GLOBAL TIPPING POINTS REPORT 2025



GLOBAL TIPPING POINTS

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Edited by

Timothy M. Lenton:
Report lead: Global Systems Institute (GSI), University of Exeter, UK; Earth Commission

Manjana Milkoreit:
Section 1 lead: Department of Sociology and Human Geography, University of Oslo, Norway; GSI, University of Exeter, UK

Simon Willcock:
Section 1 lead: School of Environmental and Natural Sciences, Bangor University, UK; Net Zero and Resilient Farming, Rothamsted Research, UK

Jesse F. Abrams:
Section 2 lead: GSI, University of Exeter, UK; Earth Commission

David I. Armstrong McKay:
Section 2 lead: School of Global Studies, University of Sussex, UK; Stockholm Resilience Centre (SRC), Stockholm University, Sweden

Joshua E. Buxton:
Section 2 lead: GSI, University of Exeter, UK, Earth Commission

Jonathan F. Donges:
Section 2 lead: Potsdam Institute for Climate Impact Research (PIK), Germany; Stockholm University, Sweden; Department Integrative Earth System Science, Max Planck Institute of Geoanthropology, Germany

Sina Loriani:
Section 2 lead: PIK, Germany; Member of the Leibniz Association, Germany; Earth Commission

Nico Wunderling:
Section 2 lead: Center for Critical Computational Studies (C3S), Goethe University Frankfurt, Germany; PIK, Member of the Leibniz Association, Germany; Senckenberg Research Institute and Natural History Museum, Germany.

Floor Alkemade:
Section 3 lead: Eindhoven University of Technology, Netherlands

Mike Barrett:
Section 3 lead: WWF-UK

Sara Constantino:
Section 3 lead: Stanford University, USA

Tom Powell:
Section 3 lead: GSI, University of Exeter, UK

Steven R. Smith:
Section 3 lead: Green Futures Solutions and GSI, University of Exeter, UK; World Economic Forum, Geneva; Centre for the Understanding of Sustainable Prosperity, University of Surrey, UK

Chris A. Boulton:
Section 4 lead: GSI, University of Exeter, UK

Donovan Dennis:
Section 4 lead: PIK and Max Planck Institute of Geoanthropology, Germany

Henk Dijkstra:
Section 4 lead: Utrecht University, Netherlands

Paul Pearce-Kelly:
Section 4 lead: Zoological Society of London, UK

Patricia Pinho:
Section 4 lead: The Amazon Environmental Research Institute, Brazil

Rosa M. Roman-Cuesta:
Section 4 lead: European Commission, Joint Research Center, Italy; Technical University Munich, Germany

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The Global Tipping Points Team

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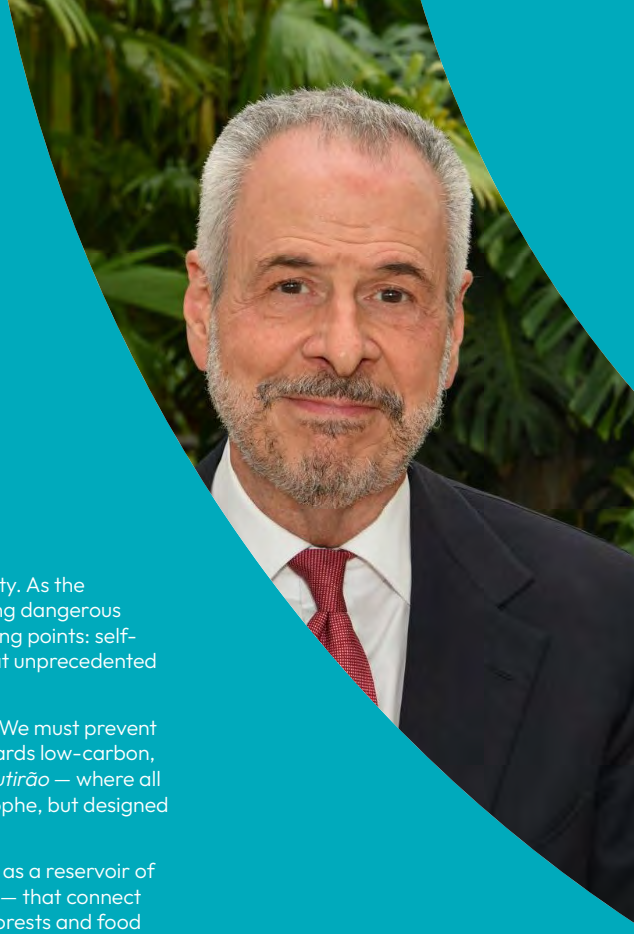
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Contents

Foreword – André Corrêa do Lago, COP30 President	**4**
Summary	**6**
Key messages	**7**
Governance of Earth system tipping points	13
Earth system tipping points and risks	19
Positive tipping points	27
The Amazon rainforest	40
Atlantic Ocean circulation	41
Warm-water coral reefs	42
Mountain glaciers	43
Introduction	**45**
Section 1 Governance of Earth system tipping points	**50**
1.1 Acting on Earth system tipping points: Why and how?	51
1.2 Governance to prevent Earth system tipping points	59
1.3 Impact governance for Earth system tipping points	71
1.4 A human rights framework for Earth system tipping points governance	81
1.5 Actors, agency and strategies in Earth system tipping points governance	88
Section 2 Earth System tipping points and risks	**96**
2.1 Introduction to Earth system tipping point risks	97
2.2 Status of Earth system tipping points: What's new?	107
2.3 Implications of overshooting 1.5°C for Earth system tipping points	136
2.4 Earth system tipping point risk assessment	142
Section 3 Positive tipping points	**165**
3.1 Identifying positive tipping potential	166
3.2 Acting on positive tipping points	173
3.3 Progress on positive tipping points in key systems	188
3.4 Renewable power and electrification: From tipping in technology adoption to system transformation	219
3.5 Positive tipping points in food systems, land use and nature	223
Section 4 Case Studies	**231**
4.1 The Amazon rainforest	232
4.2 Atlantic Ocean circulation	242
4.3 Warm-water coral reefs	254
4.4 Mountain glaciers: Áak'w T'áak Sít' (Mendenhall Glacier)	267
Appendices	**281**
1 Glossary	281
2 Contributing authors	284
3 Reviewers	291
References	**293**



Foreword to the Global Tipping Points Report 2025

The **Global Tipping Points Report 2025** comes at a time of urgency — but also of possibility. As the world prepares to gather in Belém for COP30, science warns us of ecosystems approaching dangerous thresholds. Yet this same science also shows us the extraordinary potential of positive tipping points: self-reinforcing shifts in policies, technologies, finance, and behaviours that can drive change at unprecedented speed and scale.

Brazil's vision for COP30 is to transform the narrative of tipping points from fear to hope. We must prevent irreversible harm but equally **trigger positive tipping points** that can propel societies towards low-carbon, resilient development and inclusive prosperity. This requires collective effort — a *Global Mutirão* — where all nations and communities act together, by choice, to build a future not imposed by catastrophe, but designed through cooperation.

The COP30 **Action Agenda** embodies this approach. Its *Granary of Solutions* is conceived as a reservoir of concrete tools and initiatives — scalable, replicable, and aligned with the Paris Agreement — that connect ambition with implementation. By mobilising actors and resources across six axes - from forests and food systems to energy, cities, finance, and technology, the Action Agenda has been conceived as a platform for channeling global cooperation for triggering positive tipping points of transformation leveraging solutions that already exist.

The Global South is central to this endeavour. Across Africa, Asia, and Latin America and the Caribbean, communities are pioneering regenerative agriculture, restoring mangroves and forests, developing new bioeconomy value chains, and advancing innovative financial instruments for just transitions. These are not peripheral experiments: they are **seeds of systemic change**, able to cascade into global impact if nurtured with solidarity, resources, and political will.

Every tipping point of danger can be mirrored by a tipping point of opportunity. If coral reefs are dying back, restoration of coastal ecosystems can still drive resilience and livelihoods. If forests are at risk, their regeneration can unlock carbon removal, biodiversity recovery, and sustainable prosperity. If energy systems remain carbon-intensive, the exponential uptake of renewables and electrification — already led by many countries of the South — can define a new development model that cascades into positive change across other sectors.

Our three objectives for COP30 are clear:

1. **Reinforce multilateralism** — because only united can we safeguard the climate regime and make it deliver.
2. **Connect climate action to people's lives** — because climate action must begin and end with people.
3. **Accelerate the implementation of the Paris Agreement** — inclusively, and beyond negotiation rooms, by mobilising every sector, every international institution and every community.

This report is therefore not only a warning but a guide: it maps where dangers converge, but also where opportunities to tip systems positively are within reach. COP30 in Belém must be remembered as the moment when we chose to **scale up solutions from all parts of the world — especially the South — into a global wave of renewal.**

The time to act is now. United, we can reverse the dangerous trend towards a sequence of systems collapses in domino effect. Let us build on and support each other to prevent a potentially devastating chain-reaction. Let us trigger instead a "chain of action," for exponential low-carbon and climate-resilient solutions worldwide. Let us change by choice, together.

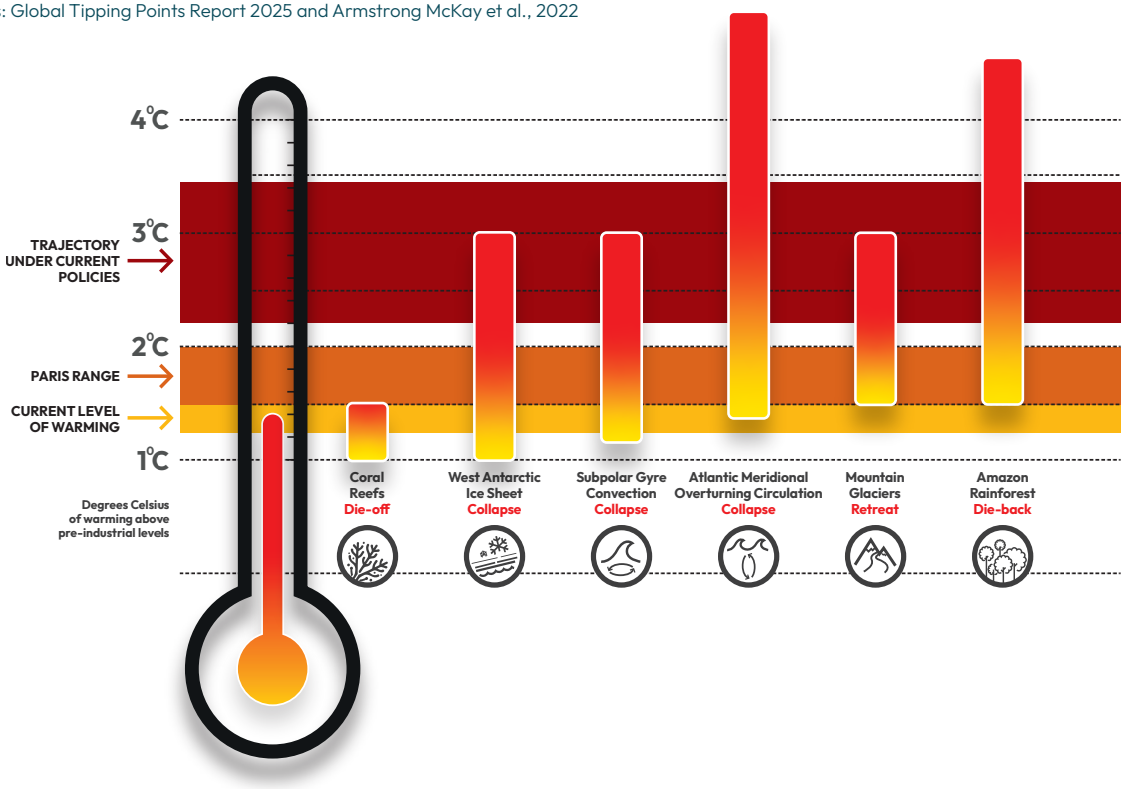


André Aranha Correa do Lago

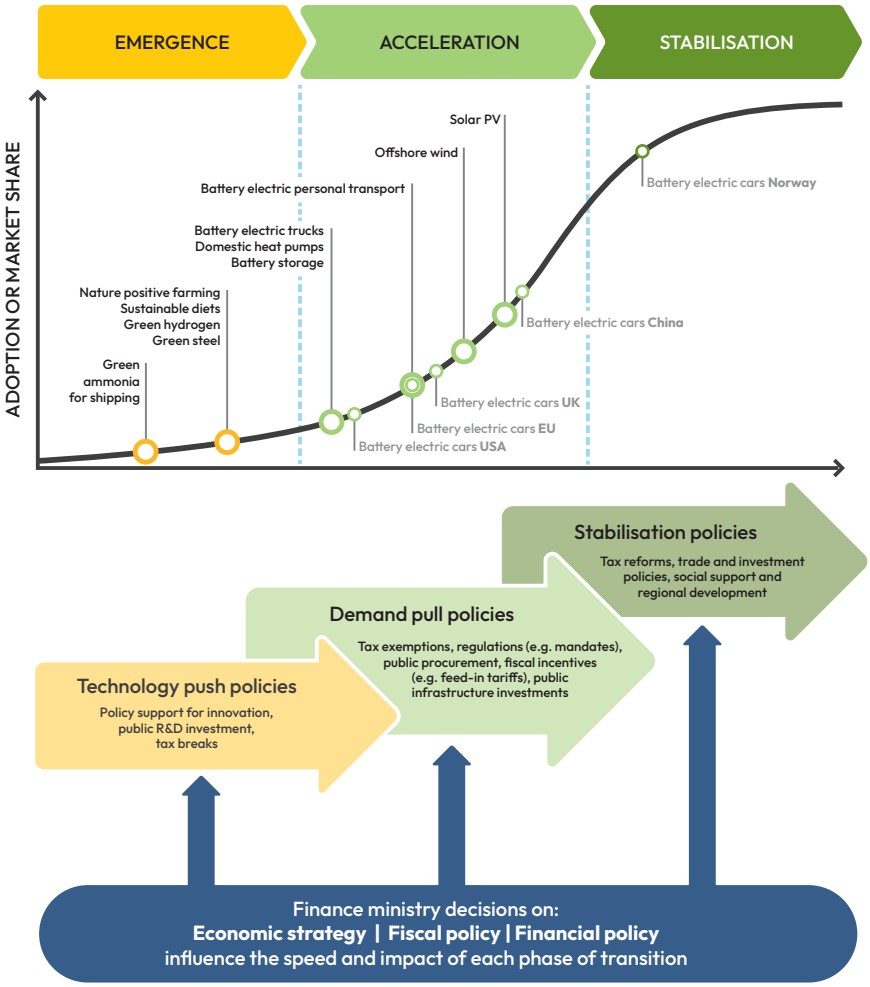
COP30 President Designate

Risks of Earth system tipping points increase with global warming

Sources: Global Tipping Points Report 2025 and Armstrong McKay et al., 2022



Policies to support positive tipping and the transition status of different technologies and markets



SUMMARY

The world has entered a new reality. Global warming will soon exceed 1.5°C. This puts humanity in the danger zone where multiple climate tipping points pose catastrophic risks to billions of people. Already warm-water coral reefs are crossing their thermal tipping point and experiencing unprecedented dieback, threatening the livelihoods of hundreds of millions who depend on them. Polar ice sheets are approaching tipping points, committing the world to several metres of irreversible sea-level rise that will affect hundreds of millions.

Every fraction of additional warming increases the risk of triggering further damaging tipping points. These include a collapse of the Atlantic Meridional Overturning Circulation (AMOC) that would radically undermine global food and water security and plunge northwest Europe into prolonged severe winters. Together, climate change and deforestation put the Amazon rainforest at risk of widespread dieback below 2°C global warming, threatening incalculable damage to biodiversity and impacting over 100 million people who depend on the forest.

These climate tipping point risks are interconnected and most of the interactions between them are destabilising, meaning tipping one system makes tipping another more likely. The resulting impacts would cascade through the ecological and social systems we depend upon, creating escalating damages. Humanity faces a potentially catastrophic, irreversible outcome. The Inter-American Court of Human Rights recognises the right of humans to a safe climate, hence preventing irreversible harm to the climate system is a legal imperative.

How hot we let it get and for how long really matters in preventing climate tipping points. The magnitude and duration of global temperature overshoot above 1.5°C has to be minimised. To achieve that, global anthropogenic greenhouse gas emissions must be halved by 2030 (compared to 2010 levels) and then reach net zero by 2050. This requires an unprecedented acceleration in decarbonisation, rapid mitigation of methane emissions and other short-lived climate pollutants and fast scaling of sustainable carbon removal from the atmosphere.

If we wait to cross tipping points before we act, it will be too late. The only credible risk management strategy is to act in advance. But the window for preventing damaging tipping points is rapidly closing. Current Nationally Determined Contributions (NDCs) and binding long-term or net zero targets are not enough. They still commit the world to ongoing global warming that will likely exceed 2°C before 2100. This demands immediate, unprecedented action from leaders at COP30 and policymakers worldwide.

To achieve such a radical acceleration of action requires triggering positive tipping points that generate self-amplifying change in technologies and behaviours, towards zero emissions. In the two years since the first Global Tipping Points Report was published, there has been a radical acceleration in the uptake of solar power and electric vehicles worldwide. However, there has also been a recent spate of backsliding on commitments in some nations and sectors, including finance.

Nevertheless, a minority can still tip the majority when they have self-amplifying feedback on their side. This is clearly evident in clean technology adoption. Solar PV panels have dropped in price by a quarter for each doubling of their installed capacity. Batteries have improved in quality and plummeted in price the more that are deployed. This encourages further adoption. The spread of climate litigation cases and nature positive initiatives is also self-amplifying. The more people undertaking them the more they influence others to act.

Positive tipping points are also starting to interact and reinforce one another. Policies targeting super-leverage points of interaction can help trigger this cascading positive change. Reinforcing feedback between civil society and policymakers is also critical to amplifying positive change. Hence the Global Mutirão, by catalysing collective action from civil society, could be key to triggering positive tipping points.

Only with a combination of decisive policy and civil society action can the world turn from facing existential climate tipping point risks to seizing positive tipping point opportunities.

01. NEW REALITY

Earth's climate and nature are already passing tipping points as global warming approaches 1.5°C.

Since the first Global Tipping Points Report in 2023, understanding of tipping point risks has increased. Already at 1.4°C of global warming, warm water coral reefs are crossing their thermal tipping point and experiencing unprecedented dieback, impairing the livelihoods of hundreds of millions who depend on them. Parts of the polar ice sheets may also have crossed tipping points that would eventually commit the world to several metres of irreversible sea-level rise affecting hundreds of millions. Crossing tipping points reduces Earth's ability to cope with human interference, further amplifying impacts, making it a fundamental human rights issue.

02. ESCALATING RISK

Overshooting 1.5°C puts the world in a danger zone where further tipping points pose catastrophic risks.

Global warming is projected to overshoot 1.5°C within a few years, placing humanity at even greater risk. Climate change and deforestation together put the Amazon rainforest at risk of widespread dieback below 2°C, threatening incalculable damage to biodiversity and impacting over a hundred million who depend on the forest. The Atlantic Meridional Overturning Circulation (AMOC) is also at risk of collapse below 2°C, which would radically undermine global food and water security and plunge northwest Europe into severe winters. Preventing climate tipping points should be a legal imperative.

03. PREVENT TIPPING

Minimising overshoot of 1.5°C is essential to prevent climate tipping points.

Every fraction of a degree and every year over 1.5°C matters for preventing climate tipping points. To minimise the magnitude and duration of global temperature overshoot above 1.5°C, global anthropogenic greenhouse gas emissions need to be halved by 2030 (compared to 2010 levels), reach net zero by 2050, and then net greenhouse gas removal needs to occur. This requires unprecedented acceleration in decarbonisation, rapid mitigation of short-lived climate pollutants – especially methane emissions, and rapid scaling of sustainable and equitable carbon removal from the atmosphere.

04. ACT NOW

Leaders at COP30 must act now to prevent damaging tipping points.

The window for preventing some damaging, irreversible tipping points is rapidly closing. If we wait for certainty that tipping points have been crossed before we act, it will be too late. Current Nationally Determined Contributions (NDCs) and binding long-term or net zero targets are not enough to prevent damaging tipping points. They commit the world to global warming that will likely exceed 2°C before 2100. Hence unprecedented action is needed from leaders at COP30 and policymakers worldwide to prevent damaging tipping points.

05. ACT LOCALLY

Tackling non-climate drivers can help avoid biosphere tipping points.

For warm-water coral reefs, the Amazon rainforest and other ecosystems at risk of tipping, reducing non-climate stressors can help increase their resilience to tipping. For coral reefs, this includes reducing overfishing and nutrient loading. For the Amazon rainforest, reducing deforestation and forest degradation are key. These local actions can give communities some agency over the fate of their ecosystems. Ultimately, however, global warming will need to be reduced below 1.5°C towards 1°C to prevent the permanent loss of coral reefs.



06. RECENT PROGRESS

Climate progress has accelerated in the last 2 years despite recent backsliding.

Since 2023, there has been a radical acceleration in the uptake of clean technologies worldwide, notably solar PV power and electric vehicles. There has also been contagious spread of climate litigation cases, nature regeneration initiatives, together with the emergence of more sustainable patterns of consumption and production in food and fibre supply chains. Despite recent backsliding on commitments in some nations and sectors, a minority can still positively tip the majority, generating self-amplifying change in societies, economies and technologies. The more people who act, the more they influence others to act.

07. TRANSITION AWAY

Policy mandates are needed to accelerate the transition away from fossil fuels.

The most effective policies to trigger positive tipping points in the energy system are generally policy mandates to phase in clean technologies and transition away from fossil fuelled ones. These include bans on the future sale of petrol/diesel cars, diesel trucks and gas boilers in key markets. They can make clean alternatives better and cheaper for everyone, helping eliminate the 75% of greenhouse gas emissions linked to the energy system, and transition away from fossil fuels in a just, orderly and equitable manner.



08. ENABLE FINANCE

Reducing the cost of capital enables positive tipping points especially in the Global South.

All sources of public and private finance can be engaged to reduce the cost of capital for low-carbon technologies and resilient infrastructure, particularly for the benefit of Global South countries. The costs of climate finance must also take into account the long-term economic and health benefits of climate action and the far greater costs of inaction or delay. The Baku-to-Belem Roadmap offers a transformational opportunity for climate finance.



09. PROMOTE JUSTICE

Positive tipping points can simultaneously combat poverty, hunger and inequality.

Positive tipping points are already reducing energy prices worldwide, accelerating access to cheap electricity for those that lack it, and benefitting the economies of net fossil fuel importing countries where three-quarters of people live. Engaging communities in rapid transition can help ensure that decarbonisation also achieves social developmental goals of combatting hunger, poverty and inequality. Digital public infrastructure can support fairness and shared prosperity by delivering essential financial, health, educational, and other social and economic services, particularly in low- and middle income countries.



10. TIP FOOD

Sustainable production and consumption can positively tip the food system.

Policy changes are needed worldwide to help eliminate the 25% of greenhouse gas emissions linked to food, farming, and deforestation and in so doing, help reverse global biodiversity loss. Domestic legal frameworks and governance, shifts to sustainable production supported by public and private finance, changes in consumption and sustainable international trade policies are critical to avoid damaging tipping points in nature. This includes avoiding dieback of the Amazon rainforest. These changes are necessary to liberate land for regenerating nature.



11. REGENERATE NATURE

Positive tipping points of nature regeneration can scale sustainable carbon removal.

Nature regeneration can be positively tipped, and social tipping points are already spreading nature positive initiatives, including marine protected areas. Action to protect indigenous rights, support community-led conservation initiatives, ensure fair and transparent valuing of nature and establish rights of nature, can help trigger further positive tipping points for nature. This will help achieve the Kunming-Montreal Global Biodiversity Framework targets and is essential to scale up sustainable removal of CO_2 from the atmosphere and limit overshoot of 1.5°C.



12. CASCADE CHANGE

Civil society and governance can catalyse each other to cascade positive change.

Positive tipping points can cascade between different parts of society and the economy. Catalysing collective action from civil society - through the Global Mutirão - is key to helping trigger positive tipping points and giving policymakers a mandate to act. Policy action should target super-leverage points that can trigger cascading positive change across sectors. Only with a combination of decisive policy and civil society action can the world tip its trajectory from facing existential climate tipping point risks to seizing positive tipping point opportunities.



SECTION 1

GOVERNANCE OF EARTH SYSTEM TIPPING POINTS



Section lead authors:
Manjana Milkoreit, Simon Willcock



Earth system tipping points pose distinct and urgent governance needs

- With global warming soon overshooting 1.5°C, developing and implementing effective governance strategies to prevent Earth system tipping points is increasingly urgent and important.
- Tipping points present distinct governance challenges compared to other aspects of climate change or environmental decline, requiring both governance innovations and reforms of existing institutions.
- Precaution, anticipatory governance and systemic risk governance are key approaches for addressing Earth system tipping points.
- Amid deepening geopolitical fragmentation and the weakening of multilateralism, governance responses to Earth system tipping points must focus on fostering a flexible, multi-scale agenda capable of advancing under challenging political conditions.



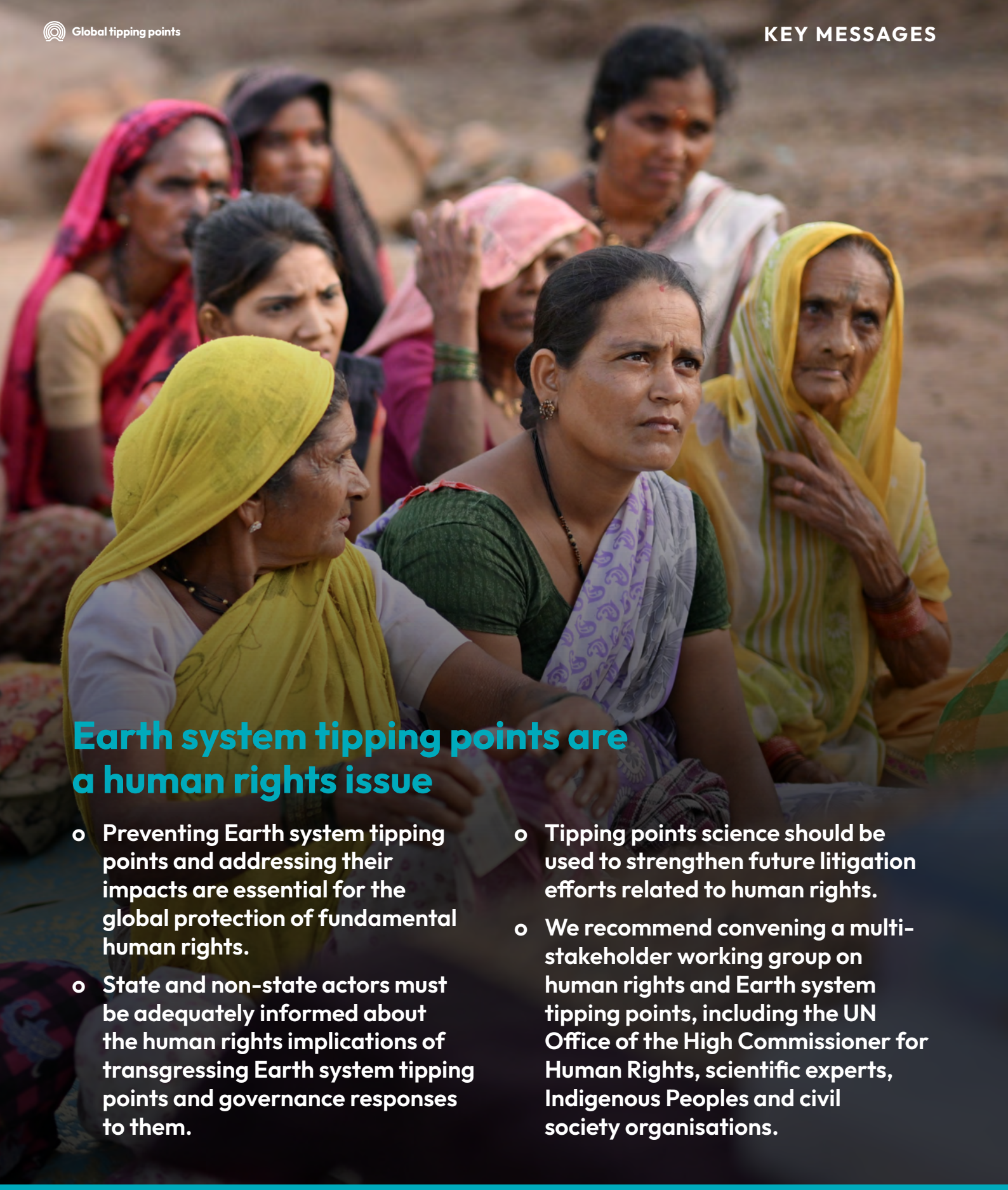
Preventing Earth system tipping points requires a change in strategy

- The risk of activating Earth system tipping processes exists at current levels of global warming and increases with every 0.1°C and every year of overshooting the globally agreed goal of 1.5°C.
- Current climate mitigation measures are not sufficient to prevent tipping events; they need to be accelerated and coupled with measures addressing non-climate drivers, such as deforestation of the Amazon rainforest.
- Preventing tipping points requires 'frontloaded' mitigation pathways that minimise peak global temperature, the duration of the overshoot period above 1.5°C and the return time below 1.5°C with immediate, comprehensive transition away from fossil fuels.
- Sustainable carbon dioxide removal approaches need to be rapidly scaled up to help return the global mean temperature to and then below 1.5°C.



The impacts of Earth system tipping points demand governance action

- Societies need governance efforts that anticipate and prepare for the specific impacts of Earth system tipping points before tipping points are crossed – these impacts differ from the observed and expected impacts of other aspects of climate change.
- Governance should assess and reduce vulnerability to tipping point impacts, build resilience and include tipping point impacts in climate adaptation policy and planning and related policy domains.
- Governments, intergovernmental organisations, economic and financial actors should integrate Earth system tipping points in risk assessments across scales.
- Justice – intragenerational, intergenerational and interspecies – must be at the centre of Earth system tipping point impact governance.



Earth system tipping points are a human rights issue

- Preventing Earth system tipping points and addressing their impacts are essential for the global protection of fundamental human rights.
- State and non-state actors must be adequately informed about the human rights implications of transgressing Earth system tipping points and governance responses to them.
- Tipping points science should be used to strengthen future litigation efforts related to human rights.
- We recommend convening a multi-stakeholder working group on human rights and Earth system tipping points, including the UN Office of the High Commissioner for Human Rights, scientific experts, Indigenous Peoples and civil society organisations.



Multiple actors are needed to govern Earth system tipping point risks

- Earth system tipping points require engagement not only from national governments and international bodies, but also municipal, regional, corporate and community actors, each of whom have particular responsibilities, capacities and opportunities to influence outcomes.
- Diverse strategies are needed to address Earth system tipping points—ranging from law and policymaking to advocacy, institutional reform and storytelling—drawing on the varied capacities, mandates and influence of actors operating across multiple scales and domains.
- In this early agenda-setting phase of Earth system tipping point governance, actors such as international organisations, science communicators and advocacy groups have a critical role to play in raising awareness, shaping narratives and mobilising political will.
- Addressing Earth system tipping points requires building trust and fostering cooperation and coordination among state and non-state actors across multiple levels of governance.

SECTION 2

EARTH SYSTEM TIPPING POINTS AND RISKS



Section lead authors:
Jesse Abrams, David Armstrong McKay, Joshua E. Buxton, Sina Loriani, Nico Wunderling



Earth system tipping points pose profound risks

- Tipping points threaten the stability of the Earth system, which our society and economy fundamentally rely on. Societal development, wellbeing, prosperity and economic health are threatened by Earth system tipping points.
- Earth system tipping points create diverse and interconnected risks that are different to other climate impacts, often characterized by irreversibility, deep uncertainty and potential for cascading failures across natural and human systems.

New risk assessment approaches are needed for tipping points

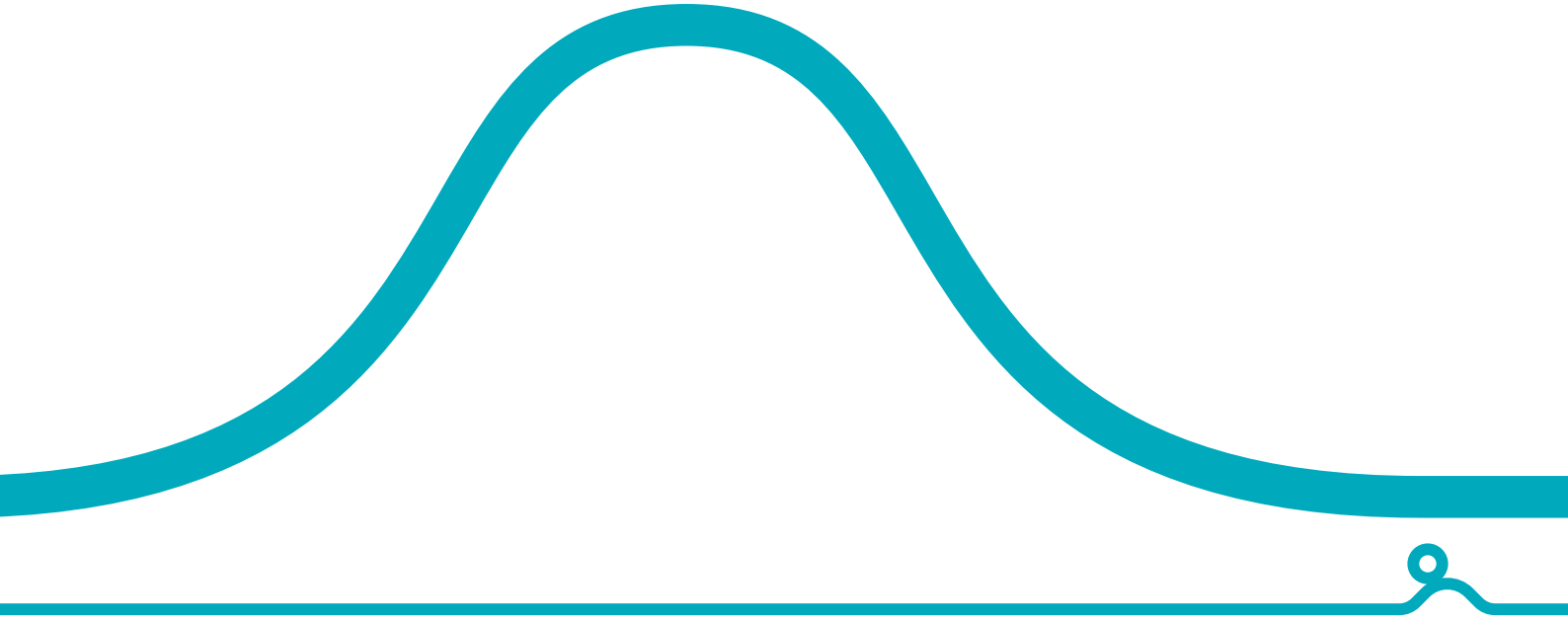
- Traditional risk assessment fails for Earth system tipping points: Conventional impact-probability matrices capturing individual climate impacts are inappropriate for tipping point risk analysis, due to uncertainty, nonlinear dynamics and the systemic scale and scope of interactions between impacts and their cascading effects.
- Assessing tipping point risks can benefit from specialized approaches including risk registers that translate Earth system changes into policy-relevant "risk currencies" while capturing cascading effects and system interactions.

