additional warming of 1°C is set to expose over 800 million people in tropical regions to unsafe levels of heat stress which would reduce working hours by 50%, impacting productivity and labour supply to economic markets. Importantly, labour exposure is subject to great inequality, with developed countries able to benefit from imports produced in increasingly heat-exposed developing countries. A recent review concludes that 3°C of warming would cut labour effectiveness by 33% in Africa's outdoor, high-exposure sectors and 25% in Asia's, with substantial impacts in low-exposure sectors too. By 2060, indirect effects on global trade and supply chains are projected to account for 12–43% of heat stress–related global economic losses, with effects varying across regions and sectors. Recent studies have found that for a high-emissions scenario (RCP8.5), labour productivity loss from heat could result in annual global GDP losses of 1.4–2.6%, and when also accounting for health costs and supply chain disruptions due to climate impacts on labour, this could increase to 2.9–4.5%. Mitigation to RCP2.6 or RCP1.9 levels could reduce these annual GDP reductions to only 0.1–0.8%.

While understanding has improved and there is consensus about negative impacts on global incomes, estimates of the aggregate economic impacts of climate change from all possible channels remain wide (Figures 7C & D). First, it is increasingly clear that estimates vary based on the method employed, with a divergence between “structural” and

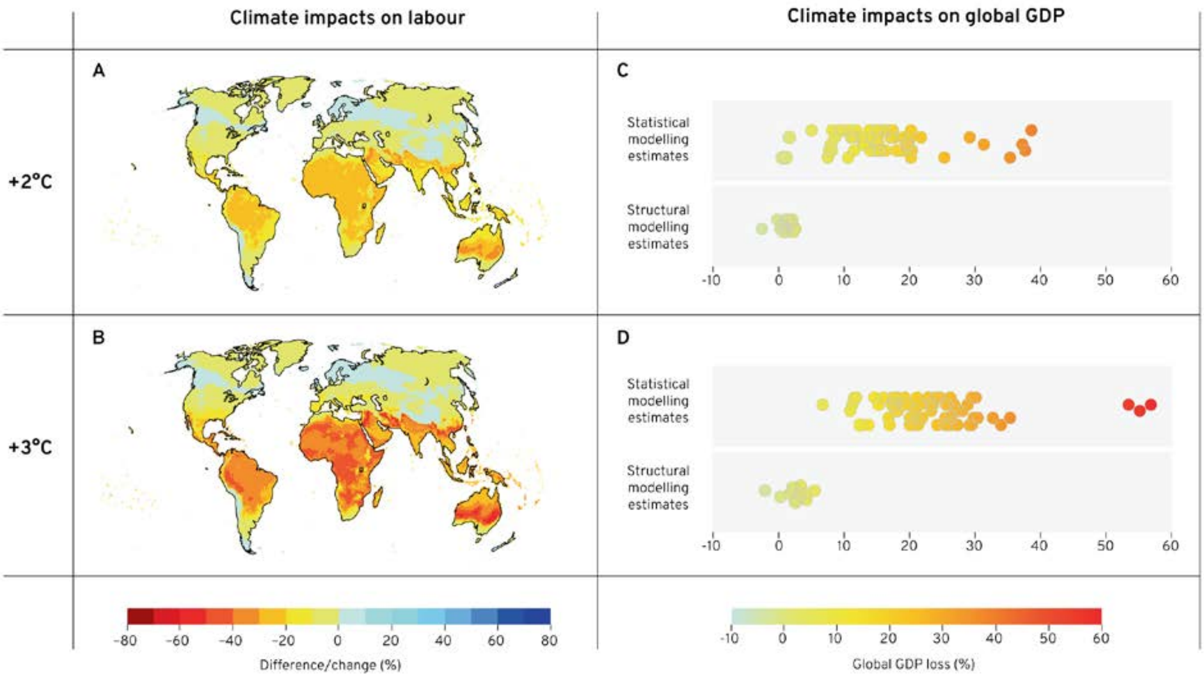

Figure 7. Impacts of climate change on labour and global gross domestic product (GDP). Projected loss of effective labour (combination of labour supply and productivity changes) under an increase in global mean temperature relative to pre-industrial levels of 2°C (Panel A) and 3°C (Panel B) (redrawn from Dasgupta et al., 2024). Range of impacts on global GDP at 2°C (Panel C) and 3°C (Panel D) of global warming from structural and statistical modelling estimates from the literature, measured in terms of the annual percent of global GDP loss relative to GDP without additional climate change (redrawn from Morris et al., 2025).

"statistical" modelling approaches. Statistical approaches are able to capture the aggregate effects of a range of sectoral impact mechanisms and their interactions but provide less insight into the relative role of those mechanisms. Their sensitivities to model specification and extrapolation of historical relationships into different potential futures are sources of widespread debate. Structural models can offer greater mechanistic clarity by explicitly enumerating specific impact chains, but they rely on certain assumptions and struggle to capture all the relevant impact channels. These different approaches are not directly comparable and should be treated as different lines of evidence rather than as interchangeable substitutes. Ongoing research efforts are attempting to better understand and reconcile these differences to reduce uncertainties.

Statistical estimates of aggregate economic impacts have undergone major revisions in recent years, typically increasing cost estimates over time. New work has highlighted the role of climate hazards in addition to average temperatures, including extremes, temperature variability, and precipitation. A complementary research strand has highlighted the global nature of climate shocks, finding that incorporating metrics of global temperature into empirical work more than doubles estimates from prior findings. And advances in the way models capture the persistence of impacts on economic growth have found at least partially persistent effects, resolving a source of prior discrepancy and supporting estimates of larger overall impacts.

Persistent knowledge gaps remain. The largest gap is in the discrepancies between models, but there are others. While advances have highlighted key impact categories such as heat stress and labour, other climate impacts have yet to be widely included, such as drought, tropical storms, and wildfires. Similarly, the costs of impacts on "non-market" sectors (e.g., biodiversity, crime and conflict, migration) are difficult to monetise and are largely omitted, despite some advances in accounting for ecosystem services. More attention to the effects of compounding climate hazards and their cascading effects across systems is also needed. Finally, the role of adaptation remains a large source of uncertainty, as statistically observed responses to weather may change under fundamentally different future socio-economic and climate conditions. Evidence exists for successful adaptation against heat-related mortalities, but other sectors show much less clear evidence of adaptation occurring historically. To better predict the aggregate costs of climate change, understanding and integrating adaptive responses is needed in statistical and structural models.