Cryosphere tipping points may already have been crossed

- We have high confidence that ice sheets - from Greenland to West Antarctica - have warming tipping points leading to irreversible collapse, locking in long-term multi-metre sea level rise and have been at risk since at least 1°C of global warming.
- While Arctic summer sea ice is unlikely to reach tipping points, Antarctic sea ice may have a tipping point that could already be underway, although highly uncertain.
- We have medium confidence in potential regional tipping points in permafrost and glaciers, which would respectively amplify emissions and commit some regions to total deglaciation.

Biosphere tipping points are approaching faster than we thought

- Warm-water coral reefs have experienced the worst bleaching event on record over 2023-2025 and the central estimate of their thermal tipping point of 1.2°C global warming has been crossed.
- The Amazon rainforest has faced two years of intense El Niño-induced drought and the combined effects of deforestation and climate change put it at risk below 2°C of global warming.
- We now recognise river deltas and peat bogs as potential tipping systems, identify the potential for localised mangrove tipping with high confidence and the potential for local-scale temperate forest tipping with low confidence.





Ocean and atmosphere circulation are already at risk of tipping points

- Recent modelling supports the Atlantic Meridional Overturning Circulation (AMOC) and Sub-Polar Gyre (SPG) deep convection having tipping points, which cannot be ruled out at current warming levels, but limited models and observations means their likelihood of tipping remains uncertain.
- In the Southern Ocean, dense shelf water formation may be declining and could reach a tipping point, but understanding of its interactions with ice remains limited.
- Recent modelling supports the Indian summer monsoon having tipping dynamics, although evidence remains limited, whereas evidence against tipping dynamics in the 'jet stream' has strengthened.

Interactions between tipping systems tend to increase risk

- Out of 20 climate tipping system interactions assessed, most are destabilising, but a few may have a stabilising effect.
- The AMOC is the key global mediator of tipping point interactions, featuring in 45% of all assessed tipping point interactions.
- A vicious cycle may form where permafrost thaw could lead to amplified Arctic sea ice retreat, which may lead to enhanced inland permafrost degradation and so on.

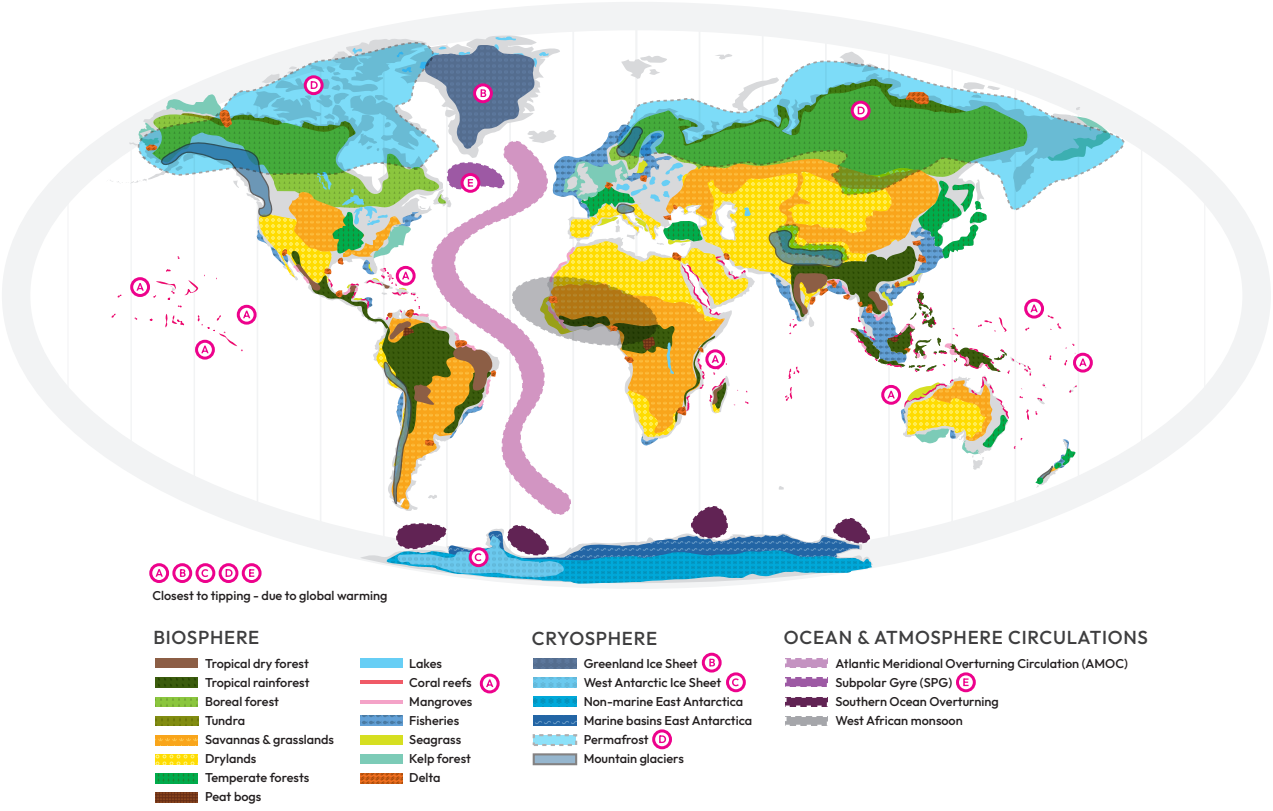
Overshooting 1.5°C increases the risk of crossing multiple climate tipping points

- Several systems (land permafrost, Greenland ice sheet, West Antarctic ice sheet and sub-polar gyre) likely have a tipping point around 1.5°C global warming.
- Several more systems (mountain glaciers, boreal forests and AMOC) likely have a tipping point around 2.0°C global warming.
- Crossing these tipping points becomes more likely for each 0.1°C of global warming.

Peak warming and time above 1.5°C must be minimised to limit tipping risks

- Limiting tipping risks requires minimising peak global warming and overshoot duration above 1.5°C and ultimately stabilising global warming below 1.5°C before 2100 and below 1.0°C on longer timescales.
- Fast tipping systems are vulnerable to even short-lived overshoots of their tipping points and therefore they constrain the allowable peak global warming.
- Slow systems can tolerate temporary overshoots of their tipping points but constrain the allowable duration of overshoot and the eventual temperature stabilisation level.

Parts of the Earth system identified in this report as featuring tipping points



Warming feedbacks and other anthropogenic stressors increase tipping risks

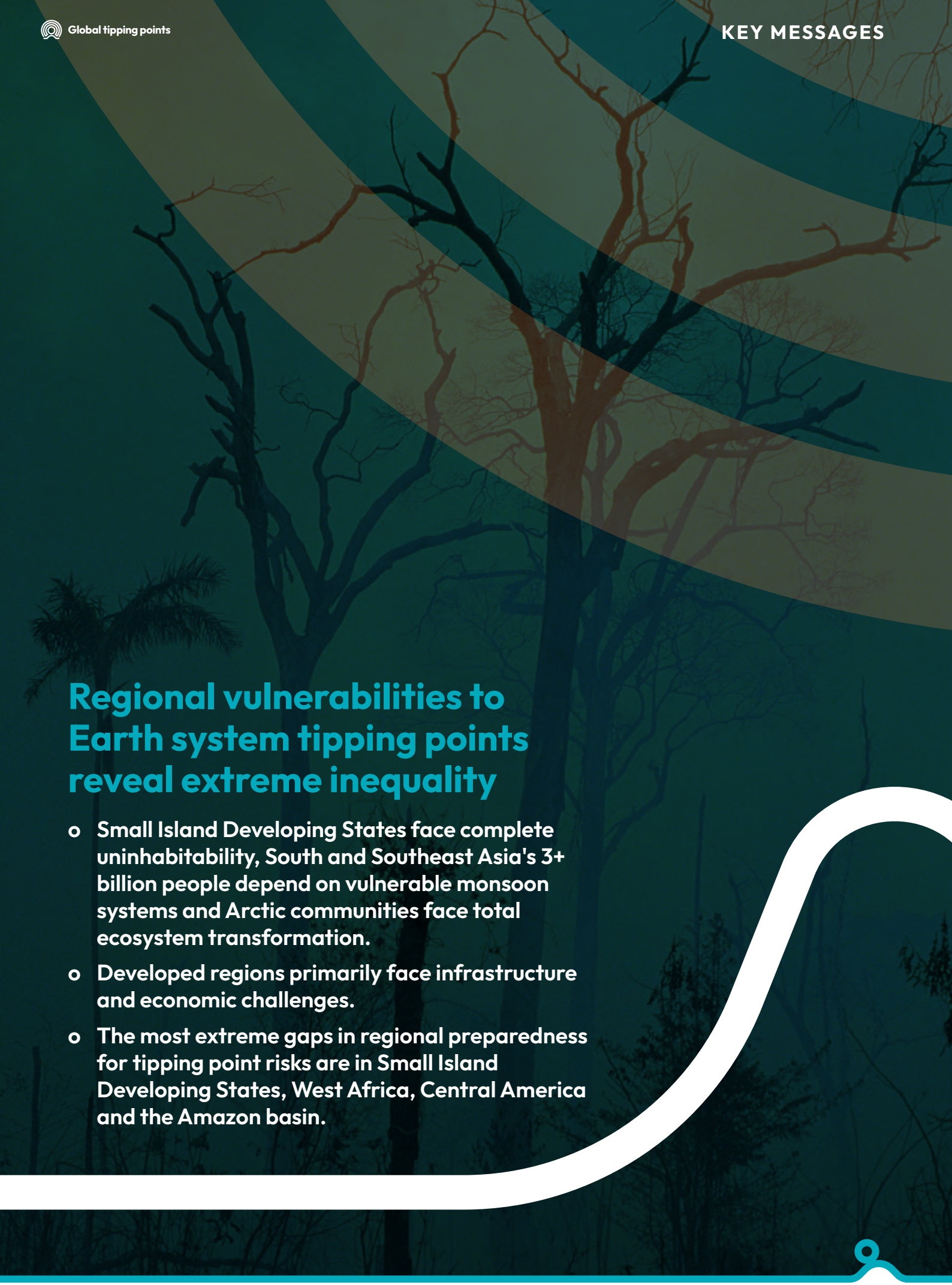
- Most tipping systems are expected to amplify global warming if tipped, making it more difficult to return to lower global warming levels in an overshoot period.
- Additional pressures, such as other anthropogenic stressors, interacting tipping systems and destabilising Earth system feedbacks, can amplify tipping risks further.
- Decreasing direct anthropogenic stressors can reduce the likelihood of climate-induced tipping for some systems (e.g. halting Amazon deforestation).

Earth system tipping points have huge impacts that demand further research

- There is an urgent need for dedicated research on the impacts of crossing Earth system tipping points especially their systemic, cascading impacts through societies.
- We provide an initial analysis of these impacts relying heavily on inferences from general climate impact literature applied to anticipated tipping point changes.
- Our assessment suggests that crossing Earth system tipping points will cause profound risks across nine critical domains, including food security, energy infrastructure, economic stability and social cohesion, affecting billions globally.
- Earth system tipping points are also a national security issue as food, water and heat stresses will impact populations. If climate change is unchecked then mass mortality, forced displacement and severe economic losses become likely.

All regions and billions of people face major impacts from Earth system tipping points

- Critical tipping point risks exist for small islands and East Asia from ice sheet loss, for South Asia, Southeast Asia and Central America from monsoon disruption, for West Africa from AMOC collapse and monsoon disruption and for North Asia from permafrost thaw and boreal forest tipping.
- Major tipping point risks exist for Northeast America from AMOC collapse and ice sheet loss, for Northwest Europe from AMOC collapse and for the Amazon region from rainforest dieback.
- The greatest population is ultimately at risk from monsoon disruption, followed by ice sheet loss, AMOC collapse and the degradation of warm-water coral reefs.

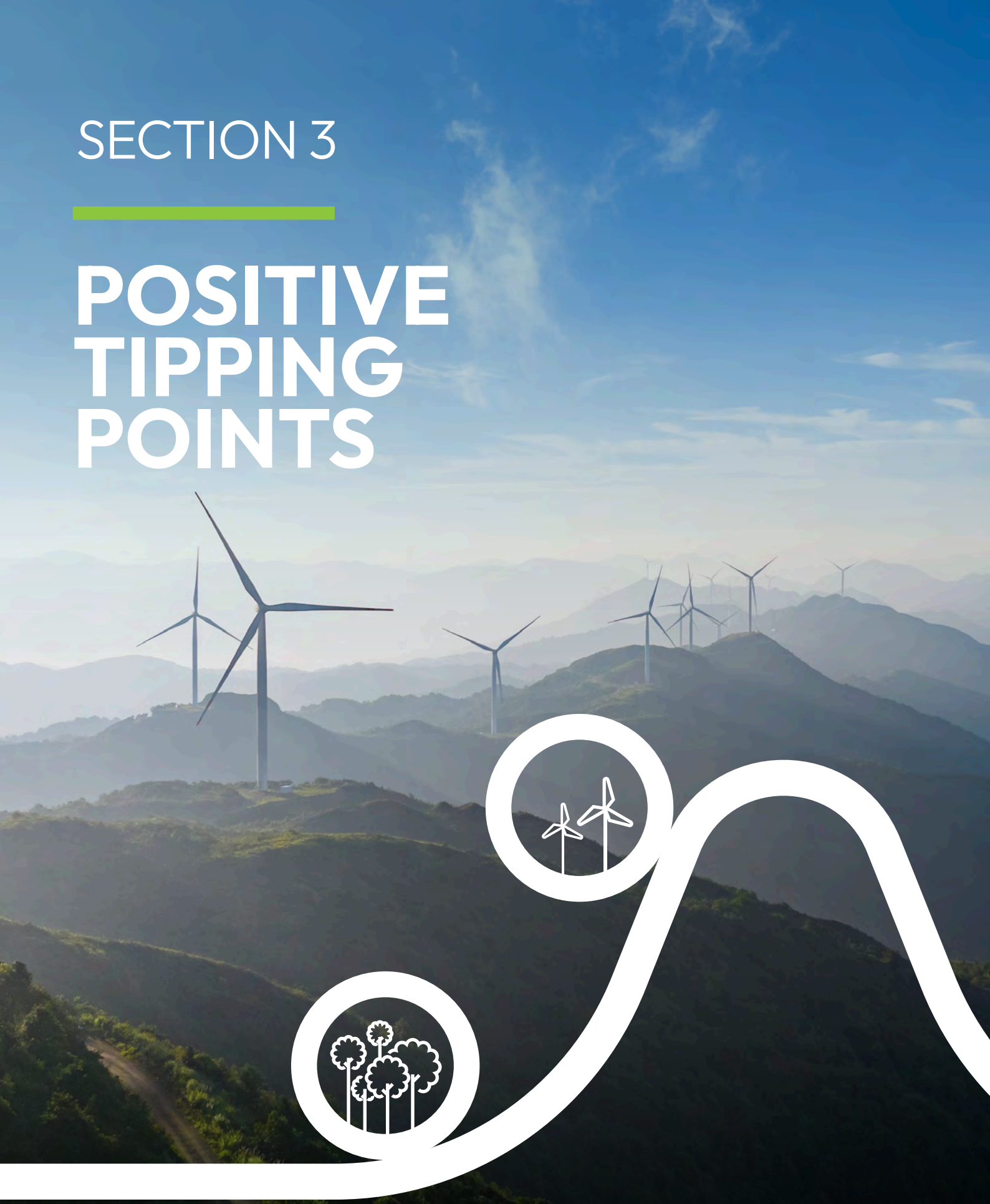


Regional vulnerabilities to Earth system tipping points reveal extreme inequality

- Small Island Developing States face complete uninhabitability, South and Southeast Asia's 3+ billion people depend on vulnerable monsoon systems and Arctic communities face total ecosystem transformation.
- Developed regions primarily face infrastructure and economic challenges.
- The most extreme gaps in regional preparedness for tipping point risks are in Small Island Developing States, West Africa, Central America and the Amazon basin.

SECTION 3

POSITIVE TIPPING POINTS



Section lead authors:
Floor Alkemade, Sara M. Constantino, Tom Powell, Steven R. Smith

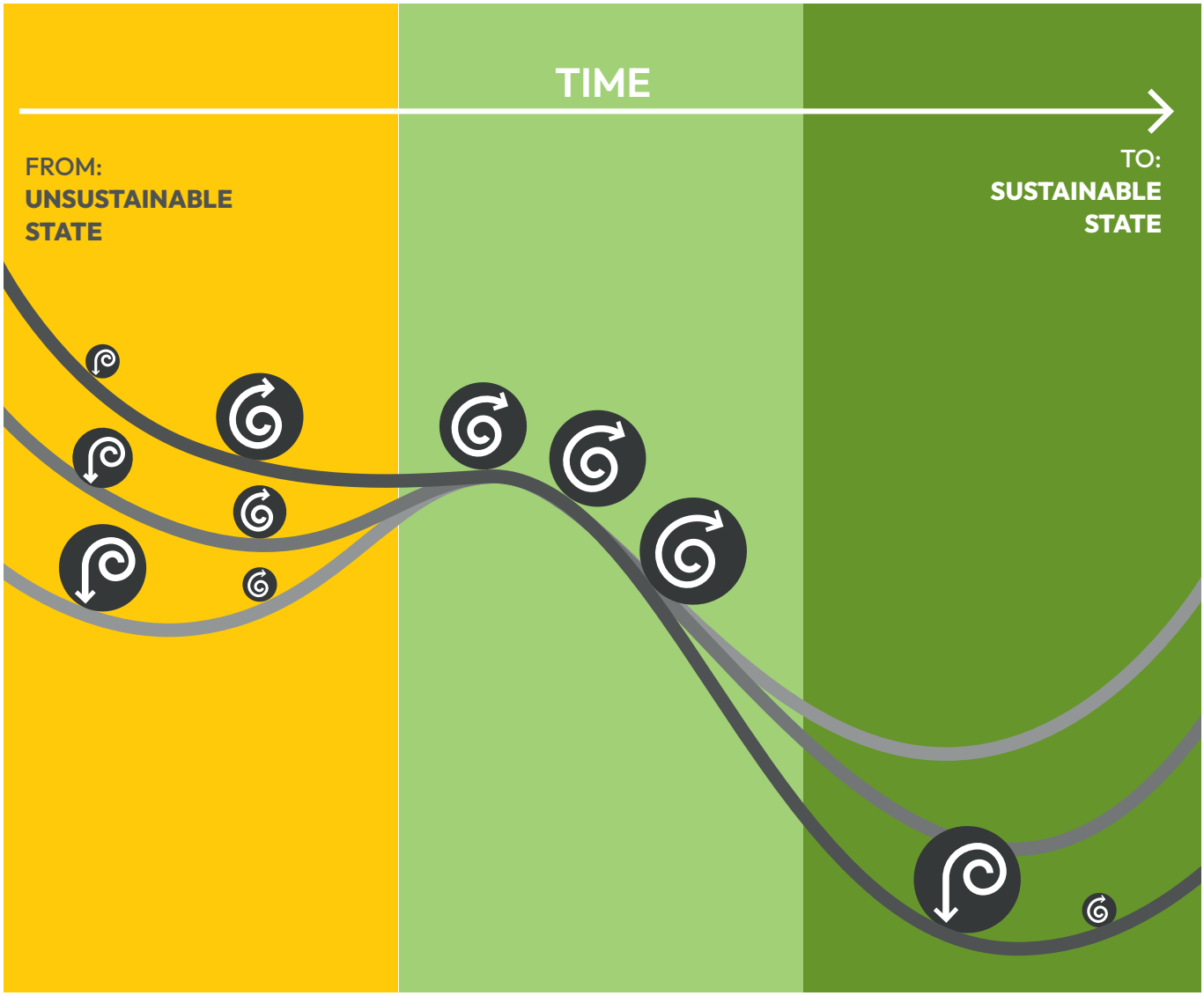
Positive tipping points must be identified and triggered to accelerate to net zero

- Positive tipping points occur when reinforcing feedbacks in a system overwhelm balancing feedbacks, triggering self-propelling change towards a more sustainable state.
- Policymakers can accelerate decarbonisation by prioritising technologies and behaviours that have the potential to positively tip.
- Easily imitatable behaviours in which social influence plays a strong role (e.g. active travel) and highly modular, mass producible technologies (e.g. solar panels), have greatest potential to be positively tipped.
- Deliberate actions can enable positive tipping by neutralising balancing feedback, promoting reinforcing feedback and helping make a desired change the most affordable, accessible and/or attractive option.

Progress towards positive tipping points can be sensed and acted upon

- Positive tipping points have already been crossed in the adoption of solar PV and wind power globally, in the adoption of electric vehicles, battery storage and heat pumps in leading markets and there is potential for them in various applications of green hydrogen, green ammonia and alternative protein foods.
- Early opportunity signals can reveal a loss of resilience of an incumbent system and a window of opportunity for positive tipping, but better indicators are needed to understand tipping potential and proximities to tipping points.
- System interactions can create opportunities for positive tipping cascades whereby tipping in one sector (e.g., battery technology) can increase the likelihood of tipping in another (e.g., renewable energy).

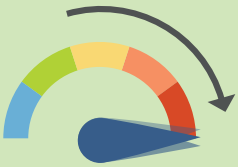
The fundamental processes behind positive tipping points



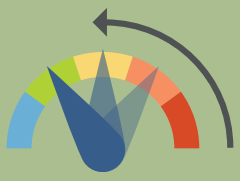
NET FEEDBACK EFFECT



1 - Balancing feedbacks resist change and lock in the status quo, but strengthening reinforcing feedbacks can weaken this resilience and create the conditions for tipping.



2 - Reinforcing feedbacks tip the system towards a new state.



3 - Feedbacks rebalance in a new stable state.

DRIVING/REINFORCING THE CHANGE

RESISTING/BALANCING



Policy design needs to match the phase of a positive tipping process

- Effective sequencing of interventions is important to activate positive tipping points. Different opportunities exist to overcome barriers and enable scaling at different phases of an S-curve of adoption. Effective policy design needs to match the system's tipping phase.
- Policy mixes need to be appropriate to the scale, context, sector, actor and phase of transition, to effectively catalyse and facilitate positive tipping dynamics.

Positive tipping points need to be well governed to ensure a rapid and just transition

- Governance can create the enabling conditions for positive tipping, including easing access to finance, providing the necessary infrastructure to support rapid deployment and cultivating sufficient stakeholder engagement and public support for policies to be approved and implemented.
- Rapid transition benefits from governance that is collaborative, localised and tailored to what communities say they want through participatory methods.
- Governments need to be aware of the potential for unintended consequences from positive tipping points including financial and political instability, stranded assets (including human assets) and perceived (in)justice of the transition.

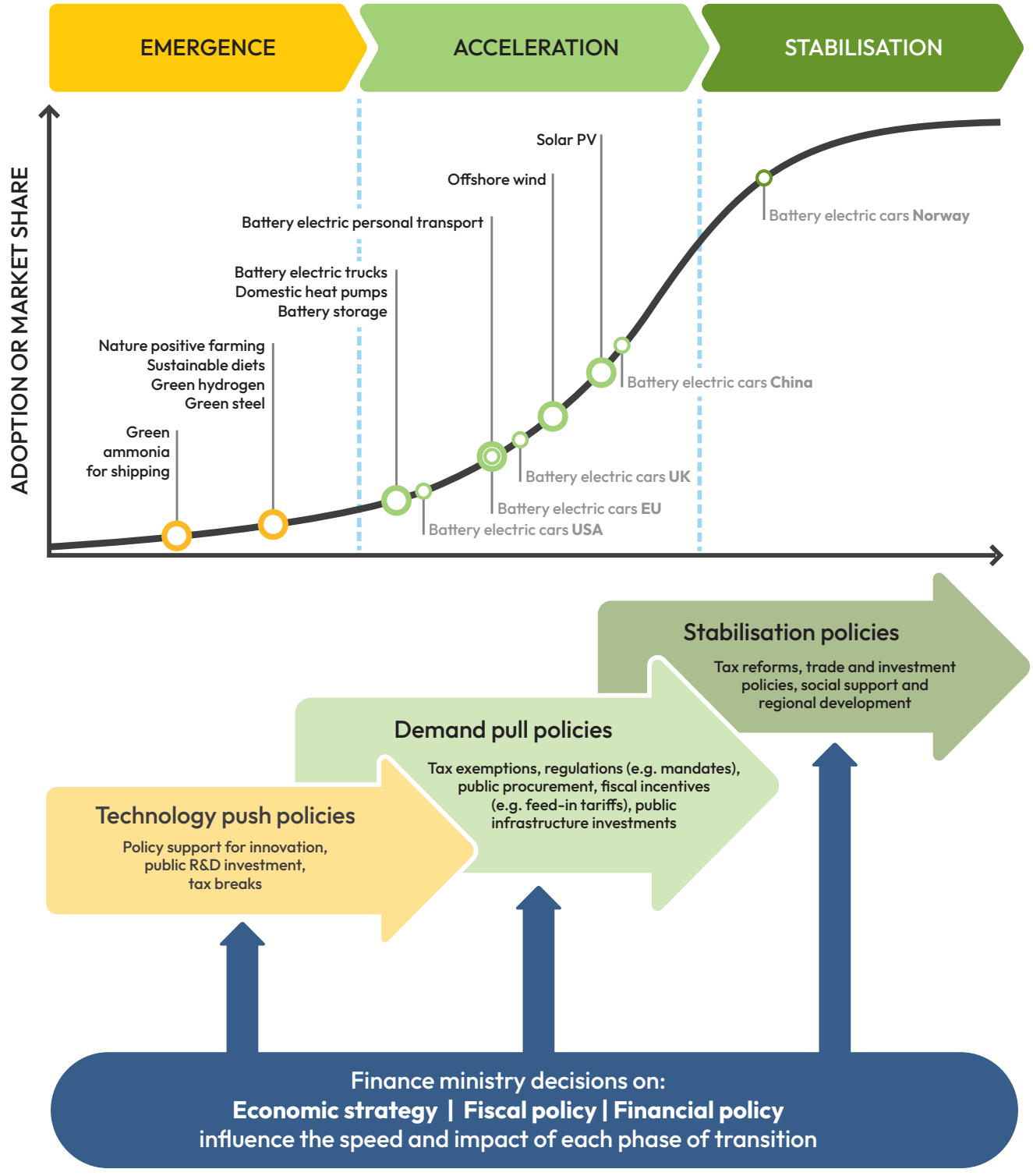
Cross-cutting factors can support positive tipping points

- Patterns of capital allocation that enable sustained financial flows into emerging low-carbon technologies and sectors can help overcome lock-ins, reduce perceived risk and build market confidence, particularly in underinvested regions and markets.
- Digitalisation and AI have the potential to accelerate positive tipping points by managing complex systems from renewable energy smart grids and transportation systems to social deliberation processes.
- Climate communications in the format of film, journalism, performance art and other media can be instrumental in generating the political momentum for positive change, particularly when connected to targeted policy advocacy and trusted messengers.

Coordination and coalitions can catalyse positive tipping points

- Coordinated cross-sectoral action at 'super-leverage points' can unleash positive tipping cascades. Coordinated mandates across interacting sectors (e.g. power, transport and heating) can bring forward tipping in all.
- Coherent, committed, ambitious coalitions can challenge incumbencies and catalyse positive tipping towards majority adoption of social and technological innovations.

Policies to support positive tipping and the transition status of different technologies and markets





Transformation is underway in the power and mobility sectors but can be accelerated

- Renewable energy is scaling rapidly but unevenly. Solar PV is doubling capacity every 2-3 years and growth of wind power is also strong. Reducing planning delays, providing grid infrastructure and finance can accelerate change.
- Battery prices have plummeted by 84% in the last decade and capacity is growing exponentially, underpinning mobility and power sector transitions.
- Electric vehicle adoption is accelerating in leading markets. China has become the dominant manufacturer. Norway has near total adoption. Price parity, battery performance and charging availability are key determinants of mass adoption.

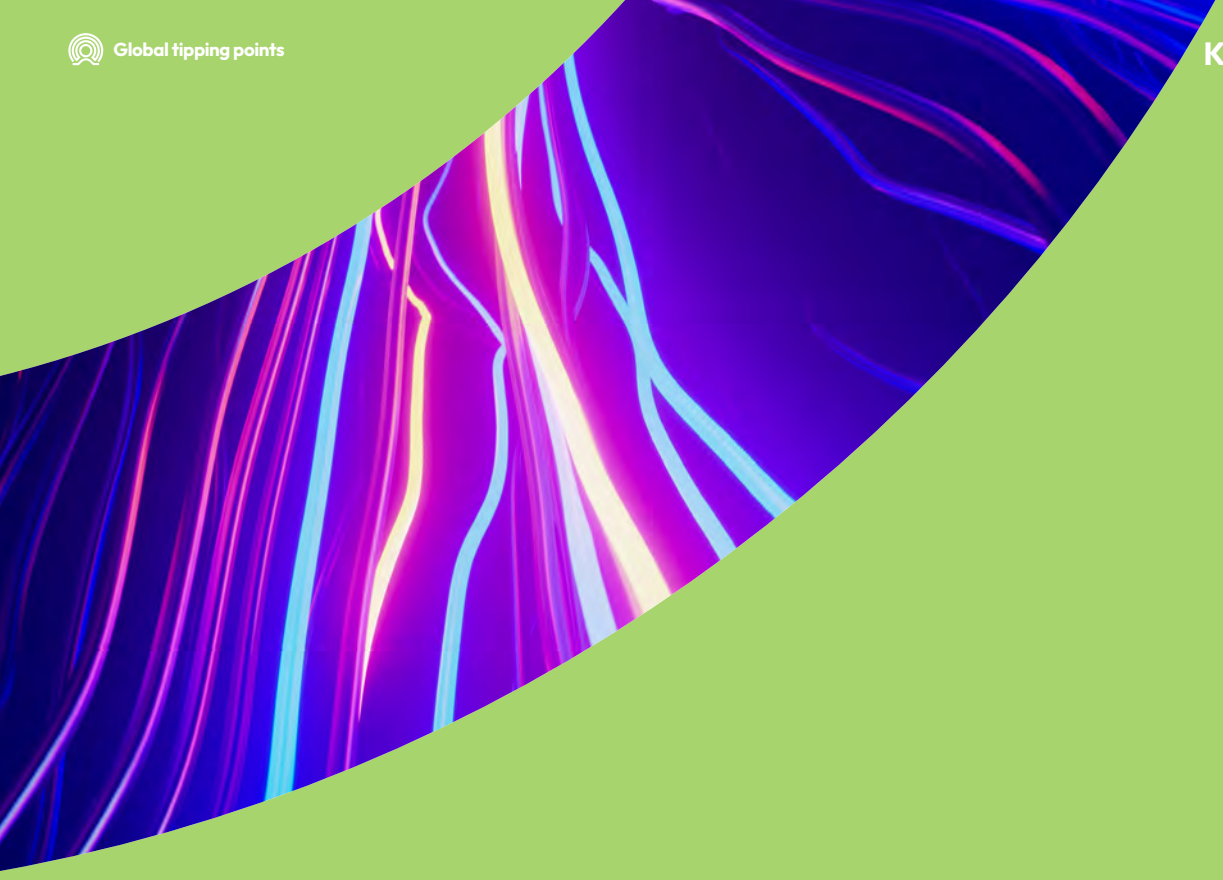


Policy action can bring forward positive tipping points in other key sectors

- Policy mandates and coordinated finance and investment are essential for bringing forward positive tipping points in the energy system.
- Heat pumps are a critical lever for decarbonising buildings, but face high upfront costs and other barriers including a shortage of skilled installers. Improved policy incentives, financing (e.g. cheap loans) and consumer trust are vital.
- Affordable green hydrogen could unlock hard-to-abate sectors such as those requiring industrial heat (eg steel and cement). Current costs are 2-3 times higher than grey hydrogen but learning curves could lead to price parity.
- Clear policy supported by financial incentives can enable farmers to switch to more sustainable production methods and build resilience to extreme weather events.