The evidence on global labour productivity and income loss due to climate change strengthens the case for mitigation, can narrow the focus of adaptation efforts, and helps anticipate loss and damage. For example, heat impacts on labour are a critical impact channel, which can provide guidance for adaptation strategies. Advances in statistical approaches, particularly in accounting for further climate hazards and global effects, have increased estimates of the economic cost of climate change. These vary substantially by region, sector, and demographic, with lower-income countries facing the highest economic losses, due to their higher dependence on climate-sensitive industries, lower adaptive capacity, and location in more vulnerable regions. Recognising these vulnerabilities is essential for designing policies that not only mitigate economic losses, but also foster resilient, equitable systems capable of withstanding future climatic shocks. Finally, domestic economies are impacted by climate change directly as well as indirectly via global trade effects driven by climate impacts that occur elsewhere. In an interconnected world that is experiencing a growing number of extreme weather events, it is increasingly important to design policy and business strategies towards proactive supply chain resilience and international cooperation to mitigate the economic impacts and address transboundary risks.

POLICY IMPLICATIONS

- The benefits of strong mitigation efforts to minimise the economic impact of climate change on labour productivity are a compelling justification for greater ambition and faster implementation. Parties could use labour productivity data to strengthen their Nationally Determined Contributions (NDCs) and support more ambitious global targets.

- Integrating labour productivity impact assessments would be a useful component for national-level climate policy cost-benefit analyses. Similarly, integrated assessment models could incorporate best available knowledge on climate-induced income loss and labour productivity reduction to better inform projections of the economic implications of climate change.

- At the national level, governments could use labour productivity impact projections to prioritise adaptation investments in worker protection infrastructure, such as cooling systems and modified work schedules during extreme heat periods, and advance regulation on occupational heat stress with sector-specific heat action plans, particularly for high-exposure industries. In this regard, the WHO-WMO Climate change and workplace heat stress guidance offers key recommendations.

- Labour considerations under the Just Transition Work Programme currently focus on transition-related impacts on jobs lost/gained. This scope should be complemented with greater attention to the direct impacts of climate change on the workforce, its well-being and productivity.

- At the national level, governments should engage a broad range of stakeholders, including employers, trade unions, workers, physicians, and local authorities, to identify climate-related risks to worker safety and productivity and co-develop effective and equitable policy responses.

8 Safe scale-up of CO_2 removal is needed to tackle hard-to-abate emissions and climate risks

KEY MESSAGES

- Carbon Dioxide Removal (CDR) is essential for meeting Paris Agreement goals and is a necessary complement to deep and sustained GHG emissions reductions. Yet, current national plans fall far short, creating an emerging 'CDR gap'.
- Large-scale CDR deployment entails significant sustainability risks, competing for land, energy, and materials, and should be limited to compensating for hard-to-abate residual emissions and, eventually, to achieving net-negative removals, rather than being used to offset additional emissions from sources in which abatement options are readily available.
- Novel CDR methods are technically feasible and are beginning to be deployed at scales of tens of millions of tons. Dedicated support for research, development, and deployment is needed to accelerate progress to close the CDR gap.
- Additionally, significant 'preventive CDR' capacity is needed to stabilise temperatures in the longer term through net-negative removals, especially to hedge against climate system uncertainties.

To achieve the Paris Agreement's climate objectives, we must scale up CO_2 removal (CDR) alongside deep and sustained emissions reductions. Yet there are risks and uncertainties. Recent evidence shows that scale-up is limited by sustainability constraints, and using it to compensate for otherwise unavoidable emissions risks falling far short of climate goals. A "preventive CDR capacity" is also needed for overshoot (see Box 3 for definitions, henceforth indicated with *) and to hedge against physical climate uncertainties, but countries are failing to plan and implement an adequate scale-up (Figure 8).

CDR involves extracting CO_2 from the atmosphere and storing it in geological sinks, the biosphere, or products (e.g., harvested wood). "Conventional" methods* include afforestation/reforestation and forest management practices, while "novel" methods* such as Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), enhanced weathering, carbon mineralisation, and biochar, are technically feasible but not yet scaled up. Current deployment is primarily conventional and low, at 2 Gt CO_2/yr, while overall net emissions from land use and forestry are about 4.4 Gt CO_2/yr, so emissions from deforestation and peat fires still significantly outweigh CDR in the land sector.

A key purpose of CDR is to compensate for future "residual emissions"*, and allow countries, cities, or companies to achieve net-zero emissions targets by a given date (Figure 8A). Residual emissions will remain because it may not be possible to eliminate all emissions sources, especially those that are "hard-to-abate"* due to high mitigation costs and limited substitution options, such as emissions from livestock, international aviation, and some heavy industry. These sectors could still reduce emissions via demand-side measures.

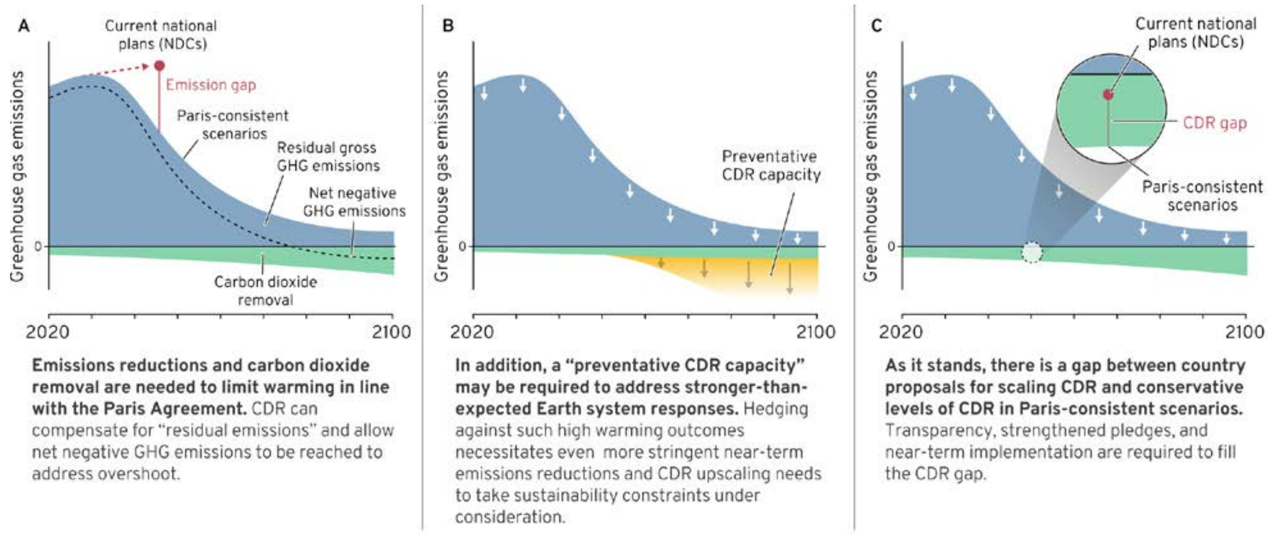

Figure 8. A stylised sketch of the possible scenario pathways that reach net-zero CO_2 and greenhouse gas emissions. Emissions reductions and CO_2 removal (CDR) are needed to limit warming. CDR can compensate for "residual emissions" and allow net-negative GHG emissions to be reached to address overshoot; however, CDR will be limited by land area and other sustainability constraints (Panel A). This implies the need for faster and deeper emissions reductions, reserving CDR to compensate only for residual emissions from "critical needs". A "preventative CDR capacity" may be required to address unexpected Earth system responses (Panel B). As it stands, there is a gap between country proposals for scaling CDR and conservative levels of CDR in scenarios (Panel C). Reducing the need for preventative CDR capacity will depend on stronger national pledges and implementation of emissions reductions (based on Lamb et al. 2024).

The interplay between CDR and residual emissions can be observed in integrated assessment modelling (IAM) scenarios. For example, CDR deployment across 81 scenarios (type C2 scenarios, i.e., 1.5°C with high overshoot*) averaged over 2050–2100 balances residual emissions of CO_2, N_2O and F-gases* over the same period. Though later in the century, CDR often reaches higher levels, becoming substantially larger than the residual long-lived greenhouse gas emissions. In C1 or C3 scenarios (i.e., 1.5°C or 2°C scenarios with no/limited overshoot, respectively), modelling suggests a slightly smaller average over 2050–2100, so residual emissions remain higher.

The risks to sustainability implied in the deployment of CDR at the levels envisioned in these models are great. Conventional CDR will compete with both food production and biodiversity protection for land, while novel CDR at scale could require significant energy and materials (Figure 8B). More sustainable C1–C3 scenarios which take into account these considerations have lower overall CDR deployment levels and more stringent and deep emissions reductions in the near term.

Given sustainability constraints, it is important to minimise emissions such that achievable CDR capacity is available to compensate for the residual emissions from truly hard-to-abate sectors that serve critical needs (Figure 8C). Yet many IAM scenarios deploy CDR to compensate for emissions that are relatively easier to abate, such as the power sector, where cost-effective alternatives are readily available. Similarly, voluntary carbon markets and company net-zero targets will need to adjust for a limited supply of CDR.

Another purpose of CDR is achieving long-term global temperature decline after overshoot. Most studies focus on median warming scenarios, like a 50% chance to limit warming to 1.5°C by 2100. However, assessing overshoot risks and CDR requirements for warming reversal requires accounting for uncertainties in Earth system feedbacks. If these are stronger than expected, it could require hundreds of gigatonnes of additional CDR, beyond current pathway estimates. In a 1.5°C no-overshoot pathway, it is estimated that high-warming outcomes (which have a 1-in-4 probability of occurring) would need CDR deployment up to 400 Gt CO_2 (cumulative) by 2100, approximately double the amount in IPCC AR6 WGIII scenarios.

It is increasingly important to evaluate national plans for implementing and scaling CDR activities. In their Nationally Determined Contributions (NDCs) and Long-Term Low-Emission Development Strategies (LT-LEDS) under the Paris Agreement, countries currently plan only minimal additions of 0.05–0.53 Gt CO_2/yr by 2030, primarily through conventional CDR methods. By 2050, additions of 1.5–1.9 Gt CO_2/yr are suggested in the LT-LEDS, potentially including novel CDR methods (Figure 8C). These plans fall short of the scenario levels needed to limit warming to 1.5°C, even in scenarios focused on reducing demand and limiting CDR dependence. This indicates an emerging "CDR gap" between country plans and needed future deployment levels. More ambitious commitments, early policy support for CDR, and strengthened emissions reductions, especially with a view to minimising residual emissions, are necessary to close the gap.

Despite the critical role of CDR, dedicated deployments, finance, and policies to support large-scale implementation are limited. Without robust and comprehensive policy action in the near term, achieving the CO_2 removal required by mid-century will be a challenge. Funding for research, development, and demonstration projects across multiple CDR pathways is required to foster a diverse portfolio of solutions, which will be necessary to address sustainability constraints. Policies should also include incentives for commercial-scale deployment, as well as regulatory support for high-quality monitoring, reporting, and verification. Policymakers must implement ambitious emissions-reduction policies, alongside measures to scale up CDR and minimise residual emissions from hard-to-abate sectors and reduce energy demand. Importantly, policies will be most effective if they consider regional constraints, equity, fairness and procedural justice. Responsibilities for sharing the burden of preventative CDR can be based on equity and fairness principles.

At COP28, discussions emphasised the need for global commitments to scale CDR technologies alongside emission reductions. An important first step is to strengthen net emission reduction pledges in the NDCs while increasing transparency and clarity on the role of CDR in meeting these targets. While associated sustainability risks exist and must be accounted for in policies and pledges going forward, they must also be balanced against the risks of inaction – risks that will disproportionately affect vulnerable populations. The urgency of scaling up CDR and achieving net-negative emissions cannot be overstated. They are critical to mitigating the severe impacts of climate change.