High public support for stronger action on climate change is threatened by polarisation and disinformation

- Widespread support for rapid decarbonisation can be strengthened by ensuring that the benefits are evenly distributed, e.g. through lower bills, better health outcomes and improved quality of life.
- Supportive policy and public procurement can help to normalise and spread sustainable behaviours, e.g. through promoting active transport, sustainable eating.



Electrification presents key positive tipping point opportunities

- Electrification is a decarbonisation multiplier: electrifying heating, transport and industry both reduces emission and stimulates investment in new renewables. It increases overall efficiency and flexibility of the energy system.
- Integration can accelerate the self-propelling growth of renewable electricity generation, but requires urgent grid upgrades, energy storage and demand flexibility.
- New digital technologies that can optimise energy balancing and storage between commercial and domestic energy providers need to be accelerated.



Targeted policies can accelerate electrification

- Decoupling renewable electricity pricing from fossil fuel-linked marginal pricing could significantly benefit consumers and accelerate change.
- Co-adoption strategies can trigger positive tipping: bundling complementary technologies increases value, reduces risk and speeds clean technology diffusion.
- Policy should target households during key renovation and purchasing moments.

Positive tipping points in food and fibre supply chains can end deforestation and ecosystem conversion

- Triggering positive tipping points in the sustainable production and consumption of agricultural commodities requires mutually reinforcing actions in three areas: Clear policy signals and enforcement; coordination across supply chains and between key markets; and finance to support transitions in production.
- Legal protections for tropical forests and their inhabitants need to be established and enforced.
- Standards for sustainable commodity production (e.g. soy, beef, cocoa, cotton, palm oil) and trade need to be developed and enforced. Successful moratoria (e.g. Amazon Soy) show that regulation and monitoring are essential for compliance and that sustainable alternative options must be available for producers (and financially viable).
- Demand-side interventions in import markets must align with domestic policy in major producing countries to ensure success and should support producers in meeting new standards through provision of transition finance.
- Policy and market structures currently incentivise harmful practices. Subsidies and procurement should change towards sustainable production and consumption, thereby supporting sustainably productive landscapes that include standing forests.

Positive tipping points can rapidly restore nature and biodiversity

- Ecosystem restoration can positively tip degraded systems back to health, through interventions like keystone species reintroduction, nutrient reduction and clumped planting that activate natural reinforcing feedbacks.
- Recovery of food and water resources can be positively tipped through promoting community governance of common pool resources including groundwater, forests, fish stocks and the creation of marine protected areas.
- Scaling nature-positive initiatives depends on local benefits and governance. Community management, equitable benefit-sharing and leveraging ecological feedbacks enable rapid spread. Combining local agency with supportive policy increases durability.



SECTION 4

CASE STUDIES



Authors:
The Amazon rainforest: Chris A. Boulton, Patricia Pinho, Avit Bhowmik, Sara Constantino, Bernardo M. Flores, Marina Hirota, Milena Holmgren, Isobel Parry, Tom Powell, José A. Sanabria-Fernández, Viktoria Spaiser, Sebastian Villasante, Nico Wunderling. **Atlantic Ocean Circulation:** Henk Dijkstra, Didier Swingedouw, Caroline Katsman, Sybren Drijfhout, Amber Boot, Viktoria Spaiser, Yevgeny Aksenov, Manjana Milkoreit, Jesse F. Abrams, Marius Årthun, Andreas Born, Sara Constantino, Matthew England, Timothy M. Lenton, Valentin Portmann, Paul Ritchie, Stefanie Rynders, Bablu Sinha, Sebastian Villasante, René van Westen, Claudia Wieners. **Warm-water coral reefs:** Paul Pearce-Kelly, Chris Yesson, Melanie McField, Aarón Israel Muñiz-Castillo, Melina Soto, Jesus Ernesto Arias-Gonzalez, Kyle Morgan, Alina Bill-Weilandt, Björn Kjerfve, Christopher E. Cornwall, Lorenzo Alvarez-Filip, Manjana Milkoreit, Tim E. Lenton, Rosa M. Roman-Cuesta. **Mountain glaciers:** Donovan P. Dennis, Bethan Joan Davies, Shivani Ehrenfeucht, Jeremy C. Ely, Lindsey Nicholson, Annika Ord, Judith Daxootsú Ramos, Ricarda Winkelmann

THE AMAZON RAINFOREST

Risk assessment

- The Amazon is approaching ecological tipping points due to interacting climate and land-use feedbacks that threaten to trigger large-scale forest degradation and regime shifts in the range 1.5-2 °C global warming.
- These changes risk transforming forested areas into altered ecosystems, weakening global climate regulation, altering regional climate and accelerating biodiversity loss.
- Negative social tipping points, including displacement, health impacts and cultural erosion are unfolding alongside ecological forest transitions, especially among Indigenous and traditional populations.
- These impacts and risks remain significantly under-addressed in climate policy and are intensified where governance fails to secure land rights, or enforce protections, or support adaptation.
- Indigenous Territories and Protected Areas exhibit strong climate mitigation potential, underscoring their vital role in maintaining carbon stocks and resisting ecosystem collapse.
- In contrast, undesignated Public Forests account for the majority of carbon losses from degradation, reflecting the consequences of weak governance and land tenure insecurity.
- Without immediate action, cascading risks could result in irreversible losses to both ecosystems and communities, undermining regional and global sustainability.

Recommendations

- The Amazon forest holds global significance as a biocultural and climate-regulating system; safeguarding it requires urgent, justice-centered strategies that integrate understanding of ecological thresholds, social vulnerability and climate adaptation.
- Positive social tipping points can be catalyzed by inclusive and polycentric governance, recognition of traditional knowledge systems and targeted financial investments in forest conservation, restoration and supporting Indigenous People and Communities Territories and their livelihoods.
- These interventions have the potential to reverse degradation feedbacks and ensure socio-ecological resilience across the Amazon.

ATLANTIC OCEAN CIRCULATION

Risk assessment

- The Atlantic Meridional Overturning Circulation (AMOC) and Subpolar Gyre (SPG) have different tipping points and timescales of transition but are strongly coupled via influencing stratification of the northern North Atlantic ocean.
- Crossing either tipping point has numerous impacts, including much harsher northwestern European winters, disruption of the West African Monsoon, decreased agricultural yield and marine ecosystem shifts.
- The conditions under which SPG and AMOC can tip remain uncertain, due to a limited observational record and biases in climate models, but we cannot exclude that an AMOC tipping point may already have been passed.
- Deep winter mixing in both the SPG and Greenland-Iceland-Norwegian Seas is projected to collapse in the North Atlantic before 2050 in many CMIP6 models causing AMOC to decline to weak states wwithout a deep circulation.
- The likelihood of tipping for both systems increases with global temperature.

Recommendations

- Current observational arrays in the Atlantic Ocean should be maintained and Earth System Model bias should be reduced as both are crucial for the science of AMOC or SPG tipping and future early warning systems.
- Continuous monitoring of SPG and AMOC risks and nation-specific complex risk-assessments of the impacts of AMOC or SPG tipping should be made for European countries to inform prevention and adaptation policies.
- Preventing the crossing of AMOC or SPG tipping points should be a primary governance target.
- The potential proximity of SPG collapse demands that European governments and the EU revisit and update national and European climate adaptation and preparedness plans, policies and institutions to account for the expected impacts of this tipping process.
- Global climate mitigation efforts should be accelerated to minimize temperature overshoot of 1.5°C to minimize the risk of SPG or AMOC tipping. This requires shortening net-zero timelines and immediate investment in the development and scaling of sustainable carbon removal technologies.
- The potential benefits and risks of solar radiation management (SRM) should be explored during a moratorium on SRM implementation and large-scale experiments.

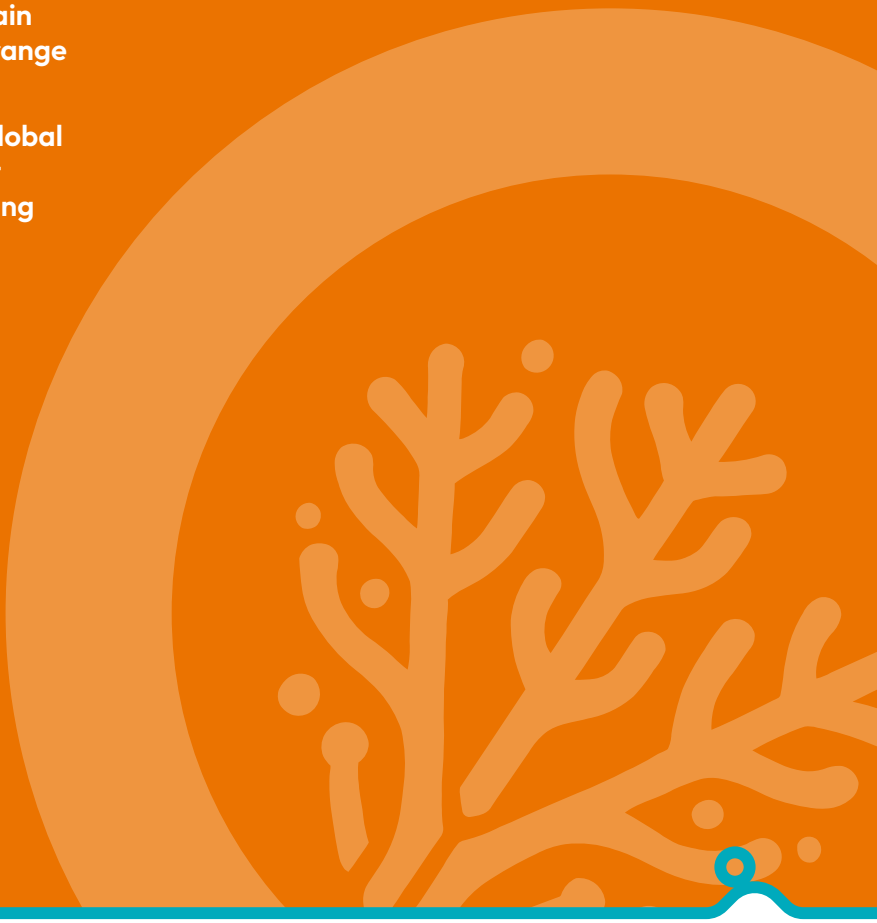
WARM-WATER CORAL REEFS

Risk assessment

- Warm-water coral reefs are vital to the wellbeing of up to a billion people and almost a million species.
- Globally, coral reefs are experiencing unprecedented mortality under repeated mass bleaching events, highlighting the impact that global warming (interacting with other, predominantly human-driven environmental stressors) is already having.
- The central estimate of the thermal tipping point for warm-water coral reefs of 1.2°C global warming above pre-industrial is already exceeded and without stringent climate mitigation their upper thermal threshold of 1.5°C may be reached within the next 10 years, compromising reef functioning and provision of ecosystem services to millions of people.
- Even under the most optimistic emission scenarios of stabilising warming at 1.5°C without any overshoot, it is considered that warm-water coral reefs are virtually certain (>99% probability) to tip, given the upper range of their thermal tipping point is 1.5°C.
- The goal of the Paris Agreement to limit global warming "well below 2°C" or 1.5°C will not prevent coral reefs from irreversibly passing their thermal tipping point.

Recommendations

- Returning global mean warming below 1.2°C with a minimal overshoot period and eventually returning to 1°C above preindustrial is essential for retaining functional warm-water coral reefs at meaningful scale, beyond a relatively few isolated refuge areas.
- Minimising non-climatic stressors, particularly improved reef management, can give reefs the best chance of surviving under what must be a minimal exceedance of their thermal tipping point.
- Risk assessments and urgent policy responses are needed to address the ecosystem and livelihood impacts of degraded or non-functional reefs.



MOUNTAIN GLACIERS (ÁAK'W T'ÁAK SÍT', JUNEAU ICEFIELD, ALASKA)

Risk assessment

- Mountain glacier tipping behaviour depends on a complex interplay between topography and climate, with mountain glaciers that experience similar external forcing having the potential to respond differently depending on local conditions.
- Áak'w T'áak Sít' and other outlet glaciers of the Juneau icefield, Alaska, have been suggested as a potential mountain glacier tipping system, with ice segregation and the bedrock hypsometry leading to nonlinear mass loss and glacier retreat.
- Rapid deglaciation of Áak'w T'áak Sít and other glaciers disrupts the relationship between Indigenous communities, glaciers and glacial landscapes, depriving future generations of this component of their identity and history, which are inseparable from the land.
- The retreat of Áak'w T'áak Sít''s tributary glaciers has led to annual outburst floods in Juneau, the future occurrence of which will depend on rates of ice retreat, the pattern of retreat and the formation of future glacier separations.
- Rapid mass loss of Áak'w T'áak Sít' could negatively impact tourism in Juneau as the glacier retreats from the Mendenhall Glacier Visitor Center viewshed, where an average of every third visitor to the state of Alaska visits.
- The economic consequences of tipping on fishing and salmon stocks are less clear, giving the complex interplay between water temperature, air temperature and riverbed scouring, all of which impact aquatic ecosystems.

Recommendations

- Anticipatory governance considerations at the local level regarding glacier loss must involve multiple partners and rights holders , including Indigenous community governments, federal and state agencies and local government, as well as community members, particularly in the context of resource management and the opening of navigable U.S.-Canada border crossings, following ice retreat.





INTRODUCTION

Authors: Timothy M. Lenton, Mike Barrett, Laurie Laybourn, David A. McKay, Manjana Milkoreit, Laura Pereira, Rosa M. Roman-Cuesta, Steven R. Smith, Sandy Trust, Sebastian Villasante, Simon Willcock

Reviewed by: Johan Rockström

Motivation (Why we need to talk about tipping points)

The world has entered a new climate reality. Global warming will soon overshoot 1.5°C. Already some damaging tipping points are being crossed and others could soon follow – with catastrophic impacts on societies and nature globally. Governance has to change to address this new reality. Linear, incremental change will not be enough to avoid the worst impacts. Instead climate action must accelerate radically to eliminate greenhouse gas emissions, to reduce non-climate stressors of ecosystems, and to regenerate nature before it is too late. This calls for actions that trigger positive tipping points, where social, technological and ecological changes toward zero emissions become self-propelling.

2024 was the warmest year on record, exceeding 1.5°C with over 150 unprecedented extreme weather events – meaning they were worse than any ever recorded in the region they occurred (WMO 2025). Super Typhoon Yagi affected 3.6 million people in Vietnam (UNDP 2024). Over 1.2 million people were displaced in Niger, Chad, and Mali. Severe droughts in Zimbabwe, Zambia, Botswana, and Namibia left millions facing food insecurity. 220 people lost their lives in the Valencia floods. In early 2025, the Los Angeles fires caused around $40 billion insured losses. Global warming (the 30 year average) has reached around 1.4°C and is set to reach 1.5°C around 2030 (Copernicus Climate Change Service).

The recent anomaly in atmosphere and ocean temperatures (above the long-term rising trend) has been unusually large and persistent (Goreau & Hayes 2024). Such climate variations are not tipping points in themselves, but they may trigger them. Already some vital parts of the Earth system are passing their thermal tipping points below 1.5°C. More than 80% of the world's reefs, already weakened by cumulative damage and recurrent bleaching events, have been hit by the worst global coral bleaching event on record over 2023–2025. The Greenland and West Antarctic ice sheets are shrinking at an accelerating rate and may also have passed tipping points.

As we head towards overshooting 1.5°C, new research indicates that other critical Earth system tipping points are closer than previously thought. The Amazon rainforest experienced a record drought in 2023–2024, and the threshold for widespread Amazon rainforest dieback could be as low as 1.5–2°C, due to the interactions between climate change and deforestation. Advances in observations and modelling show that the Atlantic Meridional Overturning Circulation (AMOC) could be at risk of collapse below 2°C, which would radically undermine global food and water security and plunge northwest Europe into severe winters.

When a system approaches a tipping point it tends to exhibit larger and more persistent fluctuations as it loses stability. This early warning signal is being seen in a growing number of the systems mentioned above including the Amazon rainforest, AMOC, and Greenland ice sheet. Similar behaviour can be observed in societies. The world is becoming more volatile as the incumbent fossil-fuelled regime starts to lose stability and fights back harder against a clean energy transition that is gaining momentum.

The last two years have witnessed growing political instability, including wars and humanitarian crises, and more extreme political positions rising to prominence. Some actors are actively countering action on climate change and dismantling the scientific institutions and instruments that monitor climate. This is dangerous; if we can no longer see where things are going wrong in the climate, we have no chance of correcting our mistakes – and adapting to their social and ecological consequences gets harder and more expensive.

At the same time, the global uptake of clean energy has accelerated markedly. Solar power is growing exponentially, doubling in installed capacity every two to three years. EV sales increased 25% globally in 2024 and far faster in emerging markets, as lithium-ion battery prices dropped 20–30%. These transformations are starting to reinforce one another (Nijsse et al. 2024). Secondhand batteries from EVs are going onto the grid to help balance renewable electricity supply and demand, while ever cheaper renewable power is encouraging electrification of mobility and other end uses.

The race is on, between these positive tipping points in the economy, and negative ones in the Earth system and our societies. In this new climate reality, either we transform to avoid the worst, limiting the overshoot of 1.5°C and managing what is unavoidable, or we face escalating, irreversible damages that pose existential threats to nature and our societies.

Specific Context

These realisations have led to growing demand for actionable knowledge about tipping points – both good and bad. In the first Global Tipping Points Report 2023 we detailed the status of Earth system tipping points, the risks stemming from these, the governance needed to address them, and the opportunities for positive tipping points to accelerate action toward zero emissions.

Since then, awareness of the need to better understand tipping point risks and opportunities has grown among policymakers and other decision makers across sectors. For example, the Nordic Council of Ministers has been briefed on the risks from an AMOC tipping point. The financial sector is starting to consider climate tipping points in their physical climate risk assessments and positive tipping points in their 'transition risk' assessments.

But the picture is mixed at the science-policy interface. The proposal for an IPCC Special Report on Tipping Points, supported by 18 governments was rejected. Chapter 8 of the forthcoming Working Group 1 contribution to the IPCC's Seventh Assessment Report will cover the science of climate tipping points – but is not expected until May 2028.

Aims of this Report

This second Global Tipping Points Report 2025 aims to support the call for timely, salient, actionable knowledge about tipping points – negative and positive – and how to govern them. We seek to update policymakers and other decision makers on the latest tipping points research and synthesise new thinking about how to move forward. This includes aiming to provide a useful stepping stone towards the IPCC's Seventh Assessment Report, and to inform regional, national and more localised decision making.

After publishing the Global Tipping Points Report 2023 we canvassed different target audiences for their reactions to learn what we could improve. There was a particular demand for more system-specific information and guidance on tipping points. In response to that feedback, here we delve deeper into specific case studies of Earth system tipping points. Based on combined urgency and importance, we focus on tipping point risks in three key systems: the Amazon rainforest, Atlantic ocean circulation, and warm water coral reefs. We also apply our overall approach to an example of a more localised tipping point with a case study of mountain glacier loss.

Earth system tipping points present distinct communication challenges and opportunities. Other academic voices have argued that talking about tipping points somehow confuses and distracts from urgent climate action (Kopp et al., 2025). Our aim is the contrary – to elucidate the latest knowledge on tipping points, and their potentially catastrophic human consequences, as a key underpinning for urgent climate action (Smith et al., 2025). In an era of growing mistrust and misinformation our aim is to equip the reader to better understand the complex and nonlinear dynamics we all increasingly have to navigate, and to highlight tangible impacts on people's lives. It would be irresponsible not to provide society with knowledge about severe threats to human wellbeing that can enable action to mitigate those threats. Equally, our experience is that communicating positive tipping points alongside negative ones can provide audiences agency and hope, showing how rapid social and economic change can counter Earth system tipping point risks.

Audience (Who this report is for)

Our primary audience are policymakers, together with decision makers in the public, private and voluntary sectors. Governments hold a fundamental responsibility (and a social contract with their populace) to lead in the protection of human lives and wellbeing and to ensure the fair, transparent and effective distribution of public resources. Leaders across sectors also have an important role to play in creating transformative change through the mobilisation of human capital and private finance.

At the same time we aim to inform a broad public audience, recognising that policy leadership needs a social license to operate, and that social activism has always been behind past transformative changes and is key to triggering current transformative change (IPBES 2024). Hence we support the COP30 Presidency's initiative of a Global Mutirão to help catalyse collective action from civil society to help trigger positive tipping points.

Authors and origins of the report

A total of 160 researchers have contributed to this Report, building on the community that wrote the Global Tipping Points Report 2023 and contributed to a special issue of the open-access journal Earth System Dynamics on 'Tipping Points in the Anthropocene'. The plan for this Report was formulated on a retreat 3–5 June 2024. Over the following year, we reviewed and synthesised the latest peer-reviewed academic research. Much of the content was presented for feedback from fellow researchers and practitioners at the Global Tipping Points Conference 2025, 30 June–3 July at the University of Exeter, UK. That conference helped us refine the narrative and key messages of this Report. The Report has subsequently been peer reviewed by at least two researchers per section.

Structure

Recognising the need for improved governance responses to tipping point risks, we have changed the structure somewhat from the Global Tipping Points Report 2023.



Section 1 outlines the unique challenges of governing Earth system tipping points and offers guidance to address them.



Section 2 provides an update on underpinning knowledge about Earth system tipping points and the risks they pose.



Section 3 updates knowledge about positive tipping point opportunities to transform the energy and food systems and regenerate nature, and actions to bring them forward.



Section 4 provides detailed case studies of critical Earth system tipping points at risk and response opportunities: the Amazon rainforest, Atlantic Ocean circulation, warm-water coral reefs, and a localised tipping point of mountain glacier loss.

Key Concepts

The Global Tipping Points Report 2023 provided a detailed introduction to tipping point concepts – here we provide a refresher of some of the key concepts.



Figure 1. Sketch of a system being forced past a tipping point.

A **tipping point** is colloquially where a small change makes a big difference to a system (Figure 1). More precisely, a tipping point is defined as occurring when change in part of a system becomes self-perpetuating beyond a threshold, leading to substantial, widespread, frequently abrupt and often irreversible impact(s). **Self-perpetuation** of change means that it comes from within the system and will continue even without any external forcing, until a new state is reached. **Abruptness** means that the change is rapid relative to any drivers forcing it. **Irreversibility** means that the change is difficult to reverse, and typically takes more effort to reverse (it is harder to push the ball back up the hill in Figure 1). Some forcing of a system is usually needed to bring it to a tipping point, and a shifting balance of feedback within the system is usually behind the tipping point.

Forcing just refers to an accumulating change that causally affects a system. For example, global warming is forcing the melt of the Greenland ice sheet, or when the UK government imposed a rising floor price on carbon emissions that forced coal to become less profitable in the UK power sector.

Feedback refers to a closed loop of causality in a system, whereby a change in the system causes a response that feeds back to amplify or dampen that initial change. Feedback mechanisms can be mathematically positive or negative, depending on whether they amplify or dampen the effects of an initial change.

Before a tipping point, damping/balancing/negative feedback tends to dominate in a system and maintain the stability of its current state (the ball initially sits in a steep-sided valley in Figure 1). However, forcing can shift the balance of feedback in a system away from damping/balancing/negative feedback to amplifying/reinforcing/positive feedback (the valley gets shallower). If positive feedback becomes strong enough to support self-perpetuating change then a tipping point occurs (the ball rolls into the other valley).

An example of amplifying feedback is when the Greenland ice sheet melt causes its surface altitude to drop into warmer air, amplifying the melt. This feedback gets stronger as global warming increases and can reach a tipping point. To take our other example, when the rising cost of coal burning caused investors to withdraw their financial support for coal power, this made it less profitable, triggering other investors to withdraw. As the floor price of carbon was increased by the UK government this reached a tipping point.

Only a subset of all amplifying feedback loops can get strong enough to support a tipping point of self-perpetuating change. The resulting change is transient – it cannot continue indefinitely because at some point it will reach a limit – for example, the ice sheet has disappeared or coal has been eliminated from the power mix. Then, different damping feedbacks tend to stabilise and 'lock-in' the new state of the system.

The small change that causes a system to pass a tipping point is often called a trigger. The trigger can come from outside or from within a system. The rate of the resulting self-perpetuating change is governed by the nature of the system, for example, the collapse of ice sheets may still appear slow to us, whereas the decline of UK coal burning unfolded in just a few years. The resulting big difference in the system can be described as a **qualitative change** (in what the system looks like and how it functions).

Tipping system denotes any system that can pass a tipping point. **Tipping element** was originally introduced to describe large parts of the climate system that could pass a tipping point (Lenton et al., 2008). When used in other contexts we use a qualifier such as 'social' tipping element (Otto et al., 2020) or 'social-ecological' tipping element, to avoid confusion. **Tipping event** describes the crossing of a tipping point. **Tipping dynamics** describes the resulting changes that unfold, and the instabilities that appear beforehand.

Governance implications of tipping points

The qualities of abruptness, irreversibility and qualitative change mean that tipping points have different governance implications than more linear, reversible, proportionate changes. Here we highlight three key implications that help motivate the report and our choice to start it with governance considerations in Section 1.

Managing irreversible, potentially catastrophic risks demands precaution

Following IPCC (2022), risk is defined as the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems.

Risk management refers to the process of identifying, assessing and controlling threats or uncertainties that can potentially impact a set of objectives. Risk management is a mature discipline, with established principles and practices applied in diverse settings across human society, which can be usefully leveraged for our approach to managing tipping point risks.

The precautionary principle emphasises caution if it is possible that a given course of action may cause significant harm, particularly where there is high uncertainty. The concept of risk appetite or tolerance assesses how much risk an organisation is willing or able to take.

Importantly, the irreversibility and magnitude of Earth system tipping points requires a different risk management approach to reversible and/or lower impact hazards, especially in the face of scientific uncertainty about both when a tipping point will be crossed and the severity of impacts that could ensue. Impacts include significant disruption to food, water, energy, transport and economic systems. Our risk appetite for such events should therefore be extremely low and we should adopt a precautionary approach.

In cases of reversible risks, overestimating the likelihood or severity of a risk early on can lead to excessive resource allocation for mitigation. If a reversible risk is initially underestimated, it can be addressed later on by allocating more resources to mitigation.

The opposite is true for managing irreversible tipping point risks. Here, underestimating a risk early on in its development can mean that the window to address it before reaching a tipping point may close on those aiming to mitigate or adapt in order to stay within their desired risk level. This loss of agency may be further exacerbated by the severity of disruptive events experienced, reducing or de-railing our capacity to take the coordinated action required to mitigate the tipping point risk.

Thus, uncertainty about where a damaging tipping point lies should not be used as a reason for delay and inaction. On the contrary, given the potential severity of impacts, action should be taken based on a precautionary assessment within the uncertainty range – in case it turns out to be correct. This is the only safe strategy to avoid irreversible tipping point risks. If it turns out later that the risk was overestimated that should be a cause for relief at having avoided the worst.

Multiple drivers provide local agency

All Earth system tipping points are at increasing risk from global warming, but some are also at risk from the combined effects of climate change and local (non-climate) drivers. Those tipping points that are predominantly climate-driven – for example, AMOC collapse – are primarily sensitive to climate mitigation as a prevention strategy. However, those with a mix of climate and non-climate drivers – such as Amazon rainforest dieback and coral reef loss – are also sensitive to mitigating non-climate drivers as a prevention strategy.

In the latter cases, this provides an opportunity for national to local action to help mitigate tipping point risk – for example, by reducing deforestation of the Amazon, or reducing overfishing of coral reefs. Both categories require coordination of prevention and adaptation efforts (e.g., mobilisation of human and financial capital, goals and timelines, information flows, institutional linkages). The latter also calls for coordinating action across policy domains and scales (e.g., global climate mitigation, national forest, agricultural and fisheries policies, and local protected areas).

This has implications for governance. Anticipating climate-driven tipping points requires a governance response aimed primarily at mitigation, and (if that fails) preparing for the situation post-tipping to limit the impacts in whatever way possible. Where there are multiple drivers of a tipping point, anticipation enables more response options to avoid the tipping event, through, for example, forest protection against deforestation, or improved ecosystem and watershed management to build resilience in coral reefs.

Urgency, opportunity and justice

The irreversible and potentially existential risk from crossing Earth system tipping points demands an urgent response to prevent triggering them (where that remains possible). In fact, it requires an unprecedented acceleration of action to mitigate greenhouse gas emissions and rapid scaling of carbon removal from the atmosphere. The most effective way – and arguably the only credible way – to achieve such acceleration is through enabling and triggering positive tipping points where the change required becomes self-propelling. But this brings its own risks and opportunities.

Among the opportunities, three out of four people in the world live in net fossil fuel importing countries that are already starting to benefit economically from decarbonising their economies. For the world's poorest without access to electricity, off-grid solar with battery storage is starting to bring affordable electricity for the first time. Eight million lives lost every year to fossil fuel air pollution can be saved whilst ensuring energy security.

However, well-intentioned urgent action can have unintended negative consequences. For example, the need to mine rare earth metals to meet growing demand for battery storage can perpetuate injustices against local communities, such as those in the Republic of the Congo facing war and instability linked to their living on mineral-rich lands. The race to mine the seabed risks entire, under-explored ecosystems and the ecosystem services they provide (Levin et al. 2020). Many scientists, government representatives, international and non-governmental organizations have expressed their deep concerns about the impacts of these activities (Villasante et al. 2025).

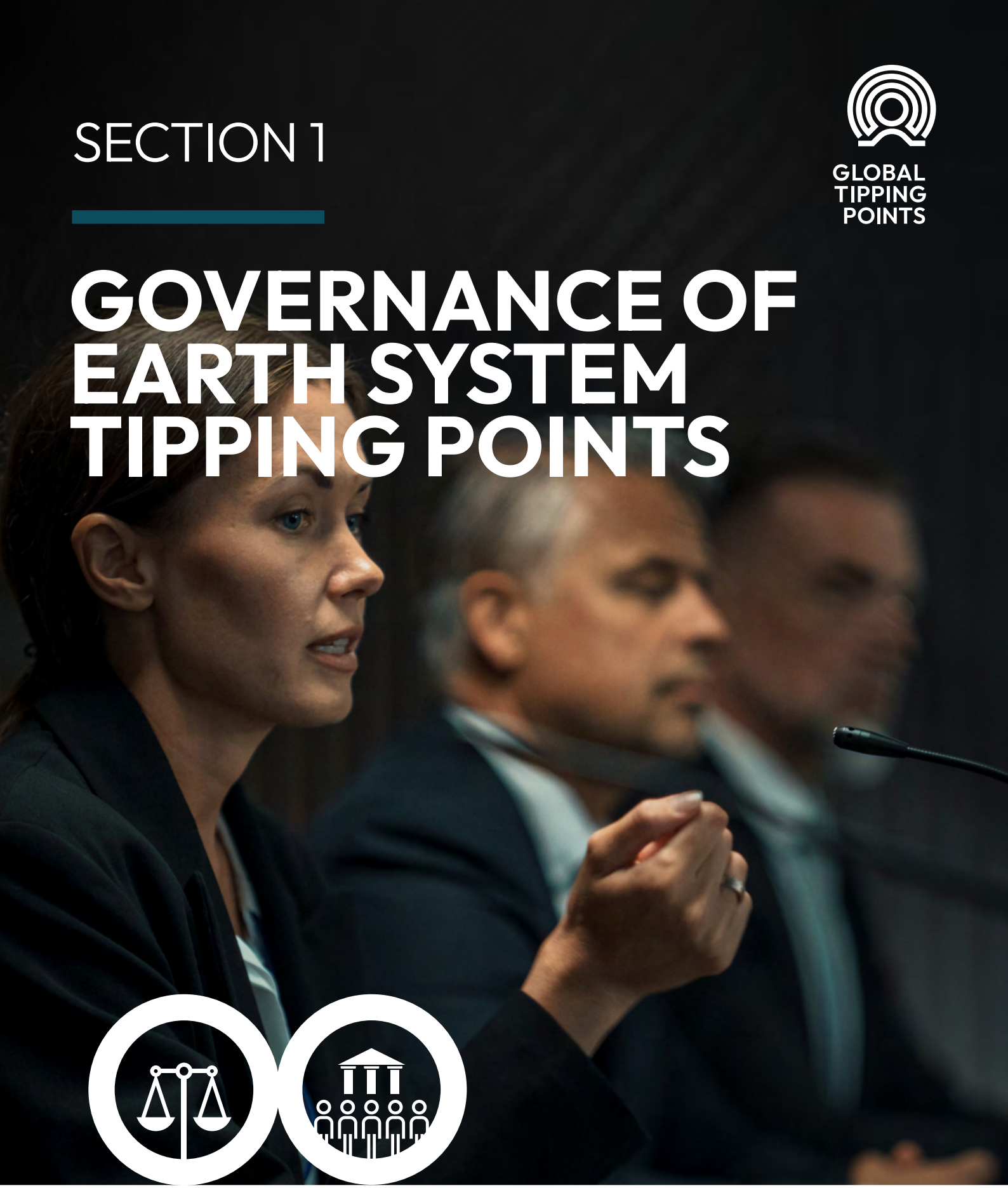
Clearly the consequences of urgent responses need to be thought through from a justice and equity perspective, to ensure that in seeking to avoid the massive human harm that crossing Earth system tipping points will cause, new harms (or disbenefits) are minimised. Governance mechanisms are needed to ensure that those with access to power and resources, who can capitalise on urgent need for transformation, do not perpetuate further harms and injustices to vulnerable people and places (Pereira et al. 2024).

In this report we highlight the critical role that governance needs to play in identifying the most just interventions, where the losers are not those that already suffer from the current system, and in ensuring that legal mechanisms and inclusive policies are in place to protect those that may be impacted (Pereira et al. 2025). We offer the report as a contribution to collective reflection and just transformation in the face of an urgent situation.

SECTION 1

GLOBAL TIPPING POINTS

GOVERNANCE OF EARTH SYSTEM TIPPING POINTS



Section lead authors:
Manjana Milkoreit, Simon Willcock

1.1 Acting on Earth system tipping points: Why and how?

Authors: Manjana Milkoreit, Yulia Yamineva, Sara Constantino, Ahjond Garmestani, Lauren Gifford, Ben Hudson, Margot Hurlbert, Rakhyun E. Kim, Malcolm Rogge, JB Ruhl, Jürgen Scheffran, Niko Soininen, Sebastian Villasante, Simon Willcock

Reviewers: Maja Groff, Louis Kotzé, Saara Leppänen, Jessica Seddon

Key Messages

- **With global warming soon overshooting 1.5°C, developing and implementing effective governance strategies to prevent Earth system tipping points is increasingly urgent and important.**
- **Earth system tipping processes present distinct governance challenges compared to conventional climate change or environmental decline, requiring both governance innovations and reforms of existing institutions.**
- **Precaution, anticipatory governance and systemic risk governance are key approaches for addressing Earth system tipping points.**
- **Amid deepening geopolitical fragmentation and weakening multilateralism, governance responses to Earth system tipping points must focus on fostering a flexible, multi-scale agenda capable of advancing under increasingly challenging political conditions.**

Humanity is now confronting a planetary challenge of unprecedented scale: the stability of the Earth system itself is at risk. Rising human pressures are pushing the Earth towards potential tipping points that could irreversibly shift large Earth system components into far less hospitable conditions for humanity and non-human life. These tipping processes unfold across vast scales of time and space, yet they can be triggered suddenly and some very soon. Their implications for human wellbeing and social stability cannot be overstated, but they are hard to imagine.

Attention to Earth system tipping points (ESTPs) has grown among international organisations, policymakers and publics since the publication of the first Global Tipping Points Report in 2023. However, this increased attention has yet to generate the governance responses–measures, actions and routines across international, national and sub-national systems – necessary to address the specific and severe risks of tipping processes.

Given that up to five tipping points could be crossed at global temperature increases between 1.5°C and 2°C, the prospect of temperature overshoot - warming above 1.5°C - by 2030 raises the stakes for and underlines the urgency of tipping point governance (Milkoreit et al., 2024), especially the need to devise effective prevention strategies (Möller et al., 2024; Wunderling et al., 2022). Governments might assume that simply accelerating their existing efforts to mitigate climate change and biodiversity loss suffice to address tipping point risks, but they do not. **Current approaches must shift fundamentally in quality, speed and magnitude** to minimize the risks of crossing tipping points. Furthermore, a new governance paradigm will be essential to address the impacts of crossing tipping points (Biesbroek et al., 2025; Kim, 2022; Ruhl and Ruhl, 2022).

In this report, we present an updated assessment of the governance implications of ESTPs - needs, options and approaches - considering the latest science on tipping risks and expected impacts (see Section 2) and global political developments over the last two years.

We include insights on the current state of ESTP governance efforts around the world based on research (interviews and text analyses) we conducted across ten countries in 2024/25. We present these findings as a set of case-analytic boxes throughout the section distinguished by background shading and marked with the headline Research Insight: State of Governance.

We also deepen the application of our assessment to specific tipping systems, especially the warm-water coral reefs, the Atlantic Meridional Overturning Circulation (AMOC)/Subpolar Gyre (SPG) ocean currents and the Amazon rainforest.

We define tipping point governance as "the rules, regulations, norms and institutions that structure and guide collective behaviour and actions" related to tipping points (GTPR 2023, Chapter 3.1.) and refer to the concrete governance systems across various levels (especially the international) and various actors, including the private sector and civil society, which address the specific risks of Earth system tipping processes.

1.1.1 Differences between governing climate change and tipping points

Tipping processes transcend familiar categories of risk management and governance, demanding new holistic thinking, systemic approaches and coordinated action at the level of the Earth system.

Earth system governance and Earth system law (Kotzé and Kim, 2019) take this broader perspective, recognizing the planet as a complex, interconnected system prone to surprising and non-linear dynamics (Biermann, 2014; Pattberg and Zelli, 2016). Yet most climate policies and laws continue to assume a predictable, linear process - treating climate change as incremental and reversible (see Chapter 2.4). This overlooks the risks of unintended consequences, accelerating changes and the irreversibility of crossing thresholds.

It also downplays the interconnected nature of various climate and social subsystems and the corresponding need for integrated, cross-domain (e.g. climate, biodiversity, human rights) and transboundary approaches. Addressing these characteristics of tipping processes requires governance approaches that differ, in some cases fundamentally, from existing policies and institutions, which were not designed with Earth system dynamics in mind.

We define a tipping point as occurring when changes in a system become self-perpetuating and difficult to reverse beyond a threshold, leading to substantial, widespread impacts (Armstrong McKay, 2024; Armstrong McKay et al., 2022; Milkoreit et al., 2018). ESTPs refer to such changes in large components of the Earth system, including major ice sheets (the cryosphere), biomes such as coral reefs or forests (the biosphere), ocean currents (the hydrosphere) or monsoons (the atmosphere). They could be catastrophic, for example, resulting in the global-scale loss of capacity to grow major staple crops. Crossing one ESTP can also contribute to triggering another, causing a cascade of accelerating and compounding damage (Wunderling et al., 2024). The characteristics and impacts of such tipping processes are fundamentally different from the ways climate change and other environmental challenges are currently understood. Table 1.1.1 identifies and describes these differences.

Table 1.1.1: Differences between conventional climate change governance and governance for ESTPs

CHARACTERISTIC	DIFFERENCE TO CLIMATE CHANGE	GOVERNANCE IMPLICATIONS
THRESHOLDS = MOMENTS OF COMMITMENT & IRREVERSIBILITY	Once a tipping point is crossed for a certain amount of time, the system is committed to irreversible changes with long-term consequences, regardless of mitigation success (ability to return from temperature overshoot).	• It is imperative to prevent tipping to avoid irreversible changes. Near-term action (or lack thereof) can have long-term consequences. • Measures should be proactive, based on heightened application of the precautionary principle. • The single most important prevention measure is a rapid phase-out of greenhouse gas emissions, methane in particular. Some tipping elements are also affected by more local actions (e.g. deforestation, pollution). • Since prevention success is not guaranteed, impact governance needs to include strategies for anticipating and preparing for 'locked-in' impacts over the long term.
ACCELERATION OF CHANGE	After a tipping point is crossed, the pace of change accelerates due to self-amplifying feedback dynamics. This acceleration can overwhelm adaptation efforts and outpace response capacities (Laybourn et al., 2023).	• Since prevention is not guaranteed, adaptive and transformative capacity building is needed to deal with potentially faster changes after a tipping point. • Proactive measures to increase institutional capacity and resilience are needed before tipping points are crossed. • Governments risk overload, e.g. having to expend significant resources on adaptation and disaster response, undermining mitigation and transition efforts ('derailment risk').
INCREASED MAGNITUDE OF IMPACTS	Crossing tipping points can substantially amplify the severity of climate change impacts, (e.g. massive ice sheet melts causing significant additional sea-level rise).	• Conduct and revise risk and vulnerability assessments that include ESTPs. • Revisit adaptation plans, preparedness strategies and emergency planning to address additional impacts. • There is increased potential for reaching limits of adaptation and experiencing loss and damage. • Increased emphasis on transformative adaptation (e.g. planned relocation).
TREND REVERSALS	The impacts of some tipping processes would reverse the current and expected direction of change in a region (e.g. cooling rather than warming in Northern Europe) (van Westen and Baatsen, 2025).	• Current adaptation plans and preparedness strategies need to be revisited to devise robust approaches that would be effective across multiple possible future trajectories. • Investments in capacity building regarding future thinking and methods (e.g. scenario development) would strengthen public organisations' ability to manage increased uncertainty. • Increased reliance on general resilience principles (e.g. response diversity, reflexivity and continuous learning, ability to rapidly respond to unexpected developments). • There is an immediate need for strategic public communication about the potential of trend reversals due to tipping points.
DIFFERENT DISTRIBUTION OF IMPACTS	The geographic distribution of the impacts of tipping processes differs to some extent from the currently expected impacts of climate change, creating distinct tipping vulnerabilities. This includes additional pressures on already vulnerable regions and peoples, but also significant novel vulnerabilities in the Global North (Thienen et al., 2025).	• New vulnerabilities could change national interests to act and reshape global geopolitical dynamics related to climate change. • Tipping point impact, exposure and vulnerability need to be mapped, revising assessments of climate vulnerability. • Need for the allocation of resources to resilience building, adaptation and loss and damage through national and international funding mechanisms. • New vulnerability distributions should shape the application of equity and justice principles (e.g. allocation of resources and support).
NOVEL IMPACTS	Uncertainty about tipping points implies unforeseen and potentially unprecedented impacts due to complex system dynamics and limited knowledge of long-term Earth system disruptions (Walker et al., 2023).	• Lack of knowledge demands robust monitoring and research to improve predictability while acknowledging that full scientific certainty about some elements is often not attainable. • Flexible and adaptive governance systems are needed that can respond to unforeseen risks and surprises. This includes response diversity – the availability of multiple options in case of failure or unexpected impacts.
CASCADE EFFECTS	Tipping elements are interconnected; crossing one tipping point can trigger others, potentially at lower thresholds than anticipated (Wunderling et al., 2024).	• Risk assessments and prevention strategies need to include (anticipate and consider) cascading potential (systemic risk). • Coordination and policy coherence across sectors and regions is vital to prevent cascading failures. • Actors need to develop measures to halt or slow cascades (e.g. active decoupling of systems).

A critical difference between ESTPs and incremental climate change lies in the **heightened uncertainty** regarding tipping dynamics, especially the location of the tipping point (in time, temperature trajectory or other metrics). For example, uncertainty about the threshold conditions for the collapse of the AMOC is combined with the potential for severe and far-reaching global consequences (Bellomo et al., 2021; Ben-Yami et al., 2024; Jackson et al., 2015; Zhang et al., 2019). Governance systems must grapple with this dual challenge: the irresponsibility of ignoring high-impact risks and the difficulty of acting effectively when the timing, likelihood and specific impacts of these events remain uncertain. For instance, northern Europe could either continue its current trajectory of warming and wetting or face a dramatic drop in temperature and drying within decades (van Westen and Baatsen, 2025). This creates a changing rationale for rapid climate mitigation efforts and profound challenges for adaptation planning, which must now contend with a broader and more divergent spectrum of possible futures and greater uncertainty about these futures.

Because tipping points involve the risk of irreversible changes with severe impacts at large scales, **uncertainty about their timing or thresholds strengthens** - rather than weakens - **the case for precautionary action**. To safeguard societies against these uncertainties, governance must shift toward flexible and anticipatory approaches that build resilience across multiple scenarios and adopt no-regrets policy options that are beneficial regardless of the climate trajectory. This includes new forms and tools of knowledge co-production between science, other forms of knowledge and policy (Wood et al., 2023), establishing monitoring and early warning systems and fostering anticipatory, cooperative multi-stakeholder governance to prepare for surprises.

Effectively responding to these challenges demands a distinct governance agenda for ESTPs, including a rethinking of governance objectives and logics, reforming and in some cases developing new approaches (norms, policies, laws, mechanisms and institutions) and engaging or creating new stakeholders.

1.1.2 Objectives, principles and logics for action

The primary objective of ESTP governance is to prevent the Earth system from crossing tipping points. The action window for prevention is likely very short for several tipping elements, although some of these tipping processes would unfold over multiple decades or even millennia. By creating causal connections between near-term actions and long-term, large-scale changes in tightly connected Earth-human systems, tipping points place a significant burden of responsibility for prevention on today's governance system.

BOX 1.1.1: Prioritising the prevention of Earth system tipping points

Preventing the crossing of ESTPs is unlikely with existing measures for climate change mitigation. It requires

- Keeping the **peak global temperature** as close to 1.5°C as possible, i.e. minimising the height of temperature overshoot. Every additional 0.1°C increases the risk of transgressing ESTPs.
- Keeping the **duration of temperature overshoot** above 1.5°C as short as possible (every year counts) and returning global average temperatures to below 1.5°C.
- Minimising temperature overshoot requires (1) **frontloaded mitigation pathways** with the heaviest cuts this and next decade and (2) immediate development and **scaling of sustainable carbon removal capacities.**
- **Addressing non-climate drivers of tipping**, such as deforestation (e.g. Amazon rainforest) and pollution (e.g. warm-water coral reefs).

At the same time, it is important to anticipate, prepare for and navigate the change process to maximally protect communities, societies and ecosystems in harm's way in the event a tipping point is not avoided. Prevention and impact governance are the first and second line of defence against ESTPs. Each of the following two chapters is dedicated to one of these governance domains (Chapter 1.2 to prevention, Chapter 1.3 to impact governance).

The framework depicted in Figure 1.1.1 can guide the development of governance responses to ESTPs (Milkoreit et al., 2024). Reflecting an unfolding tipping process, the framework distinguishes three phases: **Pre-Tipping, Reorganisation, Stabilisation**. In each phase, different governance objectives, logics, activities and actors are dominant.

Prevention is the core focus of the pre-tipping phase and aims to avoid crossing tipping points through precautionary action, especially accelerated GHG emissions reduction, but also measures to address other tipping drivers, such as deforestation (see Chapter 1.2). Adaptation planning, impact anticipation and preparedness are also tasks in phase 1. Once a tipping point is crossed, the tipping element enters a reorganization process that can last from years to millennia (phase 2).

The focus of governance for this specific tipping element shifts to addressing the impacts of the reorganization process, managing potentially rapid change, maintaining and fostering resilience, minimizing harm and tending to losses (Chapter 1.3). This phase requires swift impact responses, crisis management and adaptation strategies to navigate system transformation. Decision-making must balance immediate governance needs (e.g. responding to extreme events, managing migration, adapting health care provision) with long-term stability. While prevention efforts are only meaningful in the pre-tipping phase for a specific tipping element, impact governance evolves across all three phases of the tipping process, shifting from anticipation to response to resilience-building. The third phase (stabilization) focuses on fostering societal sustainability and resilience within the new climatic-ecological conditions of the alternative state of the tipping element, which is likely less hospitable than current pre-tipping conditions.

Different tipping elements can be in different (governance) phases at any given moment in time. For example, while the warm-water coral reef system might be in the reorganization phase in 2030, the Amazon rainforest and the AMOC might still be in the pre-tipping phase. Impact governance for one and prevention efforts for the others would have to occur in parallel.

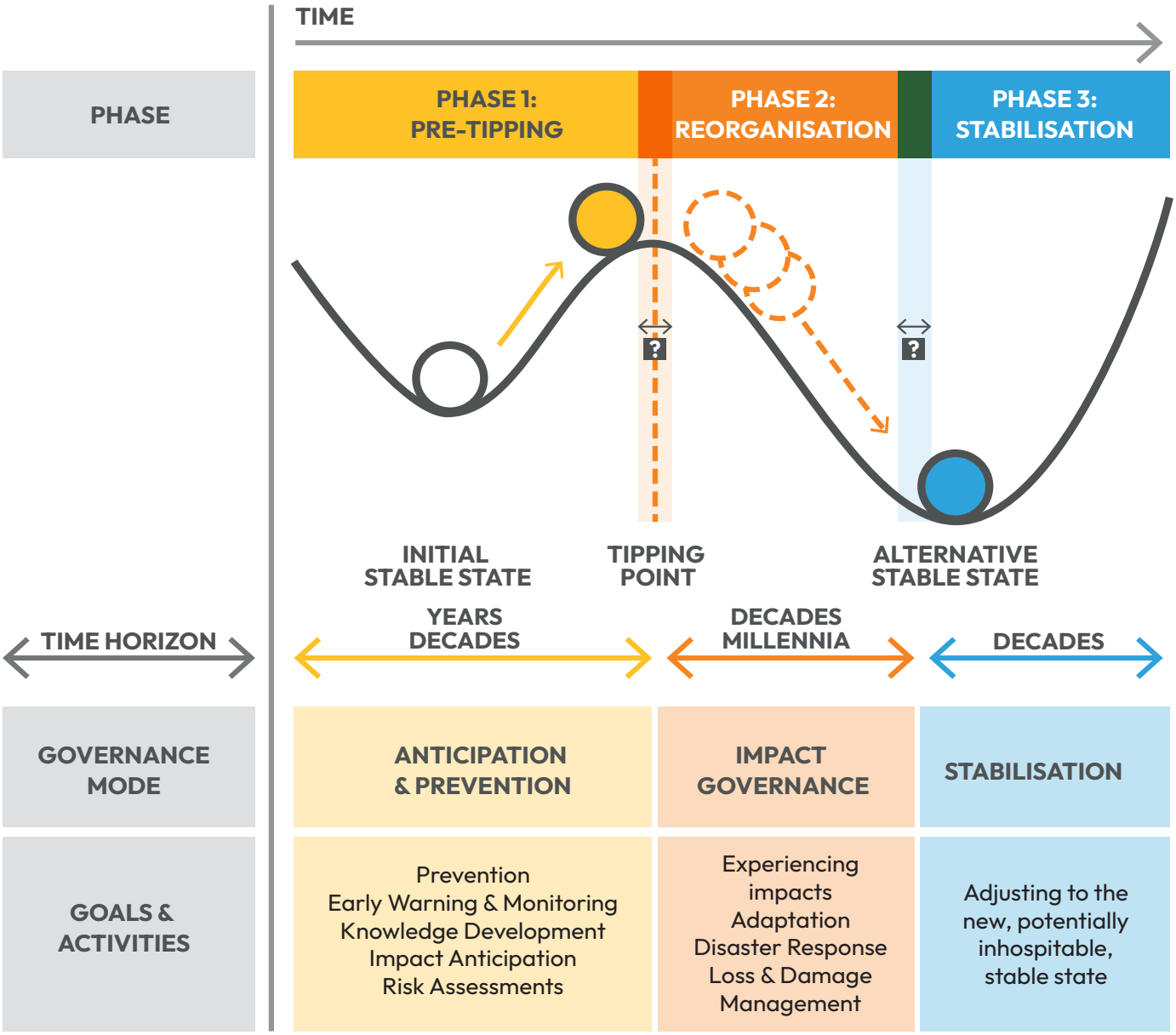


Figure 1.1.1: Three-phase framework for governance of ESTPs

Reprint of Milkoreit et al. 2024: The figure distinguishes three phases of tipping processes (pre-tipping, reorganisation and stabilization). Each phase presents distinct governance challenges and has a corresponding dominant logic (e.g. anticipation and prevention in the pre-tipping phase), specific goals and activities.

Across all phases, **knowledge and learning** play a central role in informing decision-making. Science and other knowledge actors assume key responsibilities for fostering recognition and understanding of nonlinear Earth system dynamics and the risks they present. These actors continuously generate and update the knowledge base without which effective governance responses cannot be devised. Science-policy interactions serve as the bridge that links emerging insights to legitimate and coordinated action.

The framework focuses on each tipping element independently and does not account for cascading tipping effects between systems, e.g. the fact that one tipping process can influence the likelihood and prevention requirements of another. Governance approaches must also be tailored to different tipping systems, as their timelines and intervention needs vary.

Effectively addressing ESTPs requires a specific set of **principles and approaches**. These were discussed in more detail in GTPR 2023, including examples (see Chapter 3.1 GTPR 2023) and are summarised in Table 1.1.2.

Table 1.1.2: Principles and approaches for ESTP governance

Principle/Approach	Definition
Adaptive Governance	Governance that integrates continuous learning, system monitoring and flexible policy adjustments. Recognizes the complexity of human-nature systems and the need for iterative, science-informed decision-making.
Anticipatory Governance	A proactive, forward looking approach using futures capacities and methods (e.g. scenario development) to guide decisions and strategies. Needs to address power imbalances, injustices and expand possibility thinking.
Deep Cooperation	Addressing ESTPs demands strong international, regional and sectoral collaboration. Tipping points may provoke short-term, competitive responses (e.g. resource grabbing, nationalism), which must be countered with sustained global cooperation efforts.
Justice, Equity, Human Rights & Future Care	Fair distribution of responsibilities, harms and benefits within and between nations, peoples, species and generations. This includes Earth system justice (intragenerational, intergenerational, interspecies justice) and common but differentiated responsibilities and capabilities. This demands equitable resource allocation, procedural justice and recognition of affected communities, eco- and Earth systems and institutions dedicated to safeguarding future and non-human interests, all aligned with human rights.
Multi-level Governance & Polycentricity	System of decision-making in which authority and policy responsibilities are distributed across multiple levels of government—local, regional, national and international—with full and effective participation of human rights holders and respect of human rights. Emphasizes collaboration, coordination and power-sharing to address complex challenges that transcend administrative boundaries.
Response Diversity	The presence of multiple governance measures that respond differently to a specific challenge. Response diversity creates redundancy, which incurs costs but prevents systemic failure. Needs coordinated multi-level approaches.
Systemic Risk Governance	Framework for identifying, assessing and managing risks that can trigger disruptions across interconnected systems, such as financial markets, critical infrastructure, or ecosystems. Emphasizes adaptive, multi-stakeholder approaches to enhance resilience, prevent cascading failures and ensure stability in the face of complex and uncertain threats. Apply synergistically climate law, ocean law, biodiversity law and human rights law as a legal basis for systemic risk governance.
Uncertainty & Precaution	Governance of ESTPs must navigate scientific and political uncertainties, including unknown tipping-point and impact timelines. The precautionary principle calls for preventive action despite incomplete knowledge.

Here, we highlight two principles that are particularly relevant in the pre-tipping, vital ***preventative phase*** (see Figure 1.1.1) with a view to the impending global temperature overshoot.

Anticipatory Governance embraces a stronger future orientation through disciplined engagement with possible futures. It takes seriously the deep uncertainties of ESTPs and marks a shift away from likelihood to risk severity as the primary driver for action. It utilizes diverse methods of collective future engagement, such as participatory scenario development or serious gaming, to generate and inform proactive measures. Governance time horizons are expanded beyond political cycles, with decisions that are made with long-term impact horizons. This multi-temporality involves assessing and acting upon intra- and inter-generational impacts and necessitates expanding governance actors to include younger and future generations.

Systemic Risk Governance encompasses those risks that have the potential to compound and cascade within and between different systems (such as climate, food, water, health, finance, social cohesion, technologies, etc.). The resulting crises feed into each other, increasing their severity and/or likelihood and risk escalating into potentially catastrophic harms to human societies and ecosystems. Chapter 2.4 sets out a framing of systemic risk in the context of ESTPs. This includes their direct consequences on the biophysical environment (e.g. agriculture, buildings, infrastructure), as well as the subsequent cascading consequences (e.g. financial crises, mortality, trade disruption, social unrest) (IPBES, 2024).

Governing such dynamics requires a holistic, systemic approach to assessing and responding to ESTP risks. Those undertaking assessments and those designing and implementing responses must utilise an enhanced understanding of systems interconnections and risk transmission channels, develop policies and responses that can address multiple risks simultaneously, particularly at the most fragile points of systems and their interconnections and envision pathways to transformation away from risky system conditions.

ESTP governance also must contend with tipping dynamics in social systems. It is useful to distinguish between two kinds of social tipping points, each having very different implications for ESTP response. Positive tipping points (see Section 3) involve self-amplifying feedback dynamics that drive social systems (e.g. economic sectors, consumer behaviour or social norms) towards a desirable state (Tàbara et al., 2018; Winkelmann et al., 2022). Such deliberate dynamics in social systems could potentially be leveraged for ESTP prevention efforts (Chapter 1.2) and potentially adaptation and resilience building (Chapter 1.3). The second type of social tipping dynamics concerns negative social tipping points, where self-amplifying feedbacks after a threshold drive undesirable social change, e.g. political polarization, social unrest and conflict. This type of tipping creates additional challenges for the domain of impact governance (Chapter 1.3).

1.1.3 Current context: Science and global governance reforms in times of a weakening global order

2024 was the first calendar year with average global temperatures exceeding 1.5°C above pre-industrial levels (Bevacqua et al., 2025). Critical carbon sinks, such as the Arctic tundra and Northern boreal forests, are now shifting to become carbon sources, amplifying global warming (Kelly et al., 2024; Migliavacca et al., 2025; Pan, 2024). Additionally, unusual ocean heat extremes—still not fully understood by scientists—signal nonlinear response in Earth's systems and recent observations put in question the previously assumed linearity of temperature changes (Hansen et al., 2025). These developments signal declining system resilience and suggest that the world is entering a more turbulent and unpredictable climatic era, in which the decline of natural systems could accelerate with severe implications for human wellbeing (McElwee et al., 2025).

Amid a steady longer-term decline in global environmental diplomacy, 2024 and 2025 saw some developments in global governance aimed at addressing the long-term risks of planetary change. The UN Summit of the Future in September 2024 adopted the Declaration on Future Generations and commitments to foster governance across all scales that is more future-oriented and intergenerational. The UN Secretary-General announced plans to establish a UN Envoy for Future Generations and the European Commission included intergenerational fairness in its policy portfolio, further institutionalizing intergenerational relations. Climate litigation was on the rise and several international courts and tribunals provided advisory opinions on the legal obligations of states related to climate change: the International Court of Justice (ICJ AO 2025), the Inter-American Court of Human Rights (IACHR AO 32/25) and the International Tribunal on the Law of the Sea (ITLOS AO 31/2024). At the same time, effective mechanisms for enforcing state obligations are lacking in international law.

Recent global political trends, especially a rise of right-wing, nationalist, anti-science and protectionist governments in many parts of the world have weakened the potential for multilateral cooperation on both climate change and tipping processes, as major powers prioritize sovereignty and national gain over collective action. Geopolitical fractures and realignments further erode consensus, potentially compromising multilateral, cooperative institution building. Conflicts divert attention and resources away from climate action, while domestic political agendas reduce public, governmental and private sector support for environmental policies. In this landscape, where major actors fail to identify and act on their shared interests, global governance efforts to address ESTPs may face serious constraints, emphasising the importance of subnational and non-state actors and ad hoc coalitions. Smaller scale, minilateral initiatives (e.g. the G7) have been and may remain feasible under current conditions and can provide a platform for expanding to larger scale agreements (O'Brien et al., 2025).

1.1.4 Deep dives: Four tipping-point case studies

Throughout this report, three key tipping systems - the Amazon rainforest, the world's warm-water coral reefs, the Atlantic Meridional Overturning Circulation (AMOC) coupled with the Subpolar Gyre (SPG) and mountain glaciers - serve as case studies to deepen understanding and promote practical relevance of the Report. We briefly introduce these four cases here, highlighting the comparative insights they provide specifically for ESTP governance. Section 4 includes a dedicated case study chapter for each of them and Section 2 provides more details on the tipping dynamics, risks and impacts of these and other identified tipping elements in the Earth system.

Collapse of the Atlantic Meridional Ocean current (AOC) and Subpolar Gyre (SPG): The AMOC is a critical system of ocean currents in the Atlantic Ocean, extending from the tropics to the North Atlantic. It plays a vital role in regulating global climate by transporting warm surface water northward and cold deep water southward. In its stable state, the AMOC maintains relatively mild climates in Europe and influences weather patterns worldwide. This circulation could weaken or collapse, leading to profound environmental changes—such as significant North Atlantic cooling, altered precipitation patterns, a shift of the tropical rain belt affecting the Amazon rainforest and disruptions to Monsoons in West Africa and Asia—which would have wide-ranging human and social impacts. These include threats to food security from reduced agricultural productivity and fisheries collapse, heightened risks to water availability and economic losses from damaged infrastructure, disrupted trade and energy system instability.

Closely related to the AMOC is the formation of deep water in the Subpolar Gyre (SPG), a large system of rotating currents in the northern North Atlantic. While smaller in scale, a collapse of deep-water formation in the SPG would have similar—though more geographically concentrated—consequences, particularly for European and North Atlantic climates. Impacts could include regional cooling, changes in storm tracks and disruptions to marine ecosystems with consequences for agriculture and food security, fisheries, infrastructure and public health.

The AMOC and SPG are closely interconnected. A collapse of SPG deep convection would leave only deep convection in the Greenland-Iceland-Norwegian Seas driving the AMOC and a weakening of the gyre would affect the density and flow of waters that drive overturning circulation. This interdependence underscores the importance of viewing these tipping elements not in isolation but as part of a tightly coupled Earth system, where regional changes can cascade into global consequences.

Dieback of the Amazon rainforest: The Amazon rainforest plays a vital role in regulating the Earth's climate by storing carbon, recycling moisture through evapotranspiration and generating rainfall that sustains ecosystems across South America. If deforestation and climate-change induced drought push the Amazon beyond a tipping point, large parts of the rainforest could shift irreversibly to a savanna-like state. Such dieback would release massive amounts of carbon into the atmosphere, further accelerating global warming.

The consequences would extend well beyond the forest itself. Regionally, the Amazon strongly influences South America's hydrology through its role in sustaining atmospheric rivers—bands of moisture that carry rainfall across the continent. Dieback would weaken these systems, reducing water availability for major agricultural regions in Brazil, Argentina and beyond, with cascading impacts on biodiversity, food production, hydropower generation and urban water supplies. Globally, loss of the Amazon's moisture recycling could alter atmospheric circulation patterns, including shifts in tropical rainfall belts and monsoons in Africa and Asia, with implications for agriculture, desertification and water security on multiple continents.

Human and societal impacts would be profound. In South America, reduced agricultural productivity threatens rural livelihoods and national economies, while respiratory illness from forest fires and altered patterns of infectious disease would undermine public health. Globally, disruptions to South American agricultural exports such as soy, maize, beef and coffee could destabilize global food markets, increasing price volatility and food insecurity in other regions. The Amazon's unparalleled biodiversity—harbouring around 10% of known species—would face irreversible loss, undermining global ecological resilience and the future availability of genetic resources for medicine, food and adaptation. Indigenous peoples and local communities, whose cultural identities, traditions and survival are closely tied to the rainforest, would face existential threats to their ways of life. Migration would increase, as people seek out more stability in water, food and cultural systems.

Dieback of warm-water coral reefs: Tropical coral reefs are predominantly found in shallow, warm ocean waters near the equator, with significant formations in regions such as the Great Barrier Reef in Australia, the Coral Triangle in Southeast Asia and the Caribbean Sea. These vibrant ecosystems support roughly a quarter of all marine species and provide critical coastal protection and livelihoods for millions of people. In their healthy state, coral reefs sustain rich biodiversity, fisheries and tourism economies. However, rising ocean temperatures, acidification, overfishing and pollution can lead to coral bleaching and mortality. Crossing a tipping point could result in the widespread collapse of reef ecosystems, causing a dramatic loss of marine biodiversity, diminished fish stocks and weakened coastal defences against storms and erosion.

The human and societal consequences would be severe. Regionally, hundreds of millions of people across the tropics rely on coral reefs for food security, employment and coastal protection. A collapse would jeopardize fisheries that provide both protein and income, disrupt tourism economies and expose coastal communities to intensified storm damage, sea-level rise and groundwater salination. Public health could also suffer from increased malnutrition, reduced income for healthcare and trauma from more frequent disasters.

Melting of mountain glaciers: Mountain glaciers are found on every continent, from the Andes and the Rockies to the Alps, Himalayas and East Africa. In many of these regions, glaciers are critical components of their regional hydrological systems, acting as natural reservoirs that store water throughout the year, releasing it as meltwater in warmer seasons. They regulate river flows, sustain ecosystems and provide a crucial water supply buffer during dry periods. However, rising global temperatures are driving rapid glacier retreat worldwide. In many regions, glaciers are retreating and continued warming threatens the near-total disappearance of smaller glaciers within this century. Some mountain glaciers display tipping dynamics, i.e., ice loss accelerates after a threshold and is lost irreversibly.

The impacts of widespread glacier melt are far-reaching. Regionally, hundreds of millions of people in South America and Asia depend on glacier-fed rivers such as the Ganges, for drinking water, irrigation and hydropower. Accelerated melting initially increases river flows, heightening the risk of floods, glacial lake outburst events and landslides. As glaciers shrink, water availability in dry seasons declines, threatening food production, energy security and urban water supplies. Local communities, particularly Indigenous peoples and mountain cultures, face profound disruptions to livelihoods and cultural identities tied to glaciers. The decline of iconic glaciers also represents a loss of cultural and natural heritage, with implications for tourism economies and human identity.

These four systems illustrate the diversity of tipping elements in the Earth system and the broad challenges they pose. Analysing their similarities, differences and linkages provides key insights for effective governance responses. The AMOC, Amazon Rainforest and coral reefs occupy distinct geographic regions with unique ecological and climatic roles. Each case highlights who—countries, regions and communities—will be most affected by a given tipping process. Collectively, they show that tipping impacts will reach every country and person while also underscoring their uneven distribution. This highlights the need for governance approaches tailored to each system and the importance of equity and justice in ESTP governance.

These systems also differ in their timelines and uncertainties, emphasizing why temporality matters for governance. Each tipping system is subject to different levels of scientific uncertainty and varying degrees of knowledge about expected impacts. Coral-reef tipping is imminent, unfolding over 10-15 years, the Amazon could reach its tipping point well before 2050, while AMOC tipping may occur sometime between 2030 and 2100, unfolding over multiple decades. Different timelines demand different actions—for example, preparing communities for coral reef loss while accelerating emissions reductions to prevent AMOC collapse. Examined together, their temporalities underscore both the urgency of immediate action and the need for long-term strategies. Additionally, their interconnectedness means one tipping event could trigger others, amplifying global climate risks—such as AMOC disruptions altering Amazon rainfall and accelerating dieback or vice versa.

1.1.5 A Guide to Section 1

Following this introduction, the governance section of the Report contains four chapters. The following two chapters cover prevention of ESTPs and impact governance—two distinct governance domains. Chapter 1.4 explores the link between ESTP governance and human rights. The final chapter (1.5) explores actors, their agency and potential strategies to address the risks of ESTPs.