BOX 3. DEFINITIONS OF KEY CDR TERMS

Overshoot: Temporary exceedance of global warming levels, before global temperatures are brought back down through mitigation efforts and CDR technologies.

Conventional CDR: Well-established methods of CO_2 removal that have been widely implemented and validated over time, such as afforestation and reforestation or improved forest management, soil carbon sequestration, and peatlands and wetlands restorations.

Novel CDR: Emerging and innovative technologies that are still in the early stages of development and deployment, including biochar, bioenergy with carbon capture and storage (BECCS), direct air capture and carbon storage (DACCS), and enhanced weathering and mineralisation.

Residual emissions: The gross emissions that are compensated for by CDR at the point of net-zero CO_2.

Hard-to-abate: Economic activities that are difficult to mitigate, typically defined in terms of their higher abatement costs relative to other sectors.

F-gases: Industrial chemicals containing fluorine that are also greenhouse gases.

Negative emissions: Removing more CO_2 through anthropogenic activities than is emitted.

POLICY IMPLICATIONS

- Achieving the Paris Agreement's objectives is unattainable without scaling up CDR, but expansion should not proceed "at any cost". Active measures and safeguards must be implemented to minimise social, economic, and environmental trade-offs and unintended consequences.
- Stronger international guidelines and standards are needed to ensure that CDR is used responsibly and contributes effectively and transparently to climate targets by ensuring that it complements, rather than replaces, rapid emissions reductions.
    - In particular, best-practice guidance should be developed on reflecting CDR in Nationally Determined Contributions (NDCs). While CDR was absent from the first two rounds of NDCs, some countries have included specific mentions about CDR in their updated submissions.
- CDR should be carefully considered and vetted for inclusion in emissions trading schemes (ETS). Policy makers should work closely with other stakeholders to define transparent criteria for inclusion in an ETS or other compliance-support mechanisms. Harmonising and improving quality criteria, as well as monitoring and reporting processes, are necessary to increase the transparency and impact of CDR and avoid greenwashing. In particular, CDR accounting and reporting should only include additional carbon sinks, rather than crediting already existing natural sinks.
- While conventional, land-based CDR approaches are the most tested and economically viable option today, novel CDR approaches offer greater potential, albeit with different associated risks and costs. Policymakers should rely on thorough scientific assessment to select which CDR approaches align best with their countries' economic structures, geographic realities, and available resources, as well as critically considering the long-term impacts, potential risks, and benefits associated with each method.
- Not all carbon removals offer the same level of durability. Temporary solutions cannot replace lasting emission cuts. Clear standards should distinguish between permanent and temporary storage, with priority given to more permanent solutions, while recognising that less-permanent methods (conventional, land-based) will continue to be important for the time being.
- Governments should consider procurement of CDR as a public good in order to accelerate the technical readiness of novel CDR approaches, reduce the CDR gap, and boost confidence in private purchases.

9 Carbon credit markets – integrity challenges and emergent responses

KEY MESSAGES

Voluntary carbon markets have expanded rapidly, but concerns about credit quality and credibility persist.

Evidence shows that in many cases, emissions "avoidance" projects lack additionality and nature-based removal projects overestimate carbon sequestration.

Most corporate buyers have relied on low-quality, low-cost avoidance credits, raising concerns about a "delay effect" by which offsetting results in the weakening or postponement of direct decarbonisation efforts.

Carbon credit markets face systemic flaws, but progress in establishing quality benchmarks, rating systems, and regulations – as well as a shift in using credits as *additional* contributions to mitigation efforts, rather than as offsets – aims to strengthen integrity.

Markets for carbon credits allow a variety of actors to generate revenue through climate change mitigation activities, such as forest management or renewable energy deployment. Credits are traded in different settings: voluntary markets in which credits are purchased to "offset" emissions; regulated markets that legally require companies to reduce emissions; and international mechanisms with country-to-country emission-reduction transfers under UNFCCC rules. A vast 76% of the nearly 250 million credits retired in 2024 were through voluntary markets. Credit issuances grew from approximately 200 million in 2020 to 350 million in 2021 as a result of governmental and company decarbonisation policies but have since dropped to 290 million in 2024. This drop reflects concerns about the quality of carbon credits and growing uncertainty about their role in voluntary climate action. Systemic flaws in how credits have been generated, verified, and sold demonstrate that carbon credits are not a reliable substitute for fossil fuel cuts. Still, attempts are being made to strengthen verification standards and enhance transparency, as well as to establish new governance mechanisms to improve the integrity and credibility of credits.

Quality on the supply side of carbon credit markets is a challenge. Standards and methodologies consistently fail to guarantee the effectiveness of carbon credits in mitigating climate change: an analysis of nearly one billion tons of carbon credits – around one-fifth of all issued – found that less than 16% represented actual emissions reductions (Figure 9). Project developers select favourable data or make unrealistic assumptions, while adverse selection, outdated data, and inappropriate methodologies compromise the climate benefit of carbon credits. Many project types, including wind power in China and improved forest management in the USA, show no statistically significant climate benefits, while cookstove and deforestation avoidance projects achieve lower emission reductions than claimed (Figure 9).