1.2 Governance to prevent Earth system tipping points

Authors: Simon Willcock, Claudia Wieners, Hugues Chenet, J.B. Ruhl, Manjana Milkoreit, Jürgen Scheffran, Yulia Yamineva, Ahjond Garmestani, Ida Edling Müller, Ashwin K Seshadri, Ajay Gambhir, Silvia Montagnani, Kirsty Tooke, Grace Ellsworth, Danielle Young, Bregje van der Bolt, Sara Constantino

Reviewers: Maja Groff, Louis Kotzé, Jessica Seddon

Key Messages

- **The risk of activating tipping processes exists at current levels of warming and increases with every 0.1°C and every year of overshooting the globally agreed goal of 1.5°C.**
- **Current climate mitigation measures are not sufficient to prevent tipping events; they need to be accelerated and coupled with measures addressing non-climate drivers, such as deforestation of the Amazon rainforest.**
- **Preventing tipping points requires 'frontloaded' mitigation pathways that minimise peak global temperature, the duration of the overshoot period above 1.5°C, and the return time below 1.5°C with immediate, comprehensive fossil-fuel phase out efforts.**
- **Sustainable carbon dioxide removal approaches need to be rapidly scaled up to help return the global mean temperature to and then below 1.5°C.**

1.2.1 The case for prevention

Given the substantial risks posed by Earth system tipping points (ESTPs; see Section 2), the Global Tipping Points Report (2023) highlighted that prevention should be the core goal and logic of a new and urgently needed global governance agenda. Up to five tipping points (in the warm-water coral reefs, Greenland Ice Sheet, West Antarctic Ice Sheet, North Atlantic Subpolar Gyre (SPG), and Permafrost) could be transgressed at the current level of warming, with a further five becoming at risk at 1.5°C (Armstrong McKay et al. 2022; Figure 1.2.1). The 1.5°C threshold will be reached within a few years (Bevacqua, Schleussner & Zscheischler, 2025), which means that the prevention window for some of these tipping processes may be closing quickly (e.g. there is consensus that the uncertainty range for the tipping point of the warm-water coral reefs has an upper bound at 2.0°C; Figure 1.2.1). The length of time it will remain open is different for each tipping system, depending on its specific drivers, especially the trajectory of global mean temperature and associated changes in regional means and variability, as well as other factors such as pollution, deforestation, and other more regional stressors (Global Tipping Points Report 2023).

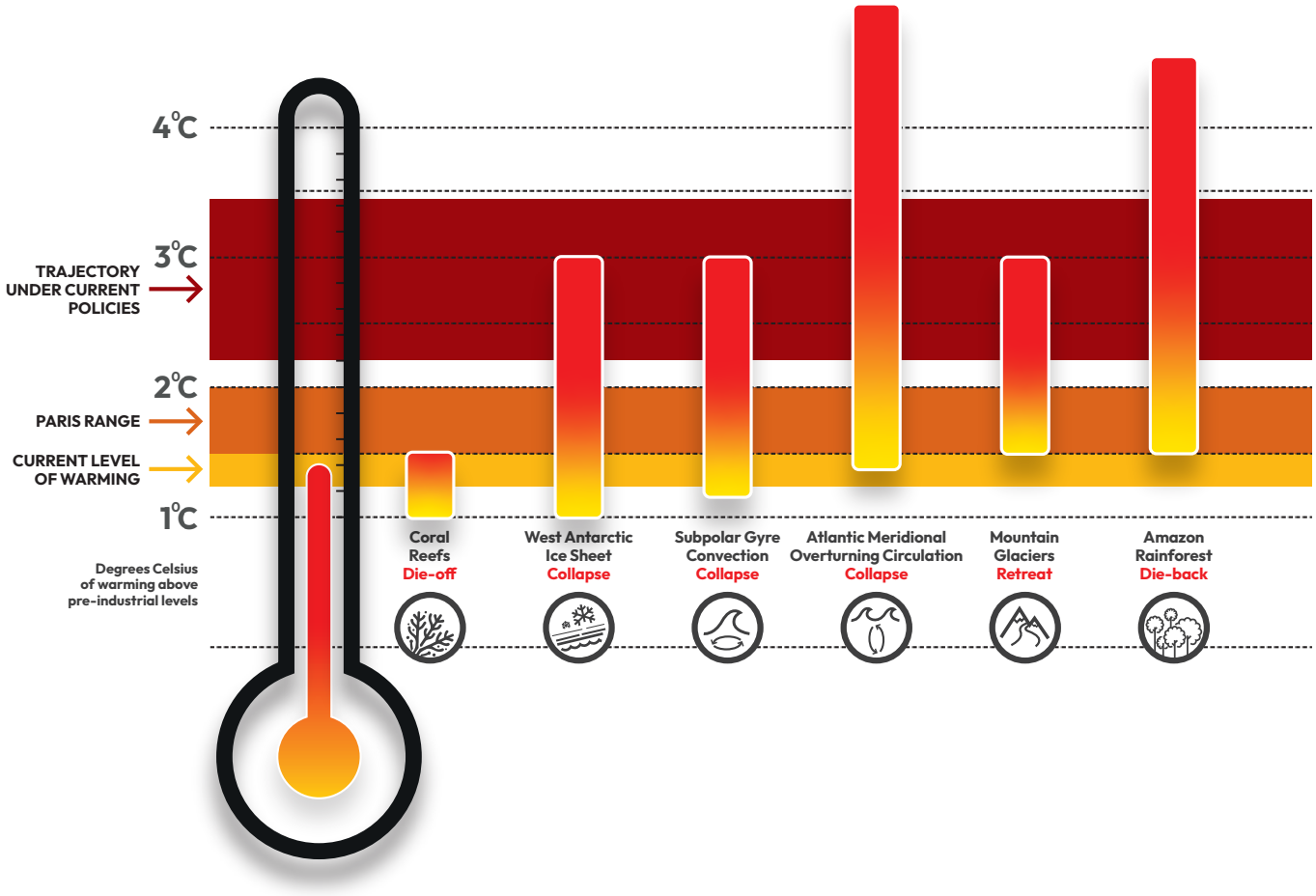


Figure 1.2.1: Risks of Earth system tipping points increase with global warming. Sources: Global Tipping Points Report 2025 and Armstrong McKay et al., 2022

When devising prevention strategies, it is useful to divide ESTPs into two groups: i) those that are predominantly climate-driven (e.g. Atlantic Meridional Overturning Circulation - AMOC collapse) and therefore are not sensitive to anything but climate mitigation as a prevention strategy, and possibly geoengineering (discussed in full below); and ii) those with a mix of climate and non-climate related drivers (e.g. Amazon rainforest dieback; Table 1.2.1; Figure 1.2.2). Both groups, but especially the latter, require coordination of efforts (e.g. goals and timelines, information flows, institutional linkages) and governance across policy domains and scales (e.g. global climate mitigation and national forest and agricultural policies). Figure 1.2.2 identifies relevant drivers for three case studies we explore throughout the report.

Table 1.2.1: Climate- vs. multi-driver (including climate) Earth system tipping elements. ESTPs can be divided into two groups: those that are nearly entirely climate-driven and are not sensitive to anything but mitigation as a prevention strategy (e.g. AMOC collapse), and those with a mix of climate- and non-climate-related drivers

ESTPs predominantly driven by climate	ESTPs driven by a mix of climate and non-climate drivers
Glacier retreat (although one driver [black carbon] is regionally generated)	Boreal forests
Ice Sheets (Greenland and East & West Antarctica)	Coral reefs
Ocean circulation (AMOC, SPG and Southern Ocean)	Dryland degradation
Permafrost thaw (except for a small contribution from vegetation change)	Lake browning
Sea ice loss (although one driver [black carbon] is regionally generated)	Mangroves
	Marine regime shifts (fisheries etc)
	Monsoon
	Savannah degradation
	Temperate forests
	Tropical forests

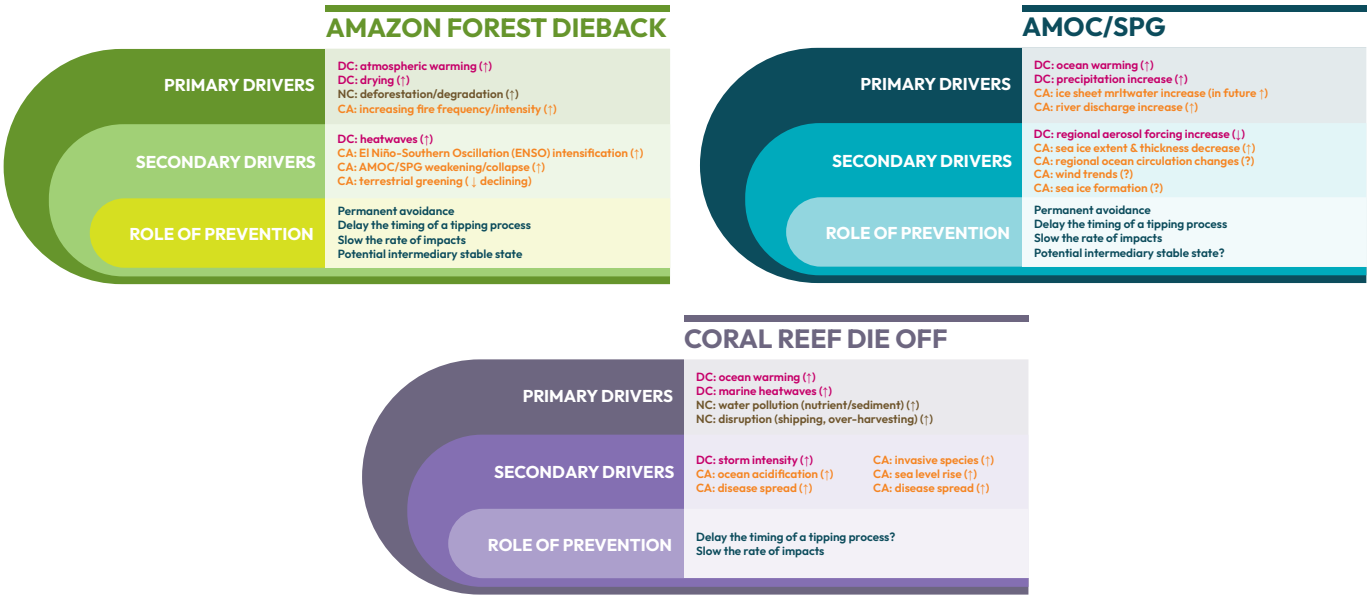


Figure 1.2.2: Multiple drivers of ESTPs. Primary (more important) and secondary (less important) drivers of the ESTPs focussed on in this report, and the role prevention can play for each. DC: Direct climate driver (direct impact of emissions on meteorological variables via radiative forcing; pink); CA: Climate-associated driver (including second-order and associated effects of climate change; orange); NC: Non-climate driver (brown). Drivers can enhance (↗) or counter (↘) tipping. Prevention efforts can have a variety of goals: complete success (permanent avoidance); delaying the timing of a tipping process – i.e. moving the time when the critical threshold is reached further into the future (e.g. beneficial for anticipatory adaptation planning); slowing the rate at which the impacts of crossing a tipping point unfold, somewhat easing the corresponding adaptation challenges; and, if a tipping system has multiple stable states, prevention efforts might fail to avoid the first tipping point, leading to significant changes until the system settles in its first alternative stable state, but might succeed in averting further tipping to the next state.

In most cases, global temperature increase is a key driver, **placing accelerated climate change mitigation at the heart of effective prevention strategies**. Entering the domain of temperature overshoot has important implications for prevention efforts (Wunderling et al., 2023; Möller et al., 2024). Tipping risk increases with every additional 0.1°C of overshoot above 1.5 °C and strongly accelerates for peak warming above 2.0°C (Möller et al. 2024; Figure 1.2.1). **Reducing the risk of tipping-point transgression requires a global collective effort to minimise both the peak temperature and the length of the overshoot period, while returning the global mean temperature to or below 1.5°C with sustainable carbon removal technologies**. As every tenth of a degree of warming increases tipping risks (Figure 1.2.1), **an immediate, inclusive, and comprehensive effort is required to phase out anthropogenic greenhouse gas emissions as quickly as possible**. Although mitigation would be required even in the absence of tipping threats, the severity and potential irreversibility of tipping points provide a strong additional reason to phase out greenhouse gas emissions swiftly and, in particular, limit temperature overshoot. As long as uncertainties remain large, a precautionary standard assumption is that every additional tenth of a degree of warming, and every additional year of temperature overshoot, increases tipping risk and should be avoided.

Global mitigation pathways should peak as close to 1.5°C as possible and return to, or even below, 1.5°C as soon as possible. This requires frontloading emission reductions, maximising efforts in the remaining 2020s and early 2030s. It also demands immediate scaling of investments in developing sustainable carbon removal capacities, which are necessary to bring the global temperature back down from its peak. Furthermore, any additional stresses experienced during the overshoot period will mean ESTPs occur sooner (Willcock et al., 2023), emphasising the importance of simultaneously managing non-climate drivers (Table 1.2.1; Figure 1.2.1).

Key factors holding back progress on climate mitigation (including, for example, power, financial interests, political economy and obstruction) are well understood and discussed elsewhere (e.g. Global Tipping Points Report 2023; Willis et al., 2022). While current political developments are making globally coordinated action even more difficult, slow progress at the global level under current processes/architecture must not be an excuse to delay action. Change can and should still be pursued at local, regional, national and supranational (e.g. EU, AU, ASEAN) levels (Box 1.2.1), as well as through novel international governance upgrades such as highly effective "smart coalition" approaches (Climate Governance Commission, 2023). For example, individual countries or trading blocs investing in electric vehicles and/or renewable energy can reduce global production costs and may make it more likely that other regions or nations will adopt these technologies (Mercure et al., 2024).

Box 1.2.1: Research Insight: State of Governance
ESTPs in European policy discourse: linking risk to governance

Over the past several years, government and parliamentary actors in Norway, Germany, and the UK have increasingly referenced climate tipping points in connection with the 1.5°C global temperature goal. Across these countries, the prospect of transgressing critical thresholds—such as Amazon forest dieback or ice sheet collapse—is being used to emphasize the urgency of rapid emissions reductions. However, there are notable differences in how this risk is translated into policy direction.

In all three countries, tipping points are largely framed as looming, irreversible threats that amplify the case for delivering on existing climate commitments—particularly mitigation targets under the Paris Agreement. Parliamentary actors and civil society groups use the language of tipping points to stress the need for faster and more ambitious climate action. For example, Norwegian officials and NGOs cite tipping risks to argue for embedding the 1.5°C target more deeply in law and policy. In the UK, political leaders frequently invoke tipping points to highlight the inadequacy of current emissions plans and the consequences of falling short.

Yet across contexts, the discourse remains anchored in reinforcing current goals rather than evolving them. Whilst current goals are helpful, more is needed. Tipping points are deployed as rhetorical devices to raise the stakes, not as drivers of new governance strategies. Despite acknowledging that these risks mark a fundamentally different class of climate threat—abrupt, nonlinear, and irreversible—there is little recognition that preventing or managing them may require distinct institutional reforms, risk governance mechanisms, or anticipatory planning. In short, tipping points have entered the political lexicon without a corresponding set of actionable ideas for how they should reshape policy and governance.

This reveals a growing gap between scientific understanding and institutional response/creativity. Strengthening the link between tipping point science and concrete governance innovation, to forge new ground in order to safeguard human flourishing, will be essential to address the unique challenges these risks pose—and to ensure that the invocation of urgency leads to more than rhetorical momentum.

Here, we provide guidance to assist governance actors (Chapter 1.5), especially those at national and international-scale, in preventing the transgression of ESTPs. We highlight specific examples of governance required to prevent irreversible transitions of the AMOC (Box 1.2.2) and Amazon rainforest (Box 1.2.3). These contrasting case studies were chosen to illustrate possible preventative action across distinct types of ESTPs based on: drivers (i.e. mostly climate drivers for AMOC vs significant non-climate drivers for the Amazon), time horizons (more distant vs urgent), and the need for multi-scale governance (predominantly international vs across scales). We did not focus on coral reef die-off as it may not be possible to prevent this ESTP (Table 1.2.1), instead, urgent impact governance should be prioritised (Chapter 1.3) in the case of this ESTP.

Box 1.2.2: An introduction to preventing the AMOC ESTP

The AMOC and Subpolar Gyre (SPG) ESTPs are only subject to climate-related drivers. For both, a reduction in surface water density in the North Atlantic can cause tipping, because it prevents surface waters from sinking (AMOC) or being mixed with deeper waters (SPG; also relevant for AMOC; Gregory et al., 2016; Golledge et al., 2019; Armstrong-McKay et al., 2022). All of these dynamics are driven by increases in atmospheric temperature. Anthropogenic aerosols (e.g. from shipping emissions) partly counteract this because they cool the ocean surface (Hassan et al., 2021). See AMOC Case Study for more details.

As AMOC and SPG have no non-climate drivers equivalent to deforestation in the Amazon (see Box 1.2.3), **ambitious climate mitigation - net phase out - is the key measure to prevent their tipping**. Key to this is strengthening international cooperation and climate action at national, regional and local scales and ensuring implementation of commitments.There is some evidence that AMOC tipping is sensitive to the rate of warming and not just the magnitude (Lohmann & Ditlevsen 2021), so limiting the rate of global temperature rises could be a key governance target.

Box 1.2.3: An introduction to preventing the Amazon ESTP

The Amazon forest is losing resilience and large parts of the Amazon could change to a contrasting degraded state, such as non-forest flammable ecosystems (Boulton et al., 2022). Flores et al., (2024) summarise the latest knowledge of when the Amazon forest may pass critical thresholds, with tipping points expected: i) after increases in global temperature of between 2 and 6°C, ii) if precipitation drops below 1,000-1,800mm per year, iii) if seasonality increases, resulting in a maximum cumulative water deficit of ~350-450mm, iv) if dry season length increases to between 5 and 7 months, or v) if deforestation reaches 10-20% of the original forest biome. However, if two or more of these thresholds are approached simultaneously, then a tipping point may occur before any of these individual thresholds are crossed (Cooper et al., 2020; Willcock et al., 2023). See Chapter 4.1 for more details.

Preventing these undesired ecosystem transitions in the Amazonian system requires not only limiting temperature and precipitation changes, but also regional and national land-use management. Given these multiple drivers operating from global to sub-national scales, the Amazon ESTP requires coordinated cross-scale approaches (polycentric prevention).

1.2.2 Building on existing governance frameworks

Existing institutions and governance measures across scales provide important entry points for ESTP prevention efforts. The international climate change regime complex, including governance of short-lived climate pollutants (SLCPs) and emerging activities related to carbon dioxide removal (CDR) and other geoengineering approaches, is particularly important for addressing climate-related drivers of tipping processes.

International climate change governance

Global climate change governance is centred around the Paris Agreement and the United Nations Framework Convention on Climate Change (UNFCCC). None of the elements of the Paris Agreement regime are specifically designed to address the risks associated with tipping points (Global Tipping Points Report 2023). The current implementation of the Agreement also falls short of achieving its temperature goals, both the overarching goal of keeping global warming to well below 2°C above pre-industrial levels and the more ambitious one of 1.5°C (United Nations Environment Programme, 2024). This matters for ESTP prevention since some tipping points could be triggered within the range of 1.5°C-2.0°C (Figure 1.2.1).

Addressing tipping-point risks within the Paris Agreement would focus on 'pursuing efforts' to limit global temperature rise to 1.5°C, and to keep them 'well below' 2.0°C. Given the 1.5°C threshold will be reached within a few years (Bevacqua et al., 2025), **actors at all levels must strive for every 0.1°C warming that can be avoided below 2.0°C** (Chapter 1.5). This requires interpreting Article 4 of the Paris Agreement ('reach global peaking of greenhouse gas emissions as soon as possible') as to minimise temperature overshoot, rethinking acceptable mitigation pathways to minimise the overshoot period, including risks of ESTPs in Nationally Determined Contributions (NDCs) and the Global Stocktake, and substantially strengthening its review and transparency frameworks (Global Tipping Points Report 2023). For example, **the second Global Stocktake process could explicitly address to what extent collective prevention efforts have limited the risk of passing ESTPs**. Further, **the risk of ESTPs should be considered as part of a third Periodic Review (UNFCCC 2024) of the adequacy of the long-term global temperature goal and the progress towards achieving it**, as well as under the Mitigation Work Programme (Global Tipping Points Report 2023).

The single most important prevention measure is to phase out net greenhouse gas emissions rapidly. Thus, there is a need to transition away from fossil fuel use, not only in the energy system, but across societies, although this is not unique to ESTP governance (Iyer et al., 2022).

Further, **an increased focus on reducing short-lived climate pollutants (SLCPs)** can lead to particularly rapid reductions in global temperature increase, thus minimising overshoot and the risk of ESTPs (Global Tipping Points Report 2023). Several institutions and initiatives address SLCPs at global and regional levels, including the Climate and Clean Air Coalition, the Global Methane Pledge, and the Arctic Council (Yamineva et al., 2023). Individual SLCPs are integrated into legal frameworks under the Gothenburg Protocol (black carbon), the Kigali Amendment to the Montreal Protocol (HFCs), and the UN Framework Convention on Climate Change (UNFCCC)/ Paris Agreement (methane). Despite these efforts, there remains significant potential for stronger action on SLCPs, particularly on methane and black carbon emissions (UNEP & CCAC, 2021; Sun et al 2022). The Norwegian Ministry of Climate and Environment has recently justified pursuing and funding international collaborative efforts to reduce SLCPs, e.g. methane, black carbon (soot) and hydrofluorocarbons (HFCs), due to tipping-point risks. Since SLCPs have a shorter lifespan than CO2, and emission reductions of this kind can have a short-term climate effect, they argued: "This is essential for achieving the Paris Agreement's temperature goals and reduces the risk of crossing irreversible climate tipping points in the Arctic, which will have major global consequences." (Norwegian Government Prop 1 S., 2024, p. 181).

Although many nations have enacted laws and policies advancing decarbonization to meet global climate goals, no existing national efforts are devoted specifically to preventing major tipping point events (Global Tipping Points Report 2023). The novel threats and risks from ESTPs warrant more urgent and robust implementation of existing national climate change mitigation laws and policies, as successful decarbonization is critical to their prevention. This alone, however, does not provide for direct governance of the prospect of crossing near-term tipping points (Box 1.2.4).

Intentional and specific integration of ESTP governance into national policies is needed, including the support of coordinated monitoring systems and a commitment to accelerating decarbonization. This is crucial to reducing the potential for crossing tipping points, even if emissions reduction goals are being met. While efforts to reform existing laws and enact new national and international laws are to be pursued (Box 1.2.4), **given the urgency, ESTP-informed interpretations of existing laws should be leveraged to implement such measures immediately;** see Garmestani et al. (2019) and Maxwell et al., (2021) for examples.

Box 1.2.4: The potential of rights of nature approaches to prevent ESTPs

Under international law, states have committed to take effective measures to address climate change, preventing and reducing greenhouse gas emissions to limit global temperature rise in line with the best available science and pursuing climate justice (ICJ, 2025). These obligations have several legal foundations, including the Paris Agreement, the UN Convention on the Law of the Sea (ITLOS, 2024), human rights stipulations (IACHR, 2025), and the principles of international law. These obligations could be interpreted to also include the prevention of ESTPs (Ritz, 2024), which constitute 'dangerous anthropogenic interference with the climate system' according to the UNFCCC (Lenton, 2011).

However, the current system of international law lacks effective enforcement mechanisms and has thus far proven ineffective in shaping states' behavior to address climate change. Given these failures, arguments for a reform of international law have been developed based on a recognition of Earth system functioning (e.g. du Toit & Kotzé, 2022; Hall, 2023).

Constructing a global legal system built on science-based Earth systems thinking, combined with learning from diverse Indigenous laws (García Ruales, 2024; RiverOfLife et al., 2020; Tănăsescu, 2020), offers new opportunities to protect Earth system tipping elements, such as forests, ice sheets, coral reefs, or ocean currents - for example, by recognizing them as legal entities with inherent rights. Rights of nature approaches (Borràs-Pentinat, 2025) have already been adopted in jurisdictions like Bolivia, Ecuador, Aotearoa/New Zealand, Spain, and India, often as a result of Indigenous advocacy efforts (O'Donnell et al., 2020; Corrigan & Oksanen, 2021) and they can focus on specific entities, such as rivers, mountains, or glaciers. Many of the legal approaches adopted include participatory elements, whereby local human guardians or councils are appointed to speak for the ecosystem and represent it in court (Chapron et al., 2019; O'Donnell & Talbot-Jones, 2018).

The traction that rights of nature are now gaining across the globe is evident in the prominence accorded to them as a necessary corollary to recent environmental human rights developments in the submissions of all five of the UN's regional groupings to the Stockholm+50 summit (Morrow, 2025). However, we acknowledge that rights provisions alone can be symbolic and ineffective unless paired with clear state duties, standing rules, remedies, monitoring and finance (Corrigan & Oksanen, 2021), and representation can be achieved without conferring legal personhood (Chapron et al., 2019; O'Donnell & Talbot-Jones, 2018).

Whilst ambitious and complex, recognising the rights of Earth system tipping elements to persist as they have done in Holocene conditions could both increase the inclusion of Indigenous and local knowledge, and create accountability mechanisms in international law - both key factors in transformations towards sustainability and justice (IPBES, 2024) and in efficacious responses on the ground. This could contribute to the prevention of tipping points especially for tipping elements that are not exclusively climate driven, but also have local and regional-scale drivers. For example, Amazon Indigenous peoples, whose stewardship is vital for safeguarding the stability of the Amazon rainforest (Science Panel for the Amazon, 2021), could cooperate to become the legal representatives of the forest, which could strengthen drastically needed forest protection and limit tipping risks (Borràs-Pentinat, 2025; Flores et al., 2024; Edling Müller, 2025). Whilst these measures are not a panacea, an international legal system with effective access to justice for Earth system tipping elements could have similar governance effects to those of the global climate litigation movement (Setzer & Higham, 2025): it could provide additional legal pathways to address climate policy failure or insufficiency, although substantial progress would be required before this could be operationalised.

Other relevant international governance

ESTPs need to be integrated into existing international governance frameworks, such as those for oceans and biodiversity. Although many ESTPs are directly linked to these domains (e.g. Amazon rainforest or coral reef dieback to biodiversity loss; AMOC to ocean governance), coordinated governance and supporting research remain limited. Strengthening these connections is essential, and emerging frameworks such as the planetary commons (Rockström et al., 2024) may provide a basis for more effective coordination.

Box 1.2.5: International Governance Opportunities to Prevent AMOC Tipping

The first and foremost prevention measure for AMOC is climate mitigation, with the aim to minimise magnitude and duration of possible temperature overshoot beyond 1.5°C. The mechanisms of the Paris Agreement can be used to consider safe mitigation pathways. Parties can include AMOC risks and relevant mitigation and action plans in future Nationally Determined Contributions (NDCs) and Biannual Transparency Reports (BTRs), and include an assessment of collective progress towards AMOC collapse prevention in future Global Stocktakes.

The acceleration of global mitigation action must be combined with the rapid development and scaling of sustainable carbon removal capacities, which could be fostered by minilateral diplomacy or transnational initiatives. There are some indications that Solar Radiation Modification (SRM) as a secondary intervention could reduce the AMOC tipping probability under certain conditions, but would require reliable international governance structures itself (Futerman et al., 2025).

It is uncertain whether AMOC tipping could be reliably detected in advance. Due to high internal variability, decades of observations may be needed to detect trends (Lobelle et al., 2020), hence consistent funding of ongoing (deep sea) observations and additional observations in the relatively under-monitored South Atlantic are vital (Chidichimo et al., 2023). It may be possible to construct early-warning signals from the behaviour of AMOC variability (Van Westen et al., 2024). Such signals may come too late to trigger prevention measures, especially since mitigation is a long-term process, but they may help adaptation (Chapter 1.3).

Box 1.2.6: International Governance Opportunities to Prevent Amazon Forest Tipping

There are opportunities for the UNFCCC, alongside global biodiversity governance (e.g. Convention on Biological Diversity, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services), to provide a context for preventive governance measures regarding the Amazon rainforest. The Paris Agreement's ambition cycle (Nationally Determined Contributions, Global Stocktakes, transparency and support mechanisms) can be deployed to minimise the magnitude and duration of any temperature overshoot (Wunderling et al., 2023). Future Nationally Determined Contribution (NDC) revisions, not only from Amazonian nations, should specifically consider the risk of Amazon forest die-back and to what extent national mitigation plans, policies and decarbonisation strategies contribute to its prevention. The Global Stocktake provides a platform for an assessment of collective progress in prevention efforts, i.e. to what extent tipping risks driven by global temperature increase are minimized. International efforts should continually monitor the risk to the Amazon, e.g. using satellite data to detect early warning signs of tipping (Boulton et al 2022).

Slowing deforestation and degradation requires strong governance efforts outside the international climate change regime. **We need net-zero forest loss on the remains of the Amazon forest, combined with restoring at least 5% of the biome** (Flores et al, 2024). Strengthening the forest stewardship of Indigenous peoples and local communities is critical to preventing both deforestation, degradation and carbon emissions from the Amazon (Walker et al., 2020). Indigenous peoples, local communities and their vital knowledge are crucial to conservation, restoration and sustainable forest use, whilst regionally connected governance strategies should be designed with their participation (Science Panel for the Amazon, 2021). Containing a large proportion of the Amazon forest, governance within Brazil is particularly important. Approximately 60% of the Amazon forest is in Brazil, and water from Brazilian forests is recycled by the forest and provided to the western parts of the Amazon forest (Flores et al, 2024). For example, Brazil's Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) has a crucial role in limiting deforestation rates (Global Tipping Points Report 2023). This will require regional governance structures, such as the Amazon Cooperation Treaty Organization, to avoid the displacement of deforestation from one region in Brazil to another, or to another Amazonian country (e.g. using The Great Green Wall as a guidance framework). International funds will be required to support these sub-national, national, and regional efforts (e.g. the Amazon Fund supports local community, NGO and governmental initiatives in promoting sustainable development). Considering the fragmented and anthropocentric nature of current Amazon governance, the region needs transformative governance structures, such as the establishment of an Andes–Amazon–Atlantic Corridor, where ecologically and socioculturally connected forest areas are conserved in line with Indigenous, local and scientific knowledge (Pereira & Terrenas, 2022; Beveridge et al., 2024).

Carbon dioxide removal governance

Rapid emission reductions have to be complemented with the immediate scaling up of sustainable carbon dioxide removal (CDR) capacities. **There is no way to limit overshoot and permanently reduce global temperature - which is vital to minimise the risk of ESTPs - without CDR and sequestration/utilisation technologies that reach net negative emissions at a global scale**. As such, CDR technologies are now an inevitable part of all strategies to minimise ESTP risks, although governance efforts may only subtly differ from wider climate mitigation activities (Box 1.2.7, Mace et al, 2021). However, **CDR should not become a tool to deal with or justify additional future emissions, but the excess already in the atmosphere.** This excess far exceeds current CDR capacities and CDR is not costless in economic or ecosystem terms (Smith et al., 2023).

CDR approaches are at varying levels of readiness. Mature and scalable approaches include nature-based solutions such as forestation and soil carbon sequestration (Griscom et al., 2017; Bossio et al., 2020). In addition, pilot projects of bioenergy (e.g. biomass waste) with carbon capture and storage show promise (Fuss et al., 2018). By contrast, operation plants performing direct air capture work and trials using enhanced weathering show promise, but are currently economically unfeasible on large scales (Realmonte et al., 2019; Beerling et al., 2020). **A collective effort to develop and scale CDR with government funding is needed, but should not reduce decarbonization efforts**. This would benefit from a cooperative international - possibly minilateral - approach, pooling investments in research and development, developing required infrastructure, and creating the framework conditions for sustained long-term private investment and sector expansion. A new transnational initiative including governments, private sector actors, science, NGOs and the financial industry might be a suitable platform for these activities.

Box 1.2.7: Reforestation in the Amazon as a form of carbon dioxide removal

Forestation could prevent an Amazon forest tipping point whilst also increasing resilience, with a target of restoring at least 5% of the biome recommended (Flores et al, 2024). Within only a few decades (Poorter et al., 2021), forest conservation and reforestation (e.g. through improved land rights for Indigenous peoples, promoting agroforestry, and improved governance) could: i) restore diversity and redundancy in a system (e.g. species diversity), ii) maintain moisture-recycling feedbacks, iii) improve local drought resilience, and iv) reduce non-climate stressors (Table 1.2.1). By planting the right trees in the right places or ringfencing key areas to allow for natural regeneration, there is potential for reforestation to trigger a positive tipping point through climate and ecological feedbacks that trigger enhanced natural regeneration that then surpasses the active reforestation efforts (Figure 1.2.3). Thus, future reforestation efforts should be focussed on the spatial locations and ecological processes most likely to maintain and enhance important moisture and regeneration feedback loops (Figure 1.2.3).

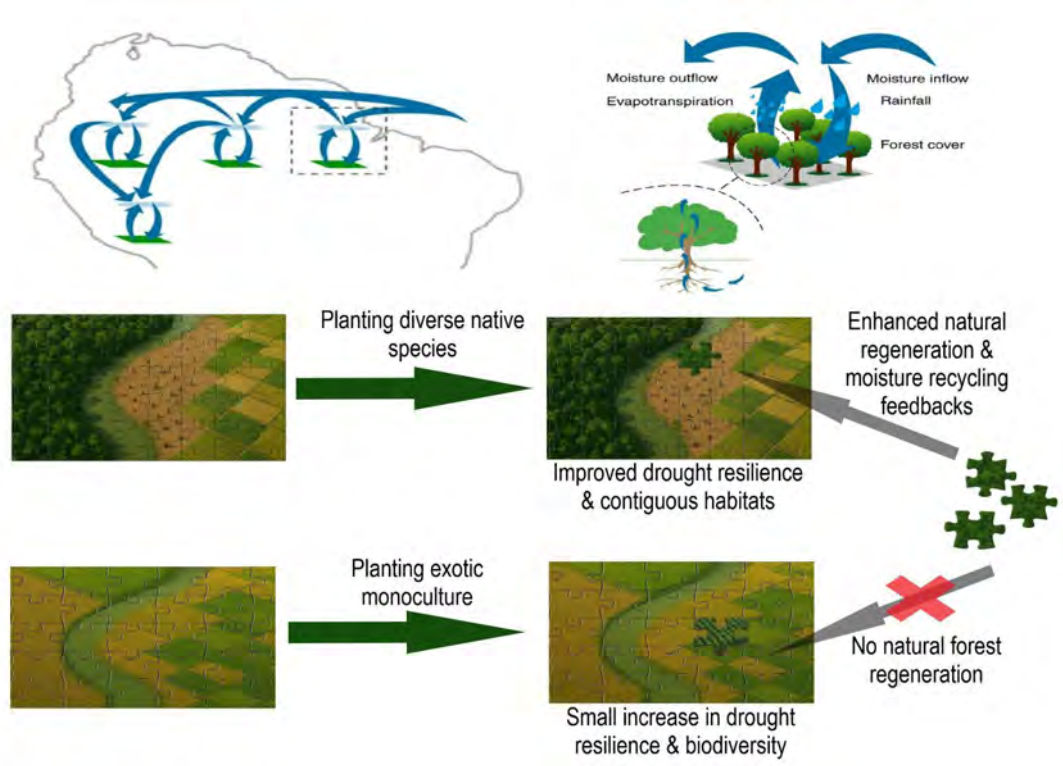


Figure 1.2.3: The location and type of reforestation efforts are important for triggering potential positive tipping points to increase the resilience of the Amazonian forest. Whilst exotic plantations can reduce pressure on natural forest, planting native species in key locations can enhance natural regeneration and moisture recycling feedbacks and increase the resilience of existing forests (Zemp et al 2017).

Solar radiation modification governance

Geoengineering methods, particularly Solar Radiation Modification (SRM; National Academies of Sciences, Engineering, and Medicine., 2021), may reduce climate drivers for some tipping points but have uncertain effects on others and pose significant physical and political risks. The term SRM includes a number of approaches: Stratospheric Aerosol Injection (SAI) places reflective particles in the stratosphere and is inherently global, Marine Cloud Brightening (MCB) uses sea water or other aerosols to enhance cloud reflectivity and has more local impacts (with long-distance teleconnections), Cirrus Cloud Thinning (CCT) thins higher clouds to allow more energy to escape into space. In some cases, the term also includes efforts to change the earth's reflectivity (albedo) by maintaining sea ice, shifting to lighter crops, and/or lighter surfaces. None of these are alternatives to mitigation and adaptation but, at best, temporary additional measures. SAI could reduce global warming, a key driver for tipping points like ice sheets and ocean currents, but its effects are uncertain for others (e.g. the Amazon) and may exacerbate risks such as ocean acidification and monsoon drying (Irvine et al., 2019; Futerman et al., 2025; Hirasawa et al., 2023; Asutosh et al., 2025). Widespread use of MCB could also affect global mean temperature, and with significant effects on precipitation. SRM itself, particularly SAI, carries severe risks, including unintended side effects, the possibility of abrupt termination, political challenges (such as the need for unilateral action) and creating a distraction from mitigation (Felgenhauer et al., 2022).

No geoengineering technology is currently available for deployment on scales that would affect global average temperature. Using SRM as an emergency response when tipping is imminent is risky, as detecting tipping points in time may be impossible (Lenton 2018). A gradual, preventative approach could allow testing and adjustments, but robust **SRM governance mechanisms must be in place first** (Biermann et al., 2022; Gupta et al., 2024).

As SAI or large-scale use of MCB would have global effects, its governance must be international. No comprehensive framework currently exists. Some international agreements, such as the Convention on Biological Diversity and the London Convention on ocean dumping, have been applied to different forms of geoengineering, but their scope is limited. The UN General Assembly's 2021 resolution (UNGA A/Res/76/112) addresses atmospheric modification, requiring environmental impact assessments. The Montreal Protocol addresses activities that affect stratospheric ozone, which SAI would. Other governance mechanisms, including the Vienna Convention and UNFCCC, have been proposed. Reports from COMEST (2023), the UN Human Rights Council (A/HRC/54/47), UNEP (2023), and the Climate Overshoot Commission highlight ethical and human rights concerns but also advocate cautious SRM exploration. In December 2024, the EU's Group of Chief Scientific Advisors called for a multilateral treaty on SRM governance, including a non-use agreement, a moratorium on large-scale deployment, monitoring of undeclared SRM activities, but also rigorous, ethical research (European Commission, 2024).

National policies remain fragmented. For example, the US has some SRM research guidelines, while Mexico bans outdoor experiments. In August 2024, opposition from Indigenous leaders and environmental advocates led to the cancellation of the SCoPEx outdoor experiment in Sweden, underscoring SRM's governance and ethical challenges.

We recommend a moratorium on SRM deployment and large-scale experiments, alongside international efforts to assess SRM's benefits and risks. The London Protocol, which bans large-scale ocean iron fertilization but allows regulated small-scale experiments, may serve as a model. **SRM research should be transparent, inclusive, and build capacity in the Global South to ensure informed participation.** Much of the current understanding of SRM and its potential impacts is based on insights from climate models, which vary in the way that they represent key processes in clouds and aerosol-related climate feedbacks and are limited in their ability to represent more complex ecological feedbacks between temperature, precipitation, solar radiation, and levels of CO2 (National Academies of Sciences, Engineering, and Medicine., 2021). The impacts of SRM are also highly dependent on the specific strategies (e.g. for SAI, the injection sites; Bednarz et al., 2025) being used. Some SRM risks will only become apparent after deployment, making responsible governance essential.

An effective governance framework for SRM is a priority, but there are key inter-related rationales for continuing research. The technological barriers to entry for development and deployment of different SRM methods, including SAI, are lower than the current scientific uncertainty about these potential interventions. While a moratorium on deployment is appropriate, ongoing research on SRM is crucial to understand the full range of potential impacts of coordinated use and to anticipate the effects of non-ideal, unilateral, uncoordinated or competitive deployments. SAI deployment in particular would have global physical effects. There is a risk that a climate emergency framing, including those that leverage the risk of ESTPs such as AMOC collapse, may drive non-ideal development and deployment as an 'emergency' response. Geopolitical uncertainty and competition may also contribute to a competitive race to develop and deploy SRM (Nielsen 2025). Additional research to explore potential effects of non-ideal SRM interventions may help anticipate physical risks of both scenarios.

Box 1.2.8: AMOC, the Amazon and the SRM dilemma

Limited modelling evidence suggests that global or northern-hemisphere Solar Radiation Management (SRM) may reduce AMOC weakening by surface cooling and reducing meltwater influx (Tilmes et al., 2020, Fasullo et al., 2018, Xie et al., 2022, Pflüger et al., 2024, Bednarz et al., 2025). Hence, it would probably reduce tipping risk (Futerman et al 2025; Figure 1.2.1). Other geoengineering technologies could also possibly contribute to AMOC and SPG tipping prevention, e.g. Marine Cloud Brightening (MCB; Hirasawa et al., 2023).

When viewed in isolation, the threat of AMOC collapse could motivate SRM deployment, either preventatively to reduce tipping drivers, or as an "emergency brake" if tipping seems imminent. The latter approach is particularly risky, since it is unclear whether AMOC tipping could be detected in time for SRM to be effective (Lenton 2018). If SRM were used to cool the globe while an already-weakened AMOC fails to recover, the North Atlantic region could be severely over-cooled (Pflüger et al, 2024, Schwinger et al 2022). However, SRM may be less effective, and potentially counterproductive, for the Amazon rainforest (below) and, as outlined above, SRM carries massive political risks. **Any potential decision on SRM should be driven by a holistic, systemic consideration of its risks and benefits, not its presumed efficacy for one particular tipping element.**

However, we caution against Solar Radiation Management (SRM) as the impact it may have on the Amazon is likely to be complex (i.e. reduced transpiration but also reduced growth and carbon absorption) and is poorly understood (Futerman et al, 2025). For coral reefs, SRM may reduce the primary driver of ocean warming, but might slightly increase the secondary driver of ocean acidification, although the impact on aragonite saturation, the key variable of interest, may be limited (Futerman et al 2025). Finally, Futerman et al. (2025) list some tipping points for which the effect of SAI is simply unknown due to absence of research; for these, negative (or positive) effects cannot be excluded. **The potential impact of any SRM on all ESTPs must be debated prior to the establishment of SRM actions by or within any nation**.

1.2.3 The role of the finance sector in preventing ESTPs

In order to support the above prevention strategies, a number of wider transformations across a variety of sectors are needed. We highlight the crucial role of finance in this context.

The finance sector has a critical role in the governance of ESTPs, given the influence that financing multinationals and other companies has on their activities, including those activities that increase tipping risks as a result of greenhouse gas emissions and environmental degradation (Box 1.2.9). **A broad suite of globally coordinated policy measures across fiscal, financial, industrial, and environmental policy areas is likely needed to shift global financial flows away from such harmful activities, to better prevent ESTPs** (Ameli et al., 2025, Kedward et al., 2023).

1.2.3.1 The problem of finance with respect to Earth systems

Financial efforts to mobilize 'green' investment have been inadequate to date. While having grown steadily over the last decade, current volumes of climate mitigation finance are still far below what is needed, and have to increase at least sixfold in the next 10 years to be aligned with a net-zero pathway (CPI, 2024; UNEP, 2024). Similarly, 'nature-positive' financial flows are nowhere near sufficient to fill the biodiversity conservation and restoration financing gaps (Gonon et al., 2024, CBD, 2025). From the perspective of mainstream finance's shortsightedness, it is still more financially profitable to destabilize the Earth system than to protect it, preventing any significant redirection of financial flows (Kotzé & Adelman, 2022). 'Environmental, Social and Governance investing', despite two decades of progress, has not achieved mainstream adoption and has had no discernible impact on this issue. Moreover, dedicated market-based mechanisms such as voluntary carbon markets and biodiversity offsets have also failed to catalyze meaningful action. They often suffer from poor quality, lack of integrity, and narrow scope, typically focusing on a single environmental output, such as immediate carbon sequestration, without addressing broader systemic risks on a longer time horizon. This has created a false sense of progress while allowing business-as-usual finance to continue contributing to nature degradation.

Finally, the most substantial progress has certainly been made in the area of financial risk management: since 2015 (e.g. Carney, 2015) the financial sector repeatedly acknowledged that it cannot be immune to the materialisation of climate change and biodiversity loss on its own activities, via direct and indirect impacts on, e.g., risk of default and degraded performance of financial assets. Hence, it should be in its 'rational economic interest' to fight against these and stop fueling deleterious economic activities (cf. Box 1.2.9), to avoid monetary value destruction and propagation towards a whole financial system destabilisation. Unfortunately, while indeed awareness and knowledge on climate- (and biodiversity-) related financial risks have progressed considerably over the past decade, this has not yet been sufficient to reverse the financial sector's harmful trajectory (NGFS, 2024).

1.2.3.2 Possible fixes - extending the financial risk approach

Because risk analysis underpins nearly all decision-making in the finance sector, incorporating tipping elements into assessments of climate- and biodiversity-related asset risks is a natural next step to better connect finance with Earth system stability (Kotzé & Adelman, 2023). Central banks and supervisory authorities have begun exploring the implications of environmental change for financial stability, but these efforts remain narrowly framed (Box 1.3.3). Scenario exercises still concentrate on median climate trajectories, with little attention to systemic disruptions such as tipping points (FSB, 2025). Likewise, financial risks arising from the deep dependencies of economic activities on ecosystem services remain largely absent from current models (Hadji-Lazaro et al., 2024). To address this gap, financial risk governance must move beyond marginal or isolated changes and take seriously the possibility of ESTPs. Only then will risk frameworks reflect the true scale of ecological risks and support precautionary, forward-looking financial governance (Trust et al., 2025).

However, even if the calculation of such financial risk figures eventually becomes achievable, it would not automatically translate into financial decisions that would contribute to preventing breaches of ESTPs. Indeed, a risk estimate deemed insufficiently material would not trigger much change. However, even if this were the case, it could lead to a risk management decision based on hedging or diversifying the risk, without implying a reduction in the source of the risk, i.e. without seeking to prevent the tipping point from being breached. Moreover, risk aversion is not everything: in an anticipatory move to avoid financial assets exposed to ESTPs, shifted financial flows may also divert away from essential economic activities, which would result in negative impacts (e.g. harming food security) even before ESTPs materialise.

Therefore, the fundamental limitations of financial risk approaches motivate an explicit proactive stance, involving precautionary actions to prevent the risk upfront, rather than merely managing it after occurrence (Chenet et al., 2021, 2022; Kedward et al. 2023; Marsden et al. 2024).

Recognising such an endogenous role of the financial system in the construction of environment-related financial risk is a critical step (Kreibiehl et al., 2022), as it positions finance not as a neutral intermediary but as a structurally embedded force whose reorientation is necessary to support ecological sustainability – an imperative that also reinforces the long-term resilience of the financial system itself.

Box 1.2.9: The impact of the finance sector on ESTPs

Banks financing the fossil fuel industry (and investors investing in it, as insurers insuring it or financial services providers working with it) directly contribute to increasing the supply of oil, gas, or coal, and thereby, the concentration of greenhouse gases in the atmosphere, which is the first-factor precipitating climate tipping points such as the collapses of the West Antarctic Ice Sheet or Atlantic Meridional Overturning Circulation (AMOC).

As well as financing leading to rising greenhouse gases, deforestation in the Amazon is driven by financial investments in agrifood industries, which accelerates forest dieback, undermining carbon and water cycle regulation and leading to widespread economic losses along the value chain and across sectors reliant on these services (Marsden et al., 2024).

1.2.3.3 Possible fixes - beyond the financial risk approach: finance as a tool for positive tipping

The financial system is, in fact, not just a neutral optimisation tool for capital allocation but an active driver of ecosystem destabilisation through their role in shaping incentives, norms, and governance structures (Galaz et al., 2018; Crona et al., 2021). This calls for deliberately and urgently steering the financial system toward serving clearly defined socioeconomic and ecological purposes, chief among them, the urgent need to prevent ESTPs. Such a reorientation requires reconfiguring financial incentives, governance frameworks, and regulatory mandates to ensure that capital allocation supports a just transition and economic activities that maintain ecological stability, rather than perpetuating short-term, profit-driven degradation.

For this, it is indispensable to integrate the multiple relational, intrinsic and instrumental values of ecosystem services (IPBES, 2022) into financial decision-making, through different types of indicators (biophysical, sociocultural, monetary), i.e. not only through prices. Ecosystems do not just store carbon, but also provide water regulation, pollination, disease buffering, cultural value, and much more. The values of the multiple ecosystem services can no longer be ignored. Properly valuing these services, including their role in systemic resilience, is essential. Biodiversity must indeed be recognised not only for its intrinsic value but as a form of 'natural insurance' for our socioeconomic systems. Diverse ecosystems are more resilient to shocks, better able to maintain function, and more likely to buffer societies and economies from systemic breakdowns (Loreau et al., 2021). Eroding biodiversity thus increases long-term financial risk, a dynamic not yet reflected in credit ratings, insurance models, or asset pricing. Without such a macro-ecological systemic approach to finance, investments in so-called 'green assets' may continue to overlook the functional complexity of ecological systems, and continue to stress them towards fatal levels, resulting in tipping points.

Thus, the finance sector's role in preventing or delaying tipping points is central to governance efforts. Preventing ESTPs "for real" will require vastly increased investment compared to current commitments, which are completely insufficient to achieve a net-zero emission reduction trajectory with low-temperature overshoot, nor to fill the climate adaptation or biodiversity conservation and restoration financing gaps (Möller et al., 2024; UNEP, 2024; Gonon et al., 2024, CBD, 2025). **Doing so needs massive redirection of finance from emissions-increasing and ecosystem-degrading activities, such as investment in fossil fuels and deforestation-linked agroindustry, towards low-carbon investment, adaptation and ecosystem resilience and regeneration** (Eker et al., 2023; Kreibiehl et al., 2022, Kedward et al., 2023).

Yet, finance can only flow at scale if structural reforms are introduced, including the enforcement of ESTP boundaries as financial thresholds in, for example, credit allocation and pension holdings, the integration of long-term environmental risk into macroprudential rules, and the prioritisation of public finance to de-risk early-stage, regenerative investments. As finance is only a propellant for the ecological transition, it is crucial that genuine coordination occurs between monetary, fiscal, industrial, and environmental authorities.

Thus, the financial system requires a change of governing paradigm to deliver an economy of sustainability. For this, the whole incentive mechanism within the financial system must be inverted: it cannot be profitable anymore to destroy ecosystems and precipitate ESTPs. Finance must instead be seen as an instrument to trigger systemic socioeconomic changes towards decarbonisation and nature regeneration, and hence towards long-term prosperity: finance as a '**positive tipping**' catalyst (Section 3).

Simultaneously recognising this shaping role that finance has on the economy and accounting for ESTPs and potential cascades in financial risk analysis will illuminate the scale of risks for both the biosphere and the socioeconomic sphere, justifying core regulatory intervention able to integrate the real values of nature into financial operations. Such a change is necessary to drive more concerted action to shift financial flows away from the root problem (activities causing ESTPs) and towards the potential solution (activities preventing ESTPs and contributing to building a resilient socioeconomic and financial system). This highlights the importance of coordinated, systems-level regulation that supports just transitions, acknowledges the financial system's role in actively shaping and amplifying ecological degradation/regeneration, and prioritises long-term stability over short-term optimisation.

1.2.4 Conclusions

For most ESTPs, rising global temperatures are a primary driver, making accelerated climate change mitigation essential to prevention. A coordinated, urgent effort is needed to rapidly phase out greenhouse gas emissions. Reducing the risk of crossing tipping points requires minimising both peak warming and the duration of any temperature overshoot, while striving to return global temperatures to or below 1.5°C. This necessitates strengthening the 1.5°C goal within the Paris Agreement and integrating ESTP-specific considerations, such as assessing how national and collective actions have mitigated tipping point risks, into the Global Stocktake.

Limiting temperature overshoot—and thereby reducing the risk of ESTPs—is impossible without carbon dioxide removal (CDR) and sequestration technologies that achieve net negative emissions on a global scale. For example, forestation efforts could enhance the Amazon's resilience while also reducing its tipping risk, with at least 5% of the biome recommended for restoration. Governments must invest in the development and scaling of CDR technologies, but not at the expense of immediate decarbonization efforts. We also emphasize the need to prioritize CDR efforts and to target short-lived climate pollutants (SLCPs), as removing these gases can yield rapid global cooling effects.

Geoengineering, particularly Solar Radiation Modification (SRM), may help reduce climate drivers for some tipping points but carries uncertain consequences for others and poses significant physical and political risks. SRM can only ever be a supplementary measure—it cannot replace climate mitigation and adaptation. We recommend a moratorium on its deployment and large-scale experiments, alongside rigorous international research to assess both its risks and potential benefits.

The financial sector, in particular, plays a key role in governing tipping points. Through its influence in shaping economic dynamics, it is an active driver of ecosystem destabilisation, but it is also reciprocally exposed to ESTPs. Thus, accounting for ESTPs cascading risks in financial analysis has the potential to reveal the scale of potential economic consequences – thereby justifying to "change the rules" so that financial markets can play their role in driving the redirection of capital away from harmful activities and toward those that prevent breaching ESTPs. Achieving this requires a broad suite of globally coordinated policy measures across fiscal, financial, industrial, and environmental domains to catalyse a systemic paradigm shift that embeds the real values of ecosystems into financial decision-making.

There is an urgent need to connect different risk assessment frameworks to develop multi-scale prevention strategies for specific tipping processes. Scientists, policymakers, and practitioners must collaborate to assess risks, manage trade-offs, and identify synergies between existing governance and actions to prevent ESTPs across time horizons (Table 1.2.2).

Table 1.2.2: Short- and medium-term ESTPs prevention governance measures

Time horizon	Priority actions
Short-term (0–5 years)	• Include ESTP risks in the 2nd Global Stocktake (2028), 3rd round of NDCs (2030), and national climate, biodiversity policies • Rapid phase-out of methane, black carbon, and other SLCPs • Accelerate CDR development through a new minilateral or transnational initiative and funding • Create monitoring/early-warning systems • Integrate tipping risk into financial risk assessments
Medium-term (5–10 years)	• Embed ESTPs prevention permanently in Paris Agreement's' full ambition cycle • Review and adjust global mitigation pathways to minimize overshoot • Strengthen Indigenous land rights and halt deforestation in Amazon & other critical biomes • Scale CDR capacities • Strengthen cross-scale governance • Reform financial flows • Build systemic resilience in agriculture, forestry, and fisheries to reduce non-climate stressors • Take measures to prevent unwanted SRM deployment while building governance mechanisms and assessing SRM potential benefits and risks

1.3 Impact governance for Earth system tipping points

Authors: Ben Hudson, Manjana Milkoreit, Carlo Aall, Hugues Chenet, Frank Dentener, Ajay Gambhir, Ahjond Garmestani, Sirkku Juhola, Claire Mellier, Silvia Montagnani, Malcolm Rogge, Rosa Roman Cuesta, J.B. Ruhl, Ashwin K. Seshadri, Viktoria Spaiser, Johnny Stormonth-Darling, Bregje van der Bolt, Sebastian Villasante, Tabby Watson, Simon Willcock

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Key Messages

- **Societies need governance efforts that anticipate and prepare for the specific impacts of Earth system tipping points before tipping points are crossed – these impacts differ from the observed and expected impacts of climate change.**
- **Governments should assess and reduce vulnerability to the impacts of Earth system tipping processes, build resilience, and include tipping impacts in climate adaptation policy and planning and related policy domains.**
- **Governments, intergovernmental organisations, economic and financial actors should integrate Earth system tipping points into risk assessments across scales.**
- **Justice – intragenerational, intergenerational and interspecies – must be at the centre of Earth system tipping point impact governance.**

As global temperatures approach 1.5°C, with the prospect of inevitable overshoot, crossing Earth system tipping points (ESTPs) is a plausible near-term reality. While prevention must remain a priority (see Chapter 1.2), societies must also be prepared to deal with the consequences of tipping points that may no longer be avoidable, such as widespread dieback of tropical coral reefs. This chapter addresses that emerging need: how to govern the wide-ranging and potentially irreversible impacts of crossing ESTPs, including disruptions of food systems, human health impacts, damage to critical physical infrastructure, changes in water availability, displacement of populations, and the destabilisation of economies and political systems. These effects have implications for the full spectrum of the sustainable development and human security agenda (IPBES, 2024).

As outlined in Chapter 1.1 (Table 1.1.1), tipping processes unfold in ways that differ from expected climatic changes and defy conventional policy planning — they are nonlinear, often abrupt and irreversible, and characterised by cascading effects across systems. The probabilities of tipping, details of the specific location of tipping points, pace of change, and precise distribution of impacts are often highly uncertain; however, this does not mean that such impacts are unlikely to occur. Table 1.3.1 illuminates the specific implications of these challenges for impact governance.

Table 1.3.1: Tipping process characteristics and their implications for impact governance

Tipping Process Characteristic	Implications for impact governance	Warm-water coral reefs	AMOC
Thresholds (moments of commitment and irreversibility)	Once a tipping point is crossed, a return to the prior state may no longer be possible. Governance must then shift from prevention to managing the post-tipping reorganisation.	Once thermal thresholds are crossed, there are limited prospects for restoration or recovery; adaptation must focus on alternative livelihoods.	AMOC collapse commits Europe and parts of Africa and the Americas to long-term regional climate disruption; governance must plan for persistent change.
Acceleration of change	Rapid changes reduce lead time for response and strain institutional capacities. Governance must be anticipatory, flexible, and early warning enabled.	Coral degradation can move from gradual stress to collapse within years.	Once initiated, AMOC weakening may rapidly disrupt temperature and precipitation patterns across continents.
Increased magnitude of impacts	Impacts may exceed adaptive capacity or lead to adaptation tipping points, requiring switches in adaptation strategy. Governance must include contingency planning, emergency preparedness, and systemic adaptation strategies.	Slow decline (bleaching and recovery) and partial loss vs. complete loss; adaptation to declining subsistence on fish or coral-related tourism might need to switch towards alternative forms of economic activity and potential migration.	Increased sea-level rise may render current adaptive solutions, e.g. seawalls, ineffective, therefore demanding migration from affected areas or planned relocation of communities and infrastructure.
Trend reversals	Earth system tipping could lead to trend reversals (e.g. cooling rather than warming in some regions), which may invalidate current adaptation pathways or make them maladaptive. Governance must identify and implement no-regrets strategies that are robust to trend changes (e.g. better insulated buildings and less energy reliance for both heating and cooling).	Not applicable.	AMOC weakening could cool parts of Europe and the North Atlantic, reversing regional warming trends and invalidating warming-based adaptation plans.
Different distribution of impacts	Tipping points produce uneven and shifting risk profiles and can alter geopolitical power relations. Governance must assess who is newly exposed and ensure equitable and just support.	Coral-dependent communities in the tropics are disproportionately affected, but also the tourism industries and economies of countries across the Pacific (including Australia) and the Caribbean.	Northern and Western Europe, West Africa, and parts of North and South America would be differentially impacted by disrupted rainfall and temperature patterns. AMOC tipping would disproportionately impact a specific group of geopolitical allies (UK, US and Western Europe).
Novel impacts	Governance must be open to emerging, poorly understood challenges. Monitoring across many systems and impacts, adaptive learning systems, participatory planning, and innovation capacity are key.	Unidentified.	An abrupt AMOC collapse may disrupt jet stream dynamics and create a southward shift in the intertropical rain belt; it could trigger food instability at a scale not seen in modern times.
Cascade effects	The risk of cascading impacts across systems will require systemic governance that can address multiple challenges across multiple systems simultaneously, and directly intervene to dampen or break amplifying feedbacks. There is a risk of derailment, giving rise to concerns about whether governance can adequately manage the cascade of consequences while also pursuing mitigation priorities within the limits of finite resources.	Coral collapse may destabilise broader marine food webs, reduce fish catch, decrease food security and income, disrupt coastal economies, and lead to poverty and migration.	AMOC tipping may affect Amazon rainforest stability, the West African Monsoon, and shift the Intertropical Convergence Zone. This could make some regions, including densely populated ones, less liveable, leading to poverty, migration, political tensions and conflicts.

The aim of impact governance is to address these distinct challenges through policies, institutions, and coordinated actions that: reduce harm; protect communities, ecosystems, and societies; enable effective adaptation; and foster resilience and stability in the face of large-scale and systemic disruptions caused by tipping dynamics in the Earth system.

Box 1.3.1: ESTP impact governance objectives

Minimising harm from tipping processes by:

- Developing anticipatory capacities
- Monitoring and learning about Earth system changes and human impacts
- Fostering resilience, adaptation and preparedness
- Managing transformations towards sustainability and equity
- Managing impact cascades

ESTP impact governance must be capable of addressing the interconnected and often unpredictable nature of these challenges through collaborative decision-making and multi-level cooperation. It requires multi-level governance systems that connect institutions and processes at the international, national and sub-national levels. Appropriate responsibilities need to be identified and divided across the different levels of governance, facilitating cross-scale linkages and information flow within and across levels (Schweizer and Juhola 2024).

Existing institutions for climate impact governance, such as adaptation and disaster response mechanisms, are not designed for—and are poorly equipped to manage—the systemic, cascading, and cross-scale disruptions triggered by ESTPs (Biesbroek 2025; Dryzek 2016; Young 2021). Meeting these challenges requires a fundamental shift in governance: from managing known risks to navigating deep uncertainty; from short-term crisis response to long-term resilience and justice; and from single- to multi-scale approaches. Institutional change must proceed along three complementary paths: strengthening existing systems to withstand escalating pressures, reforming outdated and inadequate policies and institutional structures, and innovating mechanisms to address novel risks and governance gaps. Only by pursuing this integrated strategy can impact governance meet the demands of a future shaped by irreversible Earth system transformations. Pursuing this integrated strategy requires acknowledging that, as much as there is no relevant historical analogue for the future impacts of tipping points on human society (and on other species), there is also no analogue for the governance systems needed to effectively and equitably manage them. Norms and principles inherent in today's conceptions of governance may need to be revisited, recalibrated, or entirely transformed in an ongoing undertaking of adaptive governance.

While the need for impact governance is increasingly urgent, many facets of ESTP impacts are not yet well understood. Consequently, there is a pressing need for knowledge generation regarding the social, economic, political and cultural impacts of different tipping systems, which can inform systematic risk assessment and decision-making. While these knowledge gaps persist and shrink with expanding scientific efforts over the coming years and decades, governance efforts need to advance with the help of anticipatory approaches and tools that can effectively bridge the state of science - what we do know - and the need for action (Wood et al. 2023).

This Chapter tackles these issues by providing an actionable multi-phase framework (1.3.1) and assessing current progress across five key tasks of impact governance (1.3.2), then turning to the urgent challenge of tipping point risk assessment (1.3.3) and the need for justice in ESTP impact governance (1.3.4), before concluding (1.3.5).

1.3.1 A multi-phase impact governance framework

To support effective ESTP impact governance, we draw on a multi-phase framework (Milkoreit et al. 2024) that aligns governance objectives with the evolving dynamics of tipping processes by differentiating three phases of a tipping process: pre-tipping, reorganisation and stabilisation (see Figure 1.3.1). Here we focus on pre-tipping and reorganisation.

Before the tipping point: Anticipation and preparedness

For most known tipping elements, the world is currently in the pre-tipping phase. Impact governance must begin in this phase and not wait for confirmed tipping. Action should not be delayed in the hope that prevention measures will be successful. Tasks and activities in the pre-tipping phase include:

- **Research and learning** about tipping systems and societies' interactions with them to improve the foundations for governance.
- **Monitoring and early warning systems** to detect loss of stability.
- **Risk and vulnerability assessments** to identify exposure hotspots, cascading risk potential, and the distribution of vulnerabilities across space and time.
- **Strengthening existing institutions and capacities** at multiple scales to fortify them against the strain of rapid change and derailment risk.
- **Reforming and integrating existing policies and institutions** for climate adaptation, disaster response, loss and damage, global food security, migration, international financial stability and others in light of expected ESTP impacts.
- **Anticipatory adaptation** to strengthen resilience in vulnerable systems and communities before impacts occur.
- **Governance innovation** through inclusive co-development including greater integration across policy domains (climate, biodiversity, oceans, etc.), and the design of novel institutions and approaches to meet tipping-specific governance needs.

This phase is also the window for integrated planning: linking impact governance, especially adaptation, and prevention efforts, embedding justice into responses, and building institutional capacity for more turbulent futures.

(When) Realising that the tipping point has been crossed

Complex governance challenges arise from the temporal dynamics between ESTP crossings and their societal recognition. Scientific confirmation of a crossing may emerge years or decades after the actual tipping point has been breached and may not manifest as a single, clear signal. In addition to muddled scientific signals over extended time periods, recognising the passing of a tipping point as a social fact poses severe challenges because tipping systems and dynamics are largely invisible to human senses, unfold across vast spatial and temporal scales beyond lived experience, and are likely to encounter political contestation and communication dynamics similar to but more severe than those that have long complicated climate change governance. The current state of the global discourse related to coral reef degradation provides evidence for the challenges in establishing a tipping point as a scientific, social and political fact.

However, once this scientific knowledge becomes accepted social reality, certain actors, particularly from the financial and insurance markets, may respond rapidly to the anticipated future impacts of the tipping process, even when those biophysical changes will unfold over decades or centuries. For instance, assets such as coastal property facing inevitable loss from accelerated sea-level rise could experience immediate repricing based on projected long-term (e.g. 50-year) impacts rather than current or expected near-term (e.g. 10-year) conditions (Hilson and Arnall, 2024, pp861-862). These financial reactions to the awareness of ESTP crossings could unfold much faster than the biophysical impacts themselves, potentially triggering undesirable cascading effects across interconnected social systems including finance, insurance, food trade, local economies, and other critical sectors, creating secondary tipping dynamics that compound the original Earth system disruption. Beyond these rapid responses, impact governance moves into a new phase after the transgression of a tipping point has been recognised.

After the tipping point: Adaptation, crisis response, loss & damage

Once a tipping point is crossed, the system 'shifts gear' and enters a phase of accelerating change towards a new system state. Impacts of the tipping process are continuous and the irreversible reorganisation of the Earth system to a new (e.g. ice-free) state becomes certain. Governance needs to shift towards continuous adaptation and responsiveness to the prolonged reorganisation of the system (e.g. accelerating sea-level rise) with a view to the expected new stable state.

This is a potentially turbulent phase that could continue for decades or centuries until a new stable system state is reached. The failure of preventive and anticipatory action in the pre-tipping phase will have significant costs in this reorganisation phase — economically, socially, and politically. The level of anticipatory investment in capacity before tipping will have some effect on the degree of disruption or process control in this phase (Desmet et al. 2018). Tasks and activities in this phase include:

- **Implementation of policies and active institutions:** Governance instruments continuously respond to impacts through adaptation and with measures to address loss and damage.
- **Adaptive decision-making and learning:** Institutions frequently adapt their goals and measures to the observed changes in affected systems based on iterative learning.
- **Building and maintaining public trust and cohesion:** Transparent, inclusive communication and participatory processes for engagement, learning and empowering communities, ensuring the legitimacy of decisions and fostering social cohesion during prolonged periods of uncertainty and disruption.
- **Crisis response coordination:** Mechanisms to manage crises, such as, extreme weather events and concurrent impacts (e.g. food shortages, migration, supply chain disruptions).
- **Cascading risk containment:** Identifying and interrupting feedback loops that may trigger additional tipping points.