Evidence of low-quality credits has mostly concerned "avoidance" projects such as forest conservation and renewable energy. However,

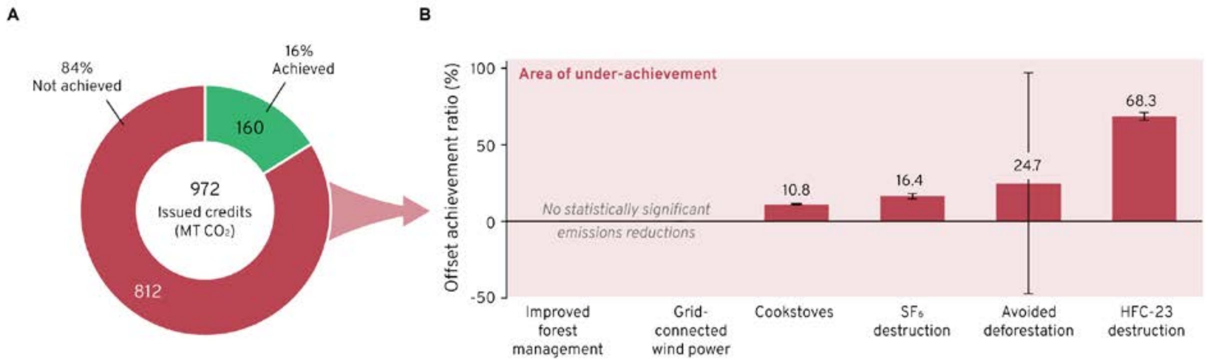

Figure 9. Achievements from issued carbon credits. Emissions reductions achieved in a selection of case studies (Panel A) and comparison of their offset achievement ratio (OAR), which is the emission reductions likely achieved relative to the quantity of carbon credits issued (Panel B) (modified from Probst et al., 2024). Note: HFC-23 (trifluoromethane) is a by-product of the manufacture of a common refrigerant.

evidence now shows that nature-based removal approaches, including afforestation and soil management, also overestimate carbon sequestration and lack additionality, meaning they often fail to generate carbon removals beyond what would have occurred in the absence of carbon credit incentives. Furthermore, upscaling natural sinks to counterbalance fossil fuel emissions is limited by slow absorption rates, increased reversal risks from wildfires and the scarcity of suitable land. Despite optimistic assumptions in IPCC models and national plans, actual capacity for terrestrial emissions removal is much lower than expected. Collectively, these recent findings suggest that nature-based carbon removals cannot reliably substitute for cuts in fossil fuel emissions or resolve the fundamental quality issues associated with avoidance credits.

Demand-side dynamics can also influence quality. A recent study analysed carbon credits purchased by the 20 largest corporate buyers for voluntary purposes between 2020 and 2023 and found that most companies have consistently relied on low-quality, low-cost avoidance credits with a high risk of overstating emission reductions. With most credits originating from older projects that started issuing credits a decade or more earlier, corporate offset spending has largely failed to support new investments in climate mitigation.

While carbon credits are often linked to claims about net-zero or carbon neutrality, most companies do not detail how they use offsets in greenhouse gas accounting. Reliance on offsetting could delay or weaken decarbonisation if companies prioritise credit purchases and divert funds away from internal decarbonisation and fossil fuel phase-out initiatives. An analysis of net-zero strategies by oil majors supports concerns about a “delay effect”, revealing the use of carbon credits to legitimise the continued production and consumption of conventional fossil fuels. While carbon credits will not replace internal decarbonisation efforts for most companies, they could divert considerable funds away from direct emissions-reduction efforts among large polluters like airlines.

Carbon credit projects have been consistently criticised for a singular focus on emissions neutralisation. As such, many projects fail to realise or systematically quantify socio-economic and environmental non-carbon benefits. Some studies suggest that adequate project design can help reduce carbon emissions while improving social welfare, yet other studies underscore inherent trade-offs between project success and equity in forest-carbon initiatives. Many emissions-reduction efforts disproportionately benefit more affluent or environmentally destructive communities, and upfront and transaction costs can be entry barriers for small-scale projects. Although more funding is needed to address deforestation, especially in tropical regions, and to support critical non-carbon benefits like biodiversity, these challenges highlight the limitations of using carbon credits as the primary funding vehicle.

Carbon market actors are responding in multiple ways. Initiatives like the Integrity Council for Voluntary Carbon Markets (ICVCM) have established governance and quality benchmarks. Several carbon credit rating services provide customers with detailed project-specific insights about relative credit quality, including co-benefits. Research suggests there is growing voluntary demand for higher-quality credits, though impacts remain uncertain. To address demand-side concerns, standard-setters such as Science-Based Targets initiative and the Voluntary Carbon Markets Integrity initiative stress that carbon credits should not substitute direct decarbonisation. This bolsters ongoing calls for a paradigm shift, under which carbon credits would be used to provide additional "contributions" to global mitigation efforts, rather than offset emissions. Nominally, this could alleviate concerns about delay effects.

Some governments have begun to respond with regulations and guidance. Under the now delayed EU Corporate Sustainability Reporting Directive (Toms et al. 2025), for example, large companies would be required to elucidate the quality of carbon credits they use and explain their role in decarbonisation efforts. In 2024, the US government issued a statement endorsing similar principles, though the administration has since changed. Similar efforts are underway elsewhere. The biggest test lies ahead: under Article 6 of the Paris Agreement, policymakers are establishing international standards that could set a quality benchmark for all carbon credit markets. Paying close attention to the unresolved quality challenges of existing standards could help ensure the same pitfalls are avoided in the future so that carbon credit markets accelerate climate action rather than undermine it.

POLICY IMPLICATIONS

- Carbon credit markets that are backed by robust integrity frameworks can contribute to emissions reductions. But carbon credits should be framed as additional contributions to mitigation, rather than as a substitute for internal decarbonisation and fossil fuel phase-out.

- To improve the credibility, transparency, and impact of voluntary carbon markets (VCMs), high-integrity standards – such as those developed by the Integrity Council for the Voluntary Carbon Market (ICVCM) and Voluntary Carbon Market Initiative (VCMI)– should be widely adopted across sectors. For greater coherence in corporate climate action, standard-setters should align on how to best incorporate carbon credits into reporting regulations, such as the EU's Corporate Sustainability Reporting Directive and the Task Force on Climate-related Financial Disclosures. These standards and reporting regulations can ensure additionality, appropriate baseline methodologies, and avoiding double-counting.

- Parties should seek the establishment of uniform global standards for carbon credit quality assessment, building on the Article 6.4 framework (Paris Agreement Crediting Mechanism) adopted at COP29. The Supervisory Body of Article 6.4 will continue to approve robust methodologies for assessing additionality, safeguarding sustainable development, and quantifying emission reductions. However, Parties should preserve negotiation space for complementary approaches beyond Article 6 (including sectoral emissions reduction agreements, industrial policies, technology transfer), which may prove more effective for sectors where carbon accounting faces inherent constraints.

- Greater attention and visibility should be given to the Global Stocktake as a mechanism to enhance transparency and accountability of climate action by both state and non-state actors. This builds on the momentum of COP29, including the UK's announcement of new principles for VCMs, the International Organization of Securities Commissions guidelines for promoting financial integrity in VCMs, and the launch of the ASEAN Common Carbon Framework.

10 Policy mixes outperform stand-alone measures in advancing emissions reductions

KEY MESSAGES

- Carefully designed combinations of policy measures often outperform stand-alone measures, resulting in larger emissions reductions. Interaction effects between instruments can generate synergies but also trade-offs, underscoring the need to account for overlaps and rebound effects.
- Policy mixes can address a multitude of market failures, increase overall policy stringency, and maximise credibility, shaping the expectations of consumers and investors.
- Policy mixes that include carbon pricing or reduced subsidies for fossil fuels typically achieve larger emissions reductions than those that rely solely on popular non-price-based instruments. Even a modest carbon price can significantly enhance the cost-effectiveness of the policy mix.
- Effective policy mixes vary by sector and national context, including level of economic development, and must be tailored to specific targeted actors, technologies, and institutional capacity.

Around the world a wide range of climate policies are used to reduce greenhouse gas emissions. Economic theory traditionally proposes one policy tool per market failure: carbon pricing for climate damages, R&D funding for knowledge spillovers, and targeted incentives for lock-in effects and network externalities. Few jurisdictions, however, have implemented an explicit carbon price near the social cost of carbon, let alone adopted a coordinated policy mix to address all market failures. The complex blend of policy instruments in place has developed across years, governments, and jurisdictional levels, resulting in limited coordination and overlaps.

Interactions between policies can alter their total impact to be more or less than the sum of their parts. In France, simulations of residential heating suggest a combination of bans on gas boilers and a subsidy scheme may increase the likelihood of carbon neutrality while reducing overall system costs and addressing distribution issues. Complementarities between policies may arise along different pathways due to spatial, temporal, or functional relationships, but individual policies may have a limited scope and are subject to rebound effects that require additional instruments like pricing. Additionally, policy mixes can address a multitude of market failures, increase overall policy stringency, and maximise credibility, shaping the expectations of consumers and investors. Identifying which instruments and policy combinations are most effective for additional emissions reductions and which lead to trade-offs across additional policy objectives represents a rapidly developing area of climate policy research.

A systematic evaluation of 1,500 climate policy measures implemented in 41 countries over the last two decades found emission reductions that match