Figure 1.3.1: Multi-phase impact governance for ESTPs. We distinguish the Pre-tipping phase (before the tipping point is reached) and the Reorganisation phase (after the tipping point has been crossed). Each phase has distinct governance implications and time horizons. We identify key tasks for each phase, with justice and equity as a cross-cutting concern.

Cascading dynamics: Anticipating and containing systemic ripples

Tipping points rarely occur in isolation. A destabilisation in one Earth system component can increase the likelihood of tipping events elsewhere, creating what is known as a tipping cascade (Wunderling et al., 2024). For example, the potential collapse of the AMOC could raise the risk of tipping the West African Monsoon (WAM) or accelerating Amazon Rainforest dieback (see chapter 2.2). Such an Earth system tipping cascade can, depending on the speed at which it unfolds, trigger impact cascades across socio-economic systems. For example, a weakened or collapsed AMOC would alter temperature and precipitation patterns, undermining agricultural productivity in vulnerable regions (e.g. Northern Europe), threatening food security and disrupting the agricultural sector. This could be compounded by adverse food-system impacts of changes in the WAM in West Africa and the Amazon (e.g. diminishing atmospheric rivers) in South America. Impaired agricultural production across multiple world regions would have knock-on effects on global food trade, raising prices of staple crops and potentially spreading food insecurity to regions otherwise unexposed to the direct and cascading effects of AMOC collapse. Effective governance must therefore anticipate both the physical interlinkages among tipping elements and the socio-economic ripples that follow.

Rather than simply reacting to tipping cascades as they occur, societies that acknowledge threshold crossings can proactively design interventions to avert or contain the most damaging systemic ripple effects.

1.3.2 Progress and recent developments in ESTP impact governance

The first Global Tipping Points Report made five recommendations to initiate ESTP impact governance. These were:

1. Existing impact governance frameworks and mechanisms need to be adjusted and significantly expanded to address the risks posed by crossing ESTPs. More resources and funding should be made available, especially if and when an Earth system tipping point has been crossed.
2. Adaptation governance needs to significantly strengthen anticipatory work and adopt a multitemporal perspective tied to the scale and dynamics of specific tipping systems.
3. Governments should advance the institutionalisation of global migration governance, building on the Global Compact for Safe, Orderly and Regular Migration.
4. Science and governance actors should co-develop early warning systems to monitor both the biophysical changes (especially indicators for tipping-point transgression) and potential societal impacts of ESTPs. For that purpose, investments in the quality and availability of data should be made, including data from low-income countries.
5. Governments should increase the use of participatory approaches to impact governance, involving local/Indigenous communities and knowledge.

While most of these recommendations have seen little progress, some advances have been made with respect to recommendation 4 - the development of monitoring and early warning capacities at the science-policy interface and recommendation 5 - fostering participatory governance approaches.

Monitoring and early warning systems (Recommendation 4)

In 2024, the UK Advanced Research and Invention Agency (ARIA) launched the Forecasting Tipping Points call, allocating £81 million to 26 projects to develop an early warning system and new models monitoring the Greenland Ice Sheet and the Subpolar Gyre. The EU's Horizon Europe programme provided new funding lines for tipping points research that will strengthen the necessary scientific capacity. The Climate Governance Commission and the High-level Advisory Board on Effective Multilateralism have been fostering a proposal for enhancing international Earth system monitoring scientific capacity. At the same time, monitoring capacity in the US has been recently reduced due to funding cuts and the dismantling of key scientific institutions like NOAA.

While methodological challenges persist (Dakos et al., 2024), integrated early warning systems offer a promising approach to support adaptive governance with information flows and frequent learning loops between science and policy-making (Galaz et al., 2016; Pescaroli et al., 2025). Rather than pursuing or waiting for precise predictions, which is neither feasible nor necessary, detecting critical slowing down and other system-specific indicators can serve as early warning signals, enabling decision-makers to proactively address system instability and mitigate potential impacts.

BOX 1.3.2:
Research Insight: State of Governance Missing the linkages with ESTPs in India'

Advancing early warning systems (EWS) for extreme events is an important governance priority in India. The main concerns are monsoon variability, extreme heat and rainfall, sea-level rise and storm surge, and glacial changes and sudden events (e.g. glacial lake outburst floods). Impact-based EWS for heavy rain, floods, heatwaves, thunderstorms and associated lightning strikes are priorities for joint efforts across government, Earth system science organisations, and the National Disaster Management Authority.

Improved forecasting and early warning of cyclones is seen as a particular success story, with substantial reductions in human mortality in the past two decades. Moreover, the growing severity of extremes as well as increasing compound events (e.g. heatwaves and droughts) is leading to widespread interest in multi-hazard EWS. In this context, multinational efforts in data sharing and technical cooperation are growing, e.g. Regional Integrated Multi-Hazard Early Warning System for Africa and Asia (RIMES). However, in India, EWS have not yet been linked to ESTPs. The failure to recognise that some of these hazards are linked to tipping processes means that these systems may quickly prove inadequate, undermining the successes achieved to date. Crucially, it also risks generating a widespread false sense of security in existing EWS that could prove fatal. There is therefore an urgent need to integrate tipping processes and risks into EWS, and to revise impact forecasting and planning across the region in light of tipping.

However, anticipatory governance requires monitoring and early warning for both approaching ESTPs and their societal impacts (See Box 1.3.2), and it requires institutions and decision-making mechanisms at the science-policy interface that can respond to the observations made and early warning signals provided. In both aspects, major research, funding and institutional innovation gaps remain. First, there is a significant need to expand research regarding the social, economic, political and cultural impacts of ESTPs. Greater knowledge of impacts is needed at national, sectoral and local scales to inform **tipping point risk assessment processes** across multiple scales (see below) and enable planning, adaptation and preparedness.

Second, while scientific and technical capacities for Earth system monitoring are being fostered by some governments and institutions, they are not yet matched by institutional arrangements capable of translating early warnings into timely and context-specific responses. To address this gap, a set of new, specialised institutions might be needed to enable continuous learning, monitoring, risk assessment, foresight and rapid action/response to tipping dynamics (see Box 1.3.3).

Box 1.3.3: Bridging science and action for Earth system tipping points

A novel type of science-to-action institution could address the urgent need for effective, continuous and rapid science-policy interactions to support anticipatory governance for ESTPs. Tipping Element Monitoring and Rapid Response Facilities (TEMRFs) could be designed to strengthen the recognition, representation, and response to tipping dynamics in the Earth system. Their core purpose is to provide early warning and rapid response capacity for critical Earth systems that may cross non-linear thresholds with cascading consequences for societies and ecosystems. Unlike existing science-policy interfaces, which often operate at a distance from decision-making and focus on long-cycle assessments, TEMRFs would be regionally grounded – each one tied to one or more specific tipping elements – yet globally networked hubs that combine scientific monitoring, foresight, and direct engagement with policymakers and communities. A key feature is their commitment to multi-stakeholder and multi-scale governance, ensuring that Indigenous Peoples, civil society, and private sector actors participate alongside governments and scientists, thereby enhancing both legitimacy and actionability.

Functionally, TEMRFs would combine multiple units to operationalise a representation-recognition–response triad: an Observatory Unit to recognise early warning signals through real-time monitoring, an Impact Foresight Lab to map vulnerabilities and cascading effects, and a Rapid Response Group to support timely and coordinated policy development in response to Earth system changes. Organised as a distributed yet interoperable network, TEMRFs would rely on and contribute to global data availability, shared standards, and digital public infrastructure to ensure open access and coordination across scales.

Increasing participatory approaches to impact governance (Recommendation 5)

There has been increasing attention given to, and interest in the use of, participatory and deliberative approaches around key societal issues, including climate change (Escobar and Elstub, 2025). Citizens' assemblies and other forms of deliberative democracy offer a compelling approach for the challenges posed by ESTPs. They bring together diverse, demographically representative 'mini publics' of ordinary people in facilitated discussions on politically challenging topics. By engaging directly with dilemmas and trade-offs, they can generate consensual policies, mobilise citizens, foster solidarity, and act as a practical response to crises in institutional legitimacy. They can be deployed at any scale, including at the global scale (see Box 1.3.4), whether commissioned by institutions or independently.

Box 1.3.4: A permanent Global Citizens' Assembly: The potential of a civic infrastructure for deliberative governance of ESTPs

The Global Citizens' Assembly (GCA) brings deliberative democracy to the planetary scale. It aims to amplify people's role in global climate governance and to become embedded in the annual COP cycle. The GCA is composed of two interrelated deliberative components supported by a coalition of governments, NGOs, firms, and civil society actors, and a cultural engagement campaign.

Civic Assembly: a transnational mini public selected by global lottery, bringing a planetary perspective to issues that transcend national borders. Its key contributions in relation to ESTPs could include:

- Legitimising planetary decisions by providing global democratic legitimacy for responses to tipping points.
- Deliberating uncertainty by tackling long-term and complex risks that outpace typical political cycles.
- Elevating justice by enabling discussions of intergenerational, interspecies, and interregional justice.
- Synthesising knowledge by integrating Earth system science with ethical and cultural insights.

Community Assemblies: bottom-up, place-based deliberative spaces that translate abstract risks into lived experience and practical action. They could contribute to:

- Contextualising risks: local realities such as drought or biodiversity loss help make tipping points tangible.
- Surfacing diverse knowledge: Indigenous, traditional, and ecological knowledge enrich global understanding and point to better ways of measuring the outcomes to which policy aims.
- Mobilising stewardship: community assemblies foster locally led solutions in climate and ecological adaptation, resilience, and regeneration.
- Building trust: participation at the local level can help to build legitimacy and readiness for broader systemic change.

The interaction between the Civic and Community Assemblies has the potential to contribute to multi-scale, distributed and reflexive governance (Curato et al., 2025) for ESTPs. The GCA delivers emerging agendas from grounded, diverse perspectives and globally coordinated mandates that are rooted in lived realities.

According to OECD data, there were on average 47 deliberative participatory processes per year across a range of issues and countries over the period 2019-2023, compared to 32 per year over the previous (2014-2018) 5-year period (OECD 2023). While there has been a mixed picture in respect to the legitimacy of such processes and the uptake of their recommendations by policymakers (Lorenzoni et al. 2025), the growing prominence of participatory approaches indicates the feasibility and potential of engaging publics on critical issues including ESTPs.

Reforming impact governance mechanisms with a view to ESTPs (Recommendations 1, 2 and 3)

The task of reforming existing governance mechanisms can take many forms ranging from adjustments of existing policies (e.g. including ESTP scenarios and risks to adaptation planning processes) to changing policy frameworks (e.g. long-term development plans), adopting different decision-making logics (e.g. precautionary, mid-century planning), and institutional reforms (e.g. introducing different structures, entities or processes dedicated to addressing cascading dynamics).

The EU has taken initial steps in identifying relevant institutions and policy frameworks that are in need of review and reform in the light of tipping point risks (see Box 1.3.5). Similar efforts will be needed around the world, across multiple scales, including in international institutions, such as the UNFCCC's governance frameworks related to adaptation, loss and damage, and climate finance. Such review efforts need to consider which governance scale is the most appropriate for the allocation of responsibility for tipping risks, e.g. not to overburden local governments with managing large, regional-scale dynamics or abandon collective international responsibility for tipping risks by leaving responses to regional organisations or national governments.

BOX 1.3.5: Research Insight: State of Governance
ESTPs remain a blind spot in anticipatory governance in the EU

The crossing of ESTPs would cause severe, irreversible changes to the European climate, economy and society. Despite this growing threat, EU risk governance frameworks, including climate adaptation strategies and disaster risk reduction mechanisms, are largely based on gradually increasing risks and currently overlook tail risks (e.g. extreme weather events that fall outside historical trends) and ESTPs. Europe is already experiencing climatic tail risk events, such as unprecedented floods, droughts, and storms. Furthermore, socio-economic models underpinning EU policy assessments omit the nonlinear damages from extreme climate events and ESTPs, severely underestimating potential economic damages and socio-ecological impacts. While the EU has a package of prevention policies in place, the absence of anticipatory discussions to manage ESTP-driven crises remains a significant governance blind spot.

In 2024, a European Commission workshop (European Commission 2025; EU 2025a) considered this challenge and identified several initiatives and policy frameworks that offer key entry points to integrate ESTP risks into European governance, including in early warning systems, long-term resilience planning, and risk assessments to support decision-making of EU institutions. These entry points include national risk assessments as part of the Preparedness Union Strategy (EU 2025b), the European Climate Adaptation Strategy (EU 2021) and its forthcoming European Climate Adaptation Plan, and the second European Climate Risk Assessment (EUCRA), expected in 2028. As a way to unlock action and to bypass methodological uncertainties, a new impulse on narrative-based methods (e.g. science-based storylines) is starting to support risk assessment processes at European and national scales, complementing efforts to quantify future climate hazards. By embedding ESTP anticipatory action as 'no regret' initiatives within ongoing climate change preparedness measures, the EU has a unique opportunity to lead a global discussion on managing systemic, non-linear climate risks.

Climate change adaptation: A decade after the Paris Agreement's adoption, global climate adaptation governance remains characterised by profound asymmetries between the Global North and South, with 3.6 billion people currently considered highly vulnerable to climate change impacts (IPCC, 2023). Adaptation governance in developing countries faces severe constraints across multiple dimensions, especially financing (Carbon Brief, 2023). While Global North countries have generally developed more robust institutional frameworks for domestic adaptation, they also often fall short of what is needed to keep up with already observed climate impacts. In this context, the multi-scale **governance system for adaptation has yet to address tipping point risks**.

Vulnerability to ESTPs does not necessarily align with historical patterns of climate risk. Countries or communities often perceived as less vulnerable could suffer significant impacts and disproportionate burdens, while local authorities in many countries—currently tasked with major responsibilities for adaptation—lack the capacity to analyse or respond to such complex threats. For example, AMOC and SPG collapse would heavily affect Northern Europe in unexpected ways, and boreal forest loss would primarily impact highly developed countries such as Canada, the Russian Federation, and Finland. These shifts underscore the need for new risk and vulnerability assessments and mapping.

Effective anticipatory adaptation requires diverse and flexible strategies that can be scaled up, adjusted, or complemented with new approaches as conditions change. Rather than relying on static solutions that risk becoming costly or ineffective, adaptation portfolios must remain open-ended, combining multiple pathways to enhance resilience and provide space for learning and adjustment (Biesbroek et al., 2025).

One critical form of adaptation is mobility, yet access to this strategy is profoundly unequal (Parsons et al. 2024, Thalheimer et al. 2025). At the same time, **global migration governance** is becoming increasingly strained: traditional protection frameworks are being eroded, political resistance to migration grows (Appleby 2024; Wibisono 2024), and climate-related displacement remains largely unaddressed. These dynamics highlight deep tensions between human mobility, rights, and geopolitics (Micinski et al. 2023, Woodworth 2023, Ullah 2025)—trends that make introducing ESTP risks into governance especially challenging, but also ever more important to ensure just and effective responses.

Earth system tipping points will expose and accelerate situations where communities reach the limits of adaptation, intensifying debates about soft versus hard limits (Berkhout et al., 2024). While many climate impacts can be managed through adaptation measures, tipping points may generate changes so abrupt and widespread that adaptive responses become unfeasible, ineffective, or prohibitively costly. These 'adaptation tipping points' (Kwadijk et al. 2010; Juhola et al. 2022) result in residual loss and damage—harms that cannot be avoided, adapted to, or recovered from (McNamara and Jackson, 2018)—posing profound challenges for existing governance frameworks. Responding effectively will require **expanding Loss and Damage mechanisms** to account for the systemic, irreversible nature of tipping point impacts, including rethinking financial instruments, insurance models, and legal responsibilities, while ensuring affected communities receive support beyond what adaptation alone can deliver.

In sum, **key policy priorities** for fostering ESTP impact governance include:

- mainstreaming ESTP risks into adaptation and development planning,
- updating vulnerability assessments to reflect ESTP risks,
- strengthening international mobility governance, and
- expanding loss and damage mechanisms.

All the recommendations presented in GTPR 2023 remain important. Cross-cutting these recommendations is an urgent need to better understand and anticipate ESTP impacts. As such, the near-term focus in building ESTP impact governance should be on developing monitoring, early warning and response systems (see above), and integrating ESTP impacts into risk assessments at the local, national, regional and international levels (see below).

1.3.3 Integrating ESTP impacts into risk assessment

The need for multi-scale risk assessments: Anticipatory governance aimed at mitigating systemic risks from crossing ESTPs must commence with systemic risk assessments across national, regional, and global scales. These assessments are critical for understanding potential impacts, catalysing institutional and policy reforms, and aligning adaptation and disaster risk management strategies with the realities of tipping dynamics. A recent policy brief by the European Commission's Joint Research Centre (JRC) (Roman Cuesta et al., 2025) underscores this necessity, as does the scientists' letter to the Nordic Council of Ministers regarding the AMOC, which argued that a regional risk assessment process would be an important measure the Nordic governments should undertake. Such risk assessments should be participatory, engaging decision-makers across multiple policy domains as well as relevant experts and a wide range of stakeholders.

At the global scale, the IPCC provides a regular authoritative scientific assessment of climate change risks. It has included the risks of ESTPs in its assessment reports since 2001. AR7 expected in 2028 will include a chapter dedicated to tipping risks ('Abrupt changes, low-likelihood high impact events and critical thresholds, including tipping points, in the Earth system'). The World Climate Research Programme (WCRP) is currently undertaking a review of science to assess Earth system tipping risks, and we provide an assessment here in Section 2 of GTPR 2025.

National and regional developments: At the national level, several initiatives have recently emerged to start assessing risks that arise from ESTPs. For example, the Finnish Meteorological Institute and Atmosphere and Climate Competence Center launched a policy brief in 2024 focusing on AMOC risks in Finland (Merikanto et al., 2024). The German government mentioned ESTPs in its National Interdisciplinary Climate Risk Assessment (NIKE 2025). The Australian government is reviewing its Reef 2050 Long-Term Sustainability Plan (launched in 2015), including an assessment of the extent to which coral reefs have already tipped (Commonwealth of Australia 2021). In some cases, like the UK, these developments are driven by non-state actors: a report by the Institute of Public Policy Research has drawn attention to security risks arising from AMOC or SPG tipping (Laybourn et al., 2024).

Most of these analyses have been advanced in developed countries and with a focus on a single or pair of tipping processes with direct geographic relevance for the country. More initiatives of this kind are needed across the globe, especially in countries facing the consequences of proximate ESTPs, i.e. those we identify as at risk between 1.5°C and 2.0°C warming.

At the regional level, the first European Climate Risk Assessment (EUCRA) published in 2024 identifies 36 climate risks threatening Europe's energy and food security, ecosystems, infrastructure, water resources, financial stability, and public health. While tipping risks served as 'wild cards' in EUCRA's scenario narratives, the report did not consider ESTP-related risks systematically. Future EUCRAs and similar regional processes in other parts of the world (e.g. under the frameworks of the African Union, ASEAN, ACTO) could be developed or strengthened to consider tipping risks and to reflect context-specific vulnerabilities and enhance regional governance capacities. The EU's JPI Climate and JPI Ocean platforms recently initiated a risk assessment process of the AMOC.

Methodological challenges & data gaps: Integrating ESTPs into risk assessment processes, policy and planning faces several methodological challenges and information gaps. Common risk calculations based on probabilities are often not possible given high levels of uncertainty. Existing IPCC assessments and socio-economic models fail to capture the nonlinear, cascading nature of tipping points, leading to a drastic, systematic underestimation of the risk and economic costs from crossing ESTPs (Roman Cuesta et al., 2025). There is an urgent need for alternative approaches (e.g. a recent proposal in Norway (Norway, 2018) to consider consequences, probability, knowledge and strength of knowledge to assess climate risks instead of the standard formula multiplying probability with expected quantified impacts) and improved modelling frameworks that integrate biophysical and socio-economic dimensions. More generally, research on the social impacts of tipping processes is lacking, leaving large data gaps concerning social or economic indicators.

Given the nature of tipping processes, the high levels of uncertainty and the challenging time horizons that need to be considered, anticipatory and participatory futures and foresight methods (e.g., horizon scanning, scenario development) will play an important role in tipping risk assessments. Approaches such as simulations (e.g. AI-enhanced agent based modelling (Gao et al., 2024; Ghaffarzadegan et al., 2024), storylines and wild cards, already trialled in EUCRA (EEA, 2024), or what-if scenarios used in a UK report on ESTP security risks (Laybourn et al., 2024), could be used to assess ESTPs risks, including those that cannot be easily quantified (e.g. risks of civil unrest).

It will be important to co-produce tipping risk assessment processes with key stakeholders, who can bring their knowledge and risk response skills to the exercise. This includes Indigenous Peoples (e.g. in the Amazon rainforest or the Arctic) and local communities, who have valuable place-based knowledge and understanding that will enhance risk assessment and the identification of effective response options.

Box 1.3.6: ESTPs and financial risk management

Financial and insurance institutions and regulators are starting the urgent task of updating their risk frameworks to reflect the growing threat of ESTPs. These risks are politically pertinent for pension funds because of their relatively long time horizons and the fiduciary duty to beneficiaries. ESTPs are nonlinear, interconnected, and lack clear historical precedents, making them difficult to model using current financial and insurance risk tools, which often use econometric approaches based on prior experience (Lenton et al., 2019; Kousky, 2019; Trust et al., 2025).

Traditional financial and insurance risk management that is focused on incremental and historically grounded scenarios has proven inadequate in the face of systemic shocks, as was shown in both the 2007–08 financial crisis and the COVID-19 pandemic. In both cases, emergency interventions by governments and regulatory bodies were required to stabilise the system, underscoring the failure of ex-ante risk governance (Bolton et al., 2020). ESTPs pose a similar challenge but with even less capacity for reactive containment and recovery. Despite this, most stress testing and portfolio risk assessment methods undertaken by financial institutions continue to assume gradual climate trajectories. There are some recent efforts to take into account the possibility of extreme events in the short term (NGFS, 2025) but the assessment of tipping points risk is only just beginning. As a result, risk assessments generally overlook the potential for cascading system failures and cross-sectoral disruptions triggered by tipping events (Battiston et al., 2017). This leads to dangerous overconfidence in asset resilience and mispricing of long-term environmental and financial risks (FSB, 2025; Marsden et al., 2024; Trust et al., 2025; WEF, 2020). Even when the consequences of passing a tipping point will take time to play out, if such consequences are irreversible, financial actors will rapidly reprice assets accordingly. This bringing of future consequences into the present is an additional source of financial instability. The early manifestations of this emerging challenge can be seen with the withdrawal of insurance and the repricing of real estate in regions affected by increasingly frequent climate-related extreme events.

The degradation of ecosystems further compounds financial vulnerability and interacts with tipping dynamics. Natural systems provide essential buffers, such as flood protection and carbon sequestration, that mitigate the severity of climate impacts (Costanza et al., 1997; 2017). Yet these services are rarely valued in financial models (Dasgupta, 2021). Biodiversity, in this context, functions as "natural insurance", but its degradation remains largely invisible to current regulatory and market structures (NGSF, 2022; OECD, 2023; IPBES, 2024).

Financial stability is a critical concern in the face of Earth system destabilisation, and the lack of consideration of nonlinear dynamics in risk analysis is a critical barrier to effective governance. Urgent reforms are needed to embed tipping dynamics into financial, insurance, and related corporate governance frameworks. A precautionary approach to financial regulation that embeds ecosystem resilience and tipping dynamics into regulatory frameworks is essential (Kedward et al., 2023). This includes revising capital requirements, integrating nature-related risks into disclosure standards (UNEP, 2022), and steering financial flows away from activities that accelerate Earth system destabilisation (WEF, 2024). The financial and insurance systems and biosphere resilience are now deeply interdependent; governance that fails to reflect this will compromise both.

Note: The role of finance in triggering and preventing ESTPs is addressed in Chapter 1.2, and positive tipping points in the financial system are addressed in Chapter 3.2.

1.3.4 Justice and intergenerational governance

ESTPs raise profound and unprecedented justice challenges. Their impacts are not only global and potentially irreversible but also distributed unequally across time, space, societies, and communities. The governance of these impacts must therefore be rooted in a robust and explicit commitment to justice, both to ensure fairness in the face of disruption and to build legitimacy for decisions made under uncertainty. The concept of **Earth system justice** (Gupta et al., 2023) offers a guiding framework here. Within the conceptualisation of Earth system justice, interspecies justice is integrated with intragenerational and intergenerational justice, considering substantive and procedural elements.

Intragenerational equity: Who bears the burden today?

While climate tipping points are planetary in scale, their consequences will be highly uneven—both geographically and socially. Many tipping points will disproportionately affect those who live near vulnerable systems (e.g. Amazon basin communities, low-lying coastal states), those with already limited adaptive capacity due to poverty or marginalisation, and those directly dependent on ecosystems at risk of collapse (e.g. coral reef fisheries, rain-fed agriculture). Crucially, specific tipping points can not only amplify existing climate risks, but they also alter how risks, impacts, loss and damage are distributed across space and time. These dynamics can **make impacts significantly worse** for communities already vulnerable to climate change by increasing the magnitude, speed, and irreversibility of impacts. At the same time, ESTPs can generate **new types of vulnerability not previously recognised**—some in places that have historically been less exposed.

For instance, abrupt ice sheet collapse, permafrost thaw, or AMOC disruption, could have cascading effects on food security, infrastructure, and livelihoods in regions previously considered relatively insulated from the worst effects of climate disruption.

This evolving risk landscape demands a shift in governance thinking. Impact governance must not only prioritise and expand support for communities already at risk, but also anticipate and respond to emerging and new vulnerabilities, especially those that fall outside current adaptation frameworks. Planning and investment decisions must ensure an equitable distribution of adaptation resources and address irreversible harms in equitable ways. Mechanisms for loss and damage need to be significantly strengthened and expanded to reflect the long-term, systemic nature of tipping point impacts.

Emerging international frameworks—such as the Loss and Damage Fund and the Santiago Network—offer entry points for addressing these concerns. But to be truly effective, such frameworks must evolve to reflect the redistributive, unpredictable, and cascading nature of tipping point risks—across both the Global South and Global North.

Intergenerational responsibility: Who bears the burden tomorrow?

Perhaps the clearest justice issue raised by tipping points is **intergenerational**. Many tipping processes, such as ice sheets or ocean circulation, take place over extended time periods - decades to millennia, and their consequences will persist for centuries and millennia. Once passed, these thresholds commit future generations to living with radically altered Earth system conditions. Unlike other environmental risks, these changes cannot be reversed or "cleaned up" later - the impacts of the current generations' decisions will be permanent.

This deep **intertemporal asymmetry** creates a powerful moral imperative: today's decisions about ESTP prevention and adaptation will shape the basic life-support systems of tomorrow's societies. Governance must therefore be designed not only to protect current populations, but also to safeguard the rights and wellbeing of those yet to be born. This requires:

- Expanding the time horizons of policy and financial planning to consider temporal patterns of tipping (at least several decades).
- Strengthening legal and institutional mechanisms that represent future generations (e.g. ombudspeople, constitutional protections, or future councils).
- Embedding precautionary principles in high-stakes decision-making, especially when uncertainty intersects with irreversibility.

Legislation such as the Well-being of Future Generations (Wales) Act 2015 shows that this is possible. The Act places a duty on public bodies to carry out sustainable development. It requires public body decision-making to take account of the long term, to prevent generating and/or exacerbating problems, to take an integrated and collaborative approach, and to consider and involve people of all ages and diversity. However, such frameworks need to be drafted with ESTPs in mind, and be seen not merely as 'aspirational' (Stokes and Smyth, 2024) but as requiring urgent and accountable implementation.

Interspecies justice and ESTPs

Many non-human species are acutely vulnerable to tipping point impacts—especially those with limited ability to adapt to rapid environmental change, such as reptiles, amphibians, and most fish. Sudden habitat shifts may exceed the adaptive capacity of numerous ecosystems.

Human activity is a key driver of these tipping points, reinforcing our responsibility to act to protect non-human species. Ensuring interspecies justice requires a better understanding of the impacts of tipping processes on non-human species and ecosystems, and the actions that can protect ecological integrity. It requires governance that aligns development pathways with ecological and Earth system thresholds.

Some governments and institutions have taken initial steps to recognise the rights of nature—steps that need to expand globally to reflect the interconnected and cascading nature of tipping elements (see Chapter 1.4, subsection 1.4.7).

Procedural justice: Inclusion in decision-making

The domain of justice concerns the way decisions are made as well as their outcomes (Sen, 2009). Decisions about how to prepare for and respond to tipping point impacts will involve trade-offs across sectors, regions, populations and generations. Such decisions must therefore be made through processes that are transparent, participatory, and inclusive, and grounded in the values of respect, neutrality, trustworthiness and voice (Meyerson, Mackenzie and MacDermott, 2020, p.8). At the same time, they must be designed to facilitate urgent action and not become an undue obstacle (Ruhl & Salzman 2023). Yet many communities most at risk — including Indigenous Peoples, youth, women, older persons, and those with limited access to resources in both the Global North and the Global South — remain underrepresented in climate governance. In the context of tipping points, greater inclusion of such groups may improve decision-making processes and outcomes in the following ways:

- **Local and Indigenous knowledge** can complement scientific models, particularly those for tipping points with significant non-climate drivers (e.g., Amazon) and improve the legitimacy of adaptation decisions addressing localised impacts.
- **Youth representation** promotes consideration of future interests in present-day planning.
- **Multi-stakeholder forums** can help navigate complex trade-offs, build consensus, and reduce the risk of conflict.

Carefully building participatory governance processes into national and regional institutions is not only fair, but it also increases resilience by aligning policy with local realities, strengthens social trust, and promotes the perceived legitimacy of decision-making.

In summary, tipping points confront policymakers with hard questions about what kind of future we are preparing for, and for whom. The just governance of tipping point impacts concerns not only resilience, but also fairness between countries, communities, generations, and species.

1.3.5 Final remarks

As global warming approaches or exceeds 1.5°C, the risk of crossing ESTPs is a near-term possibility demanding immediate policy responses. Their impacts go beyond the scope of conventional climate policy and demand a new kind of impact governance—an approach that can anticipate and manage systemic change, protect the most vulnerable populations, and maintain social, political, and economic stability amid deep uncertainty.

Governance for tipping point impacts requires a fundamental shift in approach: from managing known risks to navigating the unknown; from improving existing systems to preparing for deep transformation; and from responding to short-term crises to building long-term resilience and advancing Earth system justice. A multi-phase governance framework is needed—beginning with early anticipation and preparedness, extending through rapid response as tipping thresholds are crossed, and continuing into the turbulent period of irreversible change that follows. This shift demands that we strengthen existing institutions, reform inadequate structures, and innovate new mechanisms that are fit for navigating tipping dynamics.

Most current governance mechanisms—whether in adaptation, disaster risk reduction, or economic planning—are not designed for the scale or speed of change that ESTPs entail. Institutional reforms and innovations are needed to enable real-time risk monitoring and coordinated policy responses. At the same time, governments must integrate tipping risks into national and regional assessments and use participatory foresight tools to inform planning in the face of uncertainty. While some regions have taken initial steps, global progress remains limited and uneven.

Justice must lie at the heart of impact governance. Tipping point impacts will fall unevenly across geographies, communities, and generations—exacerbating existing vulnerabilities while creating new ones in places previously considered secure. Governance must prioritise inclusion, fairness, and transparency to build legitimacy and maintain social cohesion in the face of upheaval. Ultimately, preparing for tipping points is not just about managing risks—it is about governing for a future that will be fundamentally different, and doing so in a way that is accountable, adaptive, and just for all.

1.4 A human rights framework for Earth system tipping point governance

Authors: Malcolm Rogge, Tomas Chaigneau, Lauren Gifford, Ben Hudson, Timothy M. Lenton, Aaron Marr Page, Manjana Milkoreit, Karen Morrow, Laura Pereira, Niko Soininen, Sebastian Villasante, Simon Willcock, Yulia Yamineva

Reviewers: Maja Groff, Louis Kotzé, David A. Armstrong McKay, Annalisa Savaresi, Jessica Seddon

Key Messages

- **Preventing Earth system tipping points and addressing their impacts are essential for the global protection of fundamental human rights.**
- **State and non-state actors must be adequately informed about the human rights implications of transgressing Earth system tipping points and governance responses to them based on the best available science.**
- **Tipping points science should be used to strengthen future litigation efforts related to human rights.**
- **We recommend convening a multi-stakeholder working group on human rights and Earth system tipping points, including the UN Office of the High Commissioner for Human Rights, scientific experts, Indigenous Peoples and civil society organisations.**

1.4.1 The vital role of human rights in ESTP governance

Human rights provide a potentially powerful and globally legitimate overarching normative framework to help guide ESTP governance. The core role that human rights play within the system of global climate norms was underscored by the recent advisory opinions of the International Court of Justice (ICJ, 2025) (Obligations of States in respect of Climate Change), the Inter-American Court of Human Rights (IACtHR, 2025) (Climate Emergency and Human Rights), and the International Tribunal for the Law of the Sea (ITLOS, 2024) (Climate Change and International Law), as well as the rapid proliferation of strategic litigation efforts around the world (see 3.2.2.3). The risks to human rights of crossing ESTPs have been cited as compelling evidence in recent landmark court judgments requiring state actors to act more decisively on reducing greenhouse gas (GHG) emissions. In examining these and other juridical developments, the chapter provides support for policymakers, scientists, legal experts, environmental defenders and other actors (see Chapter 1.5) who are driving systemic and transformative change in global legal and policy frameworks for addressing the climate crisis and ESTPs.