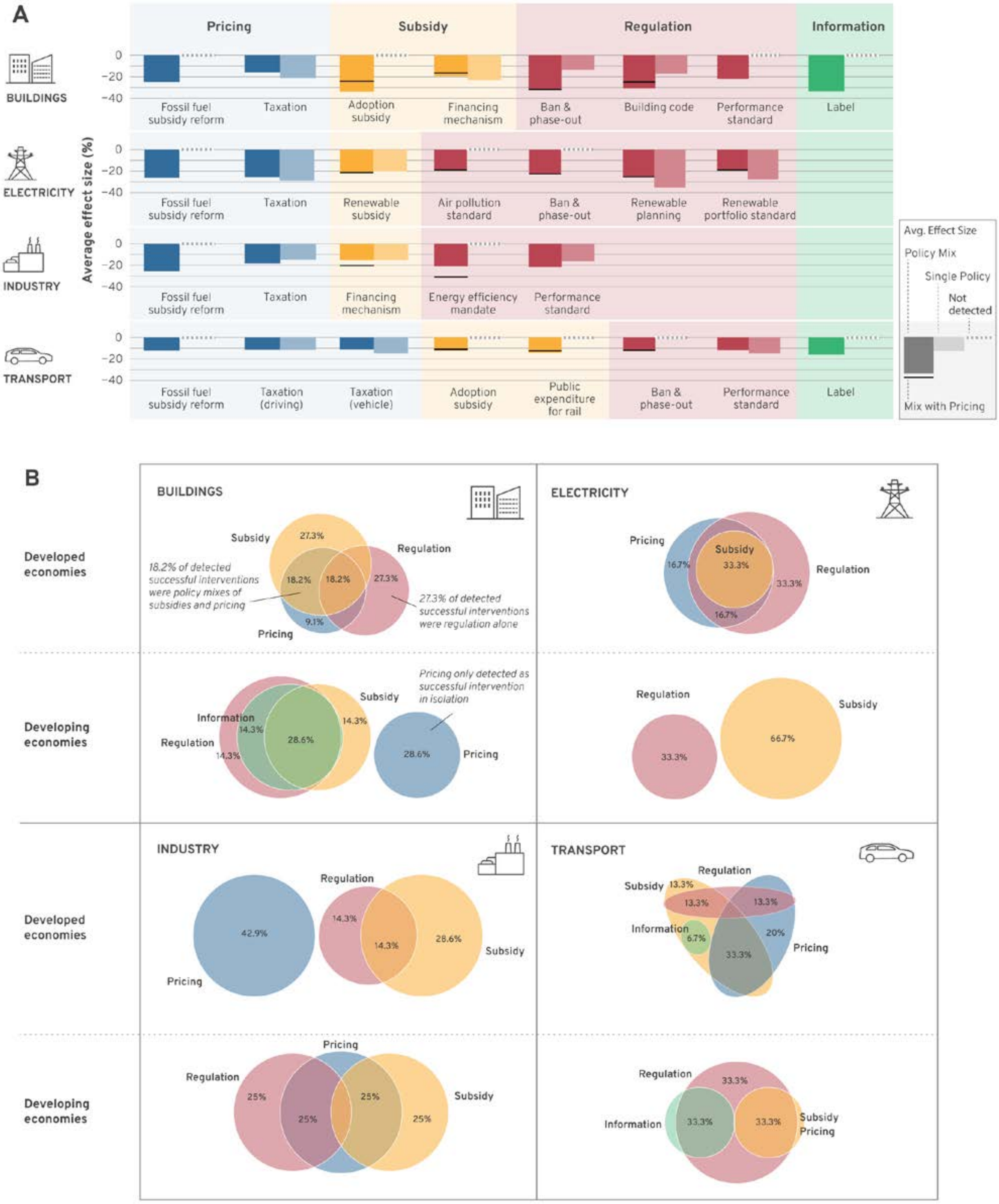

Figure 10. Comparison of the effectiveness of stand-alone policies and policy mixes: Average size of the emissions reduction if a policy instrument was successful individually vs in a policy mix (Panel A). For non-price-based policies, the black thick line indicates the average effect size of a mix that includes pricing instruments. Policy mixes often result in greater reduction effects compared to stand-alone implementations. Pricing instruments (taxation or reduced fossil fuel subsidies) are part of successful mixes with popular subsidy schemes and regulatory tools such as bans, building codes, and energy efficiency mandates. The effectiveness of policy mixes varies across sectors, country contexts, and stages of economic development (Panel B). For each circle area, the percentage indicates which share of successful interventions in this sector was made up of a specific individual policy type or a specific combination of policy types (redrawn from Stechemesser et al. 2024).

zero-emissions targets are possible but need to be scaled. The assessment identified 63 large emissions reductions leading to an average cut of 19%, with total emission reductions between 0.6 billion and 1.8 billion metric tonnes CO_2. These successful cases form a collective evidence base to learn from, and can all be explored using the Climate Policy Explorer. Carefully designed combinations of policy measures often outperform stand-alone instruments (Figure 10A). Many popular instruments – bans, building codes, energy efficiency mandates, and subsidies – either result in larger reductions only in combination with other policies or have a smaller impact alone. Policy mixes that include carbon pricing or reduced fossil fuel subsidies typically achieve larger emission reductions than reliance solely on popular non-price-based instruments (Figure 10A, black bars). Taxation stands out as the only instrument that leads to large emission reductions as a stand-alone policy.

Effective policy mixes vary by sector, country context, and stage of economic development (Figure 10B). Packages must be tailored to the characteristics of targeted actors, technologies, and institutional capacity, and implementation requires iterative learning and adjustment. Robust governance structures; systems for data collection, transparency, and monitoring; and ongoing evaluation are key for ensuring that policies remain effective over time and responsive to changing conditions. Additional challenges lie where climate policy is implemented across multiple jurisdictions and scales.

To reduce greenhouse gas emissions, there is no one-size-fits-all policy mix, but evidence on interaction effects of frequently used policy instruments is emerging, providing key lessons for policymakers. Dimanchev and Knittel (2023) have a framework for evaluating policy interactions and trade-offs and demonstrate that even a modest carbon price can significantly enhance the cost-effectiveness of the policy mix when paired with a performance standard. The relationship is nonlinear, with diminishing marginal returns as reliance on pricing grows. The importance of pricing is supported by observed emissions trajectories, with recent studies finding that successful large emission reductions within developed economies rely on the integration of tax and price incentives. There is often political resistance to carbon pricing, but the use of performance standards has expanded with greater public support and policy durability. To leverage the strengths of different instruments to balance trade-offs across multiple policy objectives requires well-designed policy mixes.

The type and design of policy instruments fundamentally shape how they interact with other instruments. When additional policies overlap with a fixed-quantity instrument like the emissions cap, they may not achieve added emissions reductions because the total quantity of allowances is unchanged. So fixed-quantity instruments must incorporate mechanisms to dynamically adjust the cap in response to market conditions reflecting lower demand. The European Union Emission Trading Scheme's Market Stability Reserve is one such innovation that can help mitigate the effect by automatically reducing the supply of allowances as other policies reduce demand. Without accounting for these interaction effects, additional policies could even increase total emissions by shifting towards unregulated sources, sectors, and facilities. Unlike fixed-quantity instruments, fixed-price instruments, such as a carbon tax, maintain their price incentive regardless of overlapping policies because the incentive from the price signal remains unchanged providing a cumulative incentive for emissions reductions.

In an increasingly complex climate policy environment, a growing body of research emphasises the importance for policymakers to consider interactions and combined effects of climate policies in order to reduce greenhouse gas emissions. It is important both to promote policy combinations that generate positive synergies and avoid negative or offsetting effects. Leveraging available evidence from real-world practice provides an opportunity to learn from circumstances in which structural breaks in emissions trajectories have been observed.

Finally, climate policy mixes rarely pursue emissions reductions alone. They are often designed or evolve to achieve multiple objectives including cost effectiveness, distributional equity, innovation, energy security, and political feasibility. Policy acceptance is a crucial factor, and sequencing of policies plays a role. Recent evidence shows that the perceived effectiveness of prior policy-induced benefits is related to greater support for higher carbon prices across sectors. Research is needed to extend the knowledge base on policy combinations and interactions across multiple objectives and time. Designing effective combinations thus requires understanding sector-specific interactions, managing trade-offs, and adapting instruments to jurisdictional needs – pointing to a critical opportunity to close both the emissions gap and the emerging knowledge gap on policy effectiveness.

POLICY IMPLICATIONS

- Reporting frameworks, at both UNFCCC and country levels, should explicitly capture the interactions between policies and measures, going beyond isolated policy tracking towards a more integrated approach – a gap that has been recognised by the IPCC AR6. To ensure these interactions are effective and avoid unintended trade-offs, systematic and continuous policy evaluation should also be built into the policy design.

- Parties would benefit from common guidelines on which policy impacts to quantify and what contextual information to provide. Harmonised baselines and reporting periods would also improve comparability across countries, enhancing peer learning under the UNFCCC and enabling more effective policy design. Standardised data have already proven useful in identifying policy changes linked to emission reductions.

- National governments should favour synergistic policy combinations (e.g., pairing bans with subsidies or combining carbon pricing with performance standards) that are known to achieve stronger emissions reductions than stand-alone measures.

- At the national level, climate goals should be set through coordinated, cross-ministerial processes rather than limited to single agencies or ministries, recognising the multiple spill-over effects and co-benefits of climate policies beyond emission reductions. In turn, greater cross-sectoral synchronisation can yield more effective emission reductions. Similarly, policy evaluation criteria should encompass a variety of outcomes, including health, equity, and social well-being.

- With ample information on effective instruments available, greater attention is needed on political feasibility, decision-making barriers, public opinion, equity and justice, and distributional effects to ensure that ambitious policy mixes can be successfully implemented. Tools like the Climate Policy Explorer provide insights into how different types of policies can lead to emissions reductions. The lessons learned can serve as input for policymakers seeking to drive emissions reductions.

- Policy packages should be tailored to actors, technologies, and institutional capacities, and implemented through robust governance, transparent monitoring, and iterative learning systems to remain adaptive over time.

Abbreviations

BECCS – Bioenergy with Carbon Capture and Storage

CBD – Convention on Biological Diversity

CDR – Carbon Dioxide Reduction

CH_4 – Methane

CO_2 – Carbon Dioxide

COP – Conference of the Parties

C1 – Category 1 scenarios: no or limited overshoot of 1.5°C by 2100 (with >50% chance), as defined by the IPCC AR6

C3 – Category 3 scenarios: to limit peak warming to below 2°C by 2100 (with a >66% chance), as defined by the IPCC AR6

DACCS – Direct Air Carbon Capture and Storage

EEI – Earth's energy imbalance

GDP – Gross Domestic Product

GGA – Global Goal for Adaptation

GRACE – Gravity Recovery and Climate Experiment

GST – Global Stocktake

GtC – Gigatonnes of Carbon

IPCC – Intergovernmental Panel on Climate Change

KMGBF – Kunming-Montreal Global Biodiversity Framework

LT-LEDS – Long-Term Low-Emission Development Strategies

MHW – Marine Heatwaves

MWP – Mitigation Work Programme

NAP – National Adaptation Plan

NDC – Nationally Determined Contributions

NCQG – New Collective Quantified Goal

N_2O – Nitrous Oxide

RCP – Representative Concentration Pathway

SSP – Shared Socioeconomic Pathway

UNCCD – United Nations Convention to Combat Desertification

UNFCCC – United Nations Framework Convention on Climate Change

VCM – Voluntary Carbon Markets

WHO – World Health Organization

WMO – World Meteorological Organization

Main references for each Insight

For a full list of references for each insight, see Ospina et al. (under review) Ten New Insights in Climate Science 2025. *Global Sustainability*. doi: 10.5281/zenodo.17457864

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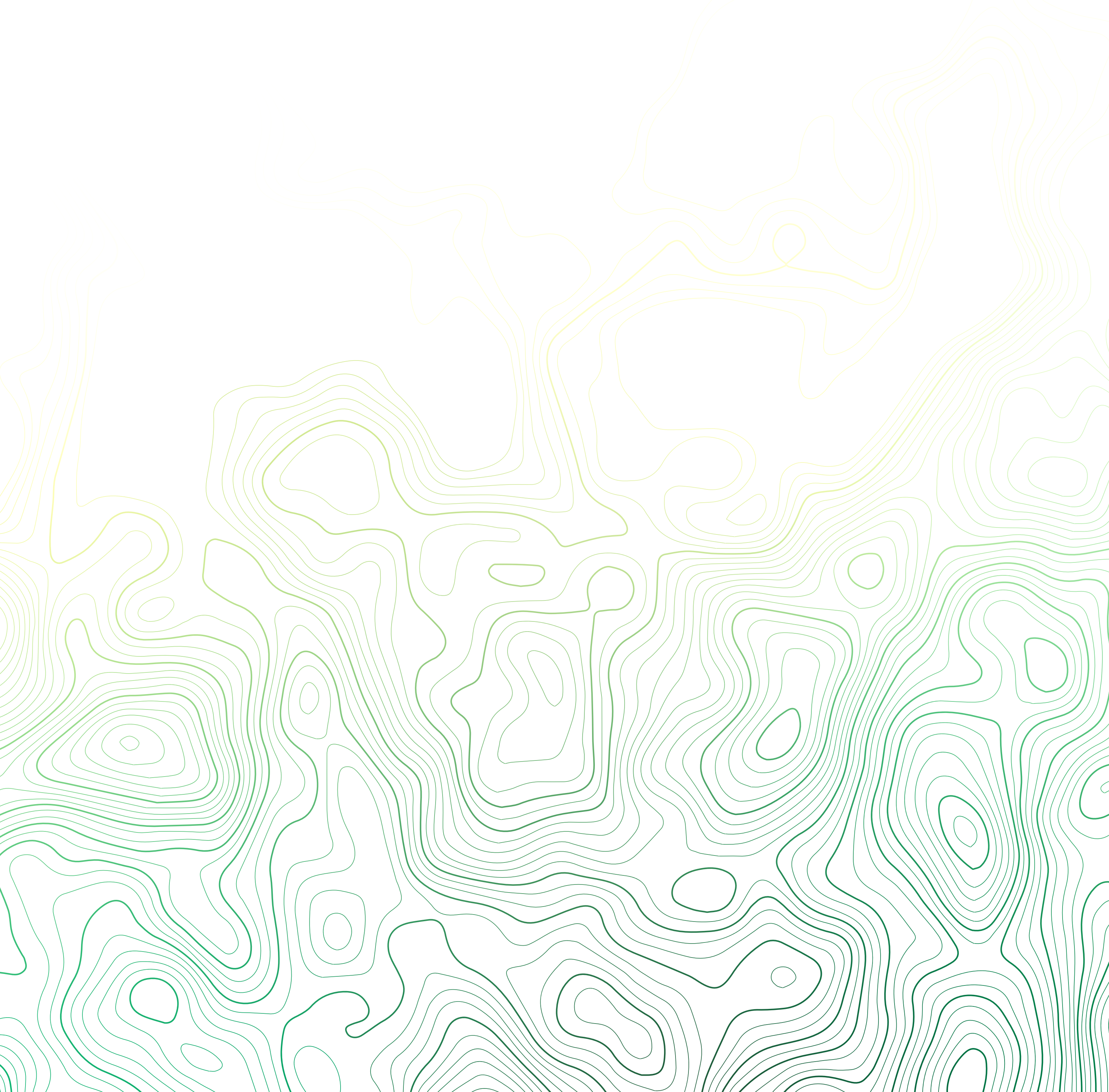

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