Human rights exist both as ethical concepts closely connected to the idea of justice (Sen, 2009) and as a mature regime of legally-binding norms and supporting institutions at the international, regional, and national levels. The 2023 Global Tipping Points report warned about the potentially "unequal and unjust consequences" of transgressing ESTPs (Key Messages, p. 8). Human rights frameworks are well-positioned to help understand and address these consequences, in conjunction with other normative tools. Critically, they help us understand both what is at stake and how to take action in the face of legitimate competing interests and priorities. Human rights frameworks are inclusive, especially with attention to the rights of future generations. They can be potent and persuasive communication tools for influencing public opinion, diversely situated policymakers and other strategic actors, including judges.

Like any other normative framework, human rights face legitimacy and practicality challenges, in particular as to enforceability and long-term societal impact in a time of growing inequality and persistent global injustice (Kotze, 2019; Moyn, 2019). There also exist patterns of political resistance to bringing human rights language into climate change negotiations (Wallbott and Schapper 2015), often making processes more contentious and difficult. Nonetheless, a diverse array of human rights norms, institutions, and practices have a proven record in guiding and constraining state and non-state actors in all regions of the world. As imperfect as they are, human rights will inevitably play a role in the motivation, conceptualisation and design of approaches to global ESTP governance, alongside other frameworks such as equity and justice (Pereira et al., 2024), the Earth system justice framework (Gupta et al., 2023), Earth stewardship (Chapin et al. 2022), and the lens of planetary resilience (Rockstrom et al., 2024).

The international human rights framework provides an overarching set of norms for addressing key governance challenges that are specific to ESTPs, including anticipatory governance, intertemporal decision-making, and systemic risk governance (on these challenges, see Milkoreit et al., 2024). In establishing principles and practices for tipping point governance, human rights laws and 'soft law' instruments provide baseline standards of conduct for states and non-state actors. Such instruments include, among others, the core UN-administered human rights instruments and enforcement mechanisms, the "UN right to a clean, healthy and sustainable environment" (General Assembly Resolution A/RES76/300), and the UN Guiding Principles on Business and Human Rights (UNGPs, 2011).

Non-state actors, such as businesses and non-governmental organisations, also play a key role in ESTPs governance (see Chapter 1.5), and they too require normative guidance and guardrails. A growing set of human rights norms apply directly and indirectly to these actors, including the UNGPs (UNGPs, 2011), the OECD Guidelines for Multinational Enterprises (OECD Guidelines, 2023), corporate sustainability governance frameworks (e.g. WBCSD, 2018), and national laws, such as the EU's Corporate Sustainability Due Diligence Directive (CSDDD, 2024) and France's 2017 Duty of Vigilance Law (Savourey & Brabant, 2021; Reinsberg & Steinert, 2024). Perhaps counter-intuitively, the human rights field can help formulate the 'business case' for taking urgent action on ESTPs. Transgressing ESTPs will lead to massive adverse impacts on the global economy (Institute and Faculty of Actuaries, 2025; Potsdam Institute for Climate Impact Research, 2025) and reducing the risk of such impacts is an important and legitimate concern for businesses. That being said, human rights, as ethical concepts, give priority to normative-ethical motivations over economic-instrumentalist motivations (Sen, 2009; Rogge, 2022). Thus, a human rights approach to ESTPs governance will give priority to the ethical motivation to prevent and mitigate harm to people and nature as ends in and of themselves.

1.4.2 Why ESTPs are a threat to human rights

Preventing ESTPs is essential for the global protection of human rights. Transgressing ESTPs will lead to dramatic and irreversible changes in regional and global climate and biophysical systems (see Section 2) with consequent severe adverse impacts on the human rights of hundreds of millions, even billions, of human beings, including future generations (IPCC AR6, 2023, Ritz, 2024). While these impacts can be described in many ways, they can be powerfully understood as violations of civil & political rights (ICCPR rights), economic, social and cultural rights (ESCR rights), environmental rights, Indigenous rights, and breaches of equity and justice (Wewerinke-Singh & Maxwell, 2025). The unjust impacts of climate change that already exist today could be exacerbated by the transgression of ESTPs, compounding harms to future generations (Rammelt et al., 2023; Pereira et al., 2023). ESTPs could also create new harms, changing the map of present climate-related vulnerability and impact distribution around the world. Such impacts threaten the foundational guarantee of human dignity expressed by the entire corpus of human rights law, as reflected in, among others, the Universal Declaration of Human Rights, the multi-state Charter of Fundamental Rights of the European Union, the national-level Constitution of the Republic of South Africa; the Constitution of the Republic of Ecuador, and the Basic Law for the Federal Republic of Germany (Ritz, 2024). As Ritz states, "[a]nthropogenic emissions largesse leading to the triggering of tipping points in the climate system most severely interferes with the right to life of millions across the planet…" (Ritz, 2024).

ESTPs give rise to two very different kinds of human rights risks: first, direct harms caused by abrupt and massive biophysical changes in the environment; second, indirect adverse human rights impacts from state and non-state responses to ESTPs risks. The direct biophysical ESTPs risks include, among others: widespread global shrinkage of crop growing areas; disruption of monsoons (e.g. West Africa); forest dieback in the Amazon Basin; degradation of savanna and drylands; die-off of coral reefs; die-off of mangrove forests; water eutrophication; and linked adverse impacts on global and regional food security, water availability, human health, housing and cultural identity (see Table 1.4.1).

Indirect human rights impacts include, among a wide range of adverse societal consequences, rising authoritarianism and crackdowns on civil liberties, the use of racist and discriminatory criteria in adaptation responses, further marginalisation of vulnerable populations, and the potentially adverse impacts of geoengineering (on the latter, see Lazard et al., 2025). The 2023 Tipping Points Report acknowledges that "[p]lanned relocation in close collaboration with affected communities will become increasingly necessary" (Key Messages, p. 23). If resettlement programs and other large scale adaptations are discriminatory, poorly designed, delayed through mismanagement, corruptly administered, imposed without meaningful stakeholder engagement (Buhmann et al., 2025), or carried out without the free, prior and informed consent of indigenous peoples (Hanna & Vanclay, 2013), there is a risk that ESTPs mitigation efforts themselves may violate human rights.

A summary of the threats to different categories of human rights of transgressing ESTPs, and how they can amplify the harms that may be caused by incremental climate change, is included in Table 1.4.1. ICCPR rights are at risk insofar as the impacts on human beings threaten peoples' freedom, dignity, and their very subsistence and survival. IESCR rights are at risk due to the adverse impacts on livelihoods and culture, labour conditions, and the viability of diverse existing human settlements. These rights are violated where there are disproportionate adverse impacts on marginalised groups within states and on the least developed countries. States are obligated to fulfil human rights for the most vulnerable groups (Pariotti, 2023), and this obligation implies that groups who are especially vulnerable to specific ESTPs risks must be protected (e.g. detrimental impacts on coral reefs and fishers; the adverse impacts on indigenous peoples of Amazon forest dieback). Non-discrimination, as a branch of both ICCPR and IESCR rights, requires that the rights of vulnerable communities should not be undermined in "green sacrifice zones" (see the 2023 Global Tipping Points Report, 4.2.4; Zografos & Robbins, 2020; Pereira et al., 2024).

Table 1.4.1: Human rights implications of climate change compared to Earth system tipping points

Human Right	Impact of general climate change	Additional/distinct impacts from earth system tipping points	Applicable human rights laws, statutes, and authoritative frameworks (not exhaustive)
Right to Life	Increased mortality from heatwaves, floods, wildfires, and disease spread.	Tipping points like AMOC collapse increase frequency/intensity of hurricanes; Greenland Ice Sheet melt more rapidly raises sea levels, threatening entire regions.	- UDHR Art. 3 - ICCPR Art. 6 - Sendai Framework for Disaster Risk Reduction
Right to Food	Crop failures due to drought, shifting seasons, pests, and storms, decline in fisheries.	Amazon dieback reduces rainfall in key agricultural zones (e.g. Brazil, Argentina); AMOC slowdown disrupts monsoon cycles, affecting agriculture in South Asia and Africa; coral reef collapse impacts fisheries.	- ICESCR Art. 11 - FAO Right to Food Guidelines - SDG 2
Right to Water	Glacial melt and drought reduce access to clean water; flooding contaminates supplies.	Permafrost thaw alters freshwater flows; AMOC and monsoon shifts drastically affect regional water cycles.	- ICESCR Arts. 11 & 12 - UNGA Resolution 64/292 - CEDAW Art. 14(2)(h)
Right to Health	Increased vector- and water-borne diseases; mental health crises; air pollution.	Environmental breakdown and associated uncertainty are detrimental to mental health; Permafrost thaw may release ancient pathogens.	- ICESCR Art. 12 - WHO Constitution - Paris Agreement - EU Charter of Fundamental Rights, Art. 35
Right to Housing	Coastal and inland displacement due to sea-level rise, fires, floods, and storms.	Greenland and West Antarctic Ice Sheet melt causes meters of sea-level rise; coral reef collapse removes natural coastal barriers; AMOC slowdown increases storm surges in certain regions.	- ICESCR Art. 11 - Paris Agreement Art. 8 (Loss and Damage) - OAS Convention Art. 21 - Kampala Convention (Africa)
Right to Development & Livelihoods	Economic stress from disrupted agriculture, fisheries, tourism, and infrastructure.	Coral reef dieback affects fishers and tourism; forest dieback undermines forest-based economies (e.g. Amazon & boreal regions); AMOC shifts impact global trade and GDP.	- ICESCR Art. 6 - ILO Convention 169 - SDG 8
Right to Culture	Loss of environmental heritage, practices, and traditional knowledge.	Coral reef loss undermines Indigenous and local cultural identity; forest degradation (e.g. boreal and Amazon) erases landscapes central to belief systems and oral traditions.	- UNDRIP Arts. 11, 25, 29 - ICESCR Art. 15 - AU Charter Arts. 17(2) and 22(1)
Right to Self-Determination	Marginalised communities face disproportionate harm with little say in climate governance.	Small Island states risk complete submersion (e.g. Tuvalu, Maldives), challenging sovereignty; forest-dependent Indigenous nations lose territorial integrity.	- UN Charter Art. 1(2) - UNDRIP Art. 3 - AU Charter Art. 20
Right to a Healthy Environment	Degradation of biodiversity, ecosystems, and air/water quality.	Transgressing tipping points will cause irreversible collapse of ecosystems (e.g. Amazon, coral reefs); permafrost thaw and albedo loss from ice sheets, thereby accelerating global degradation of ecosystems.	- UNGA Res. 76/300 (2022) - CBD (1992) - UNCLOS Arts. 192–194
Rights of Future Generations (Intergenerational Justice)	Current emissions threaten future generations' access to basic needs and livable climate.	Tipping elements risk locking in irreversible changes beyond human control, disproportionately harming those not yet born.	- Rio Declaration Principle 3 - UNFCCC Preamble - Our Common Future - UN Declaration on Future Generations - Maastricht Principles on the Human Rights of Future Generations

As the examples above show, ESTPs, if transgressed, will have direct impacts on millions and even billions of people, particularly the most vulnerable groups and populations, pushing them into poverty, deprivation, and conditions of forced migration.

1.4.3 The overarching human rights obligation to tackle the drivers of ESTPs

The primary positive human rights obligation of states related to ESTPs is the obligation to take science-based steps to prevent and mitigate the adverse effects of climate change and to adapt where necessary (ICJ, 2025, paras 72-87; 268, 273; KlimaSeniorinnen, 2024). Such steps require not only that states take responsibility for their own actions, including the actions of state-owned enterprises, but also that they effectively regulate the economic activity and business conduct of non-state actors (ICJ, 2025, para 428; IACtHR 2025, para 353). The ICJ has explicitly acknowledged "the obligation of States to regulate the activities of private actors as a matter of due diligence" (ICJ, 2025, para 428). Regulation must pertain to the negative obligation on states to not increase GHG emissions; and this negative obligation implies corollary responsibilities for businesses (McVey & Savaresi, 2025).

As the key driver of ESTPs is global temperature increase, the "heart of effective prevention strategies" lies in accelerated climate change mitigation (see Chapter 1.2). ESTPs can be divided into two groups: those that are nearly entirely climate-driven and are not sensitive to anything but mitigation as a prevention strategy (e.g. AMOC collapse), and those with both climate and non-climate-related drivers. Thus, the human rights obligation on states to prevent and mitigate ESTPs pertain to two different processes (see Chapter 1.2):

1. Prevention and mitigation of ESTPs predominantly driven by climate,
2. Prevention and mitigation of ESTPs driven by a combination of climate and non-climate drivers.

These two categories imply different but complementary human rights obligations on states (on the two different processes, see Table 1.2.1).

For ESTPs driven by a mix of climate and non-climate drivers, state obligations require targeted actions that, in some cases, have a regional focus. So, for example, in coral reef die-off, state obligations arguably include taking specific prevention actions, such as reducing water pollution/nutrient sediment, and reducing disruption caused by shipping and over-harvesting of reef fish. In the Amazon forest, state obligations arguably include reducing deforestation and degradation which will require regional and national policies that are tailored to meet the specific environmental threats that may arise from agricultural expansion, mining, oil drilling, and human settlement (see Table 1.2.1). Regional and international co-operation on land use management changes and resource allocations are needed to prevent Amazon tipping points and their consequent adverse impacts on human beings and nature (Box 1.2.2). The need for multi-scale, cross-border co-operation is supported by the ICJ's 2025 Advisory Opinion, which affirms that "[c]limate change is a common concern" and that states have a legal duty to co-operate with other states to prevent significant harm to the environment, including by avoiding transboundary pollution (ICJ, 2025, paras 301-307; 347-349).

While preventing harm from transgressing ESTPs is a priority human rights obligation in and of itself, the approaches taken by state and non-state actors to prevent specific ESTPs (e.g. to prevent coral reef and Amazon forest die off) must also be guided by human rights norms, particularly with regard to the potential unintended negative impacts of on affected populations. With the huge diversity and scale of action that is needed around the globe, it is inevitable that some ESTP governance interventions will have controversial or contested elements. In this regard, states are obliged to protect and respect the human rights of affected populations who may, now or long in the future, be critical of, or protest against, specific ESTPs governance interventions.

1.4.4 ESTP science: a trend towards greater judicial acknowledgement of nonlinear risks

The effective protection of human rights today and in the future requires state and non-state actors to be fully informed by the science of ESTPs. As recognised by the ICJ in its 2025 Advisory Opinion (ICJ, 2025), and expressed in Articles 4.1 and 14.1 of the Paris Agreement, states have an obligation to undertake rapid reductions of GHG emissions in accordance with best available science (Paris Agreement, 2015; Ritz, 2024). Integrating best available ESTPs science as summarised in this report has the potential to drive a paradigm shift for global legal advocacy efforts, policymaking, and for ESTPs-aware judicial determinations. Adducing scientific evidence that demonstrates how severe harms to human beings and ecosystems will occur if ESTPs are transgressed helps to boost the legal case for taking urgent action "to pursue a warming limit below likely tipping thresholds" (Ritz, 2024).

The adverse human rights impacts of transgressing ESTPs have been noted in a small, but important, number of recent climate change cases. A key domestic case is *State of the Netherlands v. Stichting Urgenda*, in which the Supreme Court of the Netherlands emphasised that any delay in climate action "creates a greater risk of an abrupt climate change occurring as the result of a tipping point being reached." (State of the Netherlands v. Stichting Urgenda, 2019, summary). In *Urgenda*, the court ruled that the right to life (article 2) and right to family life (article 8) of the European Convention on Human Rights (ECHR) require states to take adequate measures to address the "real and immediate risk to people's lives or welfare" posed by climate change, including abrupt changes that may be brought on by reaching tipping points (State of the Netherlands v. Stichting Urgenda, 2019, at 5.6.2; see Jodoin, et al., 2024). The link between ESTPs and human rights harm was also recognised in the German Federal Constitutional Court's groundbreaking *Neubauer* decision (Neubauer, et al. v. Germany, 2021), which required Germany to accelerate its GHG reduction targets (Sabin Center & Grantham Institute, 2025; Kotzé, 2021).

Regional human rights courts are important fora for ESTPs-informed legal advocacy. In the European Court of Human Rights' (ECtHR) Grand Chamber decision in *KlimaSeniorinnen*, the Court referenced the claimant's contention that, "...that there was a real risk of exceeding critical further thresholds known as 'tipping points', and that significant climate change mitigation measures had to be taken as a matter of extreme urgency to avoid the most catastrophic impacts, even if all impacts could no longer be avoided" (KlimaSeniorinnen, at para. 334; the court also refers to tipping points at para. 397). In its decision, the ECtHR draws a direct link between the risk of irreversible harm and state human rights obligations:

> **"...taking into account the scientific evidence regarding the urgency of combating the adverse effects of climate change, the severity of its consequences, including the grave risk of their reaching the point of irreversibility, and the scientific, political and judicial recognition of a link between the adverse effects of climate change and the enjoyment of (various aspects of) human rights (see paragraph 436 above), the Court finds it justified to consider that climate protection should carry considerable weight in the weighing-up of any competing considerations."**
>
> *[KlimaSeniorinnen, 2024, at para. 334, emphasis added]*

The ECtHR emphasised that states' human rights obligations to protect the climate system arise from "the urgency of the situation and the risk of irreversible harm," and expressed deep concern about the "prospect of aggravating consequences arising for future generations" (KlimaSeniorinnen, 2024, at para 420).

In *KlimaSeniorinnen*, the ECtHR emphasised the importance of keeping up to date on climate science for the purpose of protecting human rights. The Court noted that Swiss Federal law requires that government action on climate change and GHG emissions must be taken "in the light of current scientific knowledge and experience" and that the government "shall take into account the latest scientific knowledge" (KlimaSeniorinnen, 2024, at paras 122 and 127). The decision of the ECtHR is binding on Swiss authorities and sets an important precedent for the rest of Europe; it also has the potential to influence decisions in courts around the world (Savaresi, 2025).

As the reach of ESTP-aware jurisprudence expands, governments may be required to incorporate ESTPs science and impacts into their assessments and action plans. This line of argument is supported by the 2024 ITLOS Advisory Opinion on climate change obligations under the UN Convention on the Law of the Sea – the Tribunal referenced scientific evidence on climate tipping points to support its conclusion that the standard of the state due diligence obligation is a stringent one (ITLOS 2024, para 398).

As the cases above indicate, Courts are beginning to take note that the risk of crossing irreversible tipping points poses a threat to the human rights of billions of people, and that this threat increases the urgency of prevention action needed. In line with this trend, the IACtHR explicitly refers to tipping points in its 2025 Advisory Opinion, recognising that, "[t]he increase in the global average temperature also increases the probability of exceeding the **tipping points**" (IACtHR, 2025, at para 197, emphasis in original). The Court acknowledges the heightened risks of crossing tipping points at 1.5°C and above, and the potential for cascading effects: "[t]he feedback between these crucial points could increase the risk of triggering a global cascade in which other tipping points are exceeded, including the uncontrolled release of carbon from permafrost and the devastation of coral reefs" (para 197). Human rights claimants, their legal advocates, and policymakers in all parts of the world are now in a position to highlight the IACtHR's explicit acknowledgment of the dangerous human rights impacts of transgressing tipping points.

Looking ahead, ESTPs-informed climate litigation efforts have the potential to drive a paradigm shift in climate law. Drawing on ESTPs science, legal advocates can contribute to the formation of high-impact ESTPs-aware judicial decision-making. By building on prior successful cases, and by framing new claims within the nonlinear ESTPs paradigm, advocates can powerfully amplify the urgent need for stringent prevention obligations for states and non-state actors, as well as positive mandates (see Section 3.2).

1.4.5 Preventing regional tipping points: the urgent need to protect environmental defenders across the globe

Climate and environmental human rights defenders (also called "nature defenders" or "ocean defenders") play an integral role in worldwide efforts to raise awareness about the impacts of climate change and the risks of crossing tipping points. They also play a key role in encouraging state and non-state actors to take action to prevent and mitigate against ESTPs (United Nations UNECE End of Mission Statement, Forst, 2024; United Nations UNECE Statement, Forst, 2024; United Nations OHCHR Report, Morgera, 2024). The increasing threats to environmental defenders in both Global South and Global North (Front Line Defenders, 2024) makes their work more difficult and dangerous, and thus holds back progress on ESTPs prevention (see Section 1.2; United Nations UNECE End of Mission Statement, Forst, 2024). Environmental defenders face increasing marginalisation, intimidation, criminalisation, threats, violence, and murders, around the globe (UNECE Statement, Forst, 2024; Civic Freedoms and HRD Database). The failure to protect the human rights of environmental defenders must be urgently rectified by states, businesses, and civil society (Bennett et al., 2023). Protecting these defenders - who include Indigenous leaders, farmers, scientists and academics, paraecologists, lawyers, journalists, artists, entrepreneurs, and ordinary people - is more important than ever before (on how businesses can protect environmental defenders, see Freeman & Handagard, 2025).

Environmental defenders operate across scales – nationally, regionally, and internationally – and face different human rights risks in diverse contexts. One of the most prominent examples concerns the Amazon rainforest where, if tipping points are transgressed (causing Amazon forest dieback), the adverse human rights impacts on Indigenous and forest-dependent people will be severe, and may include the destruction of their culture and way of life. Such impacts will also have adverse human rights impacts on the millions of non-Indigenous people also living in the Amazon region, and these impacts will reverberate far beyond the Amazon itself. State repression and non-state threats and attacks on Indigenous human rights and environmental defenders in the Amazon region further undermine progress on prevention of ESTPs. In this respect, state and non-state repression of environmental and climate defenders constitutes an indirect non-climate driver of Amazon forest dieback (Box 1.2.3).

Deforestation and degradation in the Amazon region are exacerbated by illegal forestry, legal and illegal mining, oil development, and the marginalisation of Indigenous and rural populations (Siqueira-Gay & Sánchez, 2021; UNGA Report, Forst, 2017). Avoiding deforestation and increasing reforestation are critical to avoiding ESTPs (see Box 1.2.3); and yet, in some cases, the pursuit of these very goals has been linked to human rights abuses (UN OHCHR Report, Tzay, 2023; see 1.4.3, above). At scale, the aggregate effects of conflicts over land use management throughout the multi-state Amazon region have the potential to hold back ESTPs prevention efforts (Amazon Cooperation Treaty Organization, 2023). The achievement of net-zero forest loss on what remains of the Amazon and the restoration of 5 per cent of the biome (see Box 1.2.3) is unlikely to occur if the human rights of environmental defenders and Indigenous people are not respected and protected by state and non-state actors. To protect environmental defenders in the multi-state Amazon watershed, "coordinated cross-scale approaches" (see Box 1.2.3) are needed. To this end, legal advocates in the region are in a position to use ESTPs science while leveraging human rights obligations that have been acknowledged by the ICJ (ICJ, 2025) and the regional IACtHR, including the right to a healthy environment (IACtHR, paras 269-286) and indigenous environmental rights (Case of the Kichwa Indigenous People of Sarayaku v. Ecuador, 2012).

1.4.6 Taking action: Examples from the United Nations treaty bodies and the financial sector

1.4.6.1 United Nations treaty bodies

Now is the time for human rights advocates and policymakers working at the UN-level, including members of the UN treaty bodies, to shift from the predominantly linear paradigm of climate change to the nonlinear and dynamic paradigm of ESTPs. This shift can be made by creating UN-level and intergovernmental learning networks and platforms for collaborating with ESTPs physical and social scientists.

Drawing on this report and the 2023 Global Tipping Points Report, UN treaty bodies, and those who support their work, are in a position to frame their deliberations and statements on human rights and climate change within the ESTPs paradigm; and, in doing so, they are positioned to emphasise the severity, scale and urgency of climate-related threats to human rights. For instance, the Human Rights Committee's 2018 General Comment on Art. 6 of the International Covenant on Civil and Political Rights (ICCPR) can be updated to explicitly state the severe threat posed by ESTPs. The 2019 General Comment notes that, "[t]he obligation of states parties to respect and ensure the right to life extends to reasonably foreseeable threats and life-threatening situations that can result in loss of life" (United Nations Human Rights Committee, 2019, para. 7). In a similar vein, the UN Human Rights Committee is in a position to update its 2018 statement that climate change is one "of the most pressing and serious threats to the ability of present and future generations to enjoy the right to life" – appropriate updates will reflect the severity of harm, scale, and urgency associated with transgressing ESTPs. Other UN treaty bodies, such as the Committee on the Elimination of Discrimination against Women (CEDAW) are also in a position to shift to the ESTPs paradigm in their periodic reports, as these bodies have already found that states have an obligation under international human rights norms to mitigate climate change (see: Mayer, 2022; United Nations OHCHR, 2018, para 2; United Nations, OHCHR, 2023, para 3).

1.4.6.2 Integrating human rights risk from ESTPs into due diligence in the financial sector

Over the past decade, concerns about human rights risks to people and their relationship to business risk have gradually migrated into corporate governance and finance norms (Rogge, 2022; Litwin & Savourey, 2025). The global finance sector and its regulators play an important role in implementing the human rights framework for ESTPs governance. Financial firms, banks, and the businesses that they invest in should integrate ESTPs human rights risk analysis into all aspects of risk mapping (see Chapter 1.2.3.2). Such mapping should also consider the human rights risks of implementing carbon credits and mitigation technologies in response to ESTPs, including geoengineering (United Nations OHCHR Report, Morgera, 2024) (on geoengineering, see Chapter 1.2). At a minimum, financial sector and corporate ESTPs human rights risk analysis should align with the authoritative standards for human rights due diligence set out in the UNGPs (UNGPs, 2011) and the OECD Guidelines for Multinational Enterprises (OECD Guidelines, 2023).

Adequate financing is needed to help prevent the severe human rights impacts of transgressing tipping points. In line with the state and non-state human rights obligations considered above, intergovernmental and multilateral institutions (e.g. multilateral financial institutions, development banks) have an obligation to take action to prevent and mitigate ESTPs risks. At the same time, loans, insurance mechanisms, and other financial instruments extended to vulnerable countries for mitigation and adaptation in response to ESTPs risks should not worsen those countries' ability to develop and maintain appropriate social infrastructure. In other words, financial mechanisms that support ESTPs prevention and mitigation must also support human rights, thriving communities, and healthy environments for all people.

ESTPs human rights risk analysis should be incorporated into the performance standards and grievance mechanisms of major financial institutions (e.g. IFC performance standards and Compliance Advisor Ombudsman process.

1.4.7 Leveraging the rights of nature for preventing and mitigating ESTPs

ESTPs pose a threat not only to human beings, but to nature itself. In the first Tipping Points Report 2023, it was recognised that there is "a need to consider not just humans but the rights of all species to exist on a healthy planet" (Section 4.6.1). The IACtHR's 2025 Advisory Opinion acknowledges the "increasing recognition of … the rights of Nature at the global level" (IACtHR, para 285). In lengthy groundbreaking decisions, Ecuadorian courts, including the Constitutional Court, have detailed clearly how human rights, the right to a healthy environment, and the rights of nature are interdependent and mutually reinforcing concepts (Los Cedros case, 2021; Llurimagua case, 2023). Incremental advances towards granting nature legal personhood and rights have occurred in many other jurisdictions (see Global Network on the Rights of Nature database). The emerging rights of nature jurisprudence has potential to inform policymaking in regards to ESTPs (for an example pertaining to coral reef ecosystems, see Earth Law Center, 2025). While global momentum builds around the rights of nature, states and non-state actors should not be guided solely by human rights norms; rather, they should also drive transformations that respect and enhance the rights of nature - not for instrumental human benefit, but for the intrinsic value of nature in and of itself (Avila Santamaría, 2024; Rodríguez-Garavito, 2024). Human rights and the rights of nature are interdependent and mutually reinforcing: the rights of nature and "interspecies justice" can only be realised if states uphold their duty to protect, respect, and fulfil human rights; and only if non-state actors, including businesses, respect human rights.

1.4.8 Conclusion: Towards an ESTPs-driven human rights and climate law

No human rights can be, or will be, fulfilled in a significantly compromised biosphere. The impacts of climate change are already throwing people into extreme distress, poverty, and ruin. If ESTPs are transgressed, conditions will worsen dramatically for already vulnerable communities and additional vulnerabilities will emerge. The best way to protect the threats to human rights of ESTPs is to prevent them from occurring in the first place. State and non-state intervention should prioritise delaying or permanently avoiding ESTPs and slowing the rate of their impacts (see Chapter 1.2). When prevention fails, just impact governance is needed to reduce exposure and vulnerability to ESTPs impacts (see Chapter 1.3). Drawing on the information contained in this report and the 2023 Global Tipping Points Report, advocates and jurists are in a position to drive an ESTPs-informed paradigm shift in human rights and climate law - this shift has the potential to accelerate ESTPs prevention and mitigation efforts by states and non-state actors. It must be acknowledged that there remain difficult legal doctrinal hurdles to overcome in the evolution of human rights and climate law (Ahmad, 2024) and in the development of ESTPs-informed jurisprudence. Nonetheless, significant progress has been made over the last decade (Leghari v. Federation of Pakistan, 2015; State of the Netherlands v. Urgenda Foundation, 2019; Neubauer, 2021; ITLOS, 2024; KlimaSeniorinnen, 2024; ICJ, 2025; IACtHR, 2025) and promising legal advocacy efforts continue apace around the world (Rodriguéz-Garavito, 2022; Aristova & Nichols, 2024, Tigre et al., 2025).

1.5 Actors, agency and strategies in Earth system tipping points governance

Authors: Ben Hudson, Manjana Milkoreit, Yulia Yamineva, Bernardo Flores, Margot Hurlbert, Karen Morrow, Leila Niamir, Malcolm Rogge, Stefanie Rynders, Jürgen Scheffran, Viktoria Spaiser, Joan David Tàbara, Sebastian Villasante, Simon Willcock

Reviewers: Michele M. Betsill, Maja Groff, Jessica Seddon

Key messages

- **Earth system tipping points (ESTPs) require engagement from not only national governments and international bodies, but also municipal, regional, corporate and community actors, each of whom have particular responsibilities, capacities and opportunities to influence outcomes.**
- **Diverse strategies are needed to address ESTPs—ranging from law and policymaking to advocacy, institutional reform and storytelling—drawing on the varied capacities, mandates and influence of actors operating across multiple scales and domains.**
- **In this early agenda-setting phase of ESTP governance, actors such as international organisations, science communicators and advocacy groups have a critical role to play in raising awareness, shaping narratives and mobilising political will.**
- **Addressing ESTPs requires building trust and fostering cooperation and coordination among state and non-state actors across multiple levels of governance.**

Earth system tipping points (ESTPs) have relevance for many governance actors across varying scales and they affect everyone – individuals, institutions, organisations and communities. This is because of the diversity of ESTP drivers and impacts, their geographical spread, and the potential for cascading effects. Moreover, the nature and scale of ESTPs are likely to overwhelm the capacity of any single governance actor.

Urgent action is needed to prevent crossing tipping points (see Chapter 1.2) and to prepare for their impacts (see Chapter 1.3). Multiple actors need to engage and take advantage of strategies that are available to them. For example, existing state institutions across scales, especially at the international level, need to adopt responsibilities for ESTP governance and define a corresponding agenda. This chapter maps the actor landscape and action options. Focusing on the current, early state of governance efforts related to ESTPs, the chapter explores the most immediate engagement needs in the short and medium term – learning and awareness raising, mobilising, agenda-setting, developing and initiating governance reforms and innovations, and coordinating across multiple stakeholders. It then discusses critical challenges key actors face.

1.5.1 ESTP governance functions

Governing ESTPs requires mobilising a diverse set of actors – this is because each performs particular functions related to the specific characteristics of ESTPs that cannot be easily substituted by others. Two features of the governance problem make this especially clear.

(1) Global systemic interdependence. Tipping points such as AMOC collapse or Amazon dieback are planetary in scale, yet regionally and locally varied in their triggers and consequences. They cannot be governed piecemeal or by any single state. International organisations and intergovernmental forums therefore play a necessary role in providing planetary reach, convening actors and legitimising the issue. In the absence of dedicated treaties, early agenda-setting at the UN and similar bodies is essential to anchor ESTPs as a collective governance challenge. At the same time, ESTPs require governance across multiple scales, including the distinct regional (multi-country) scale of specific tipping systems. Taken together, these features underline the need for a multi-scale, multi-stakeholder, networked and participatory approach to governance.

(2) High uncertainty and scientific complexity. ESTPs involve nonlinear dynamics, cascading effects, and thresholds that are difficult to identify with precision. In the absence of established norms or institutional frameworks, policymakers depend heavily on scientific communities and knowledge brokers to understand the biophysical processes of ESTPs, communicate risks, and establish credible and compelling reasons for why acting on tipping points matters. The role of the ESTP science community is not only to communicate uncertainty but also to support rapid learning and enable decision-makers to act on what is known. Scientific uncertainty is often used to justify inaction, yet, from a precautionary and anticipatory perspective, it is instead a strong reason to take measures that minimise threats to human wellbeing (see Report Introduction and Chaper 1.1).

Different actors assume varying degrees of importance throughout **different phases of the governance process.** Drawing on the established policy cycle framework (Howlett, 2009; Jann and Wegrich, 2007; Howlett et al., 2017), but operating within a larger, multi-scale system characterised by multiple institutional layers and cross-scale interactions, four main phases can be distinguished in ESTP governance:

(1) Agenda-setting: This phase involves defining the problem, identifying governance objectives and scope, establishing foundational principles, facilitating learning processes, conducting risk assessment, and enabling interest formation among relevant stakeholders. Key activities include framing tipping point risks, building scientific consensus, demonstrating political salience for action and mobilisation, and adopting institutional mandates for the problem.

(2) Policy formulation: This phase encompasses developing and designing ESTP governance responses, including norm entrepreneurship, reforms of existing policies and institutional mechanisms, selection of new policy instruments, and devising novel policies, initiatives, offices or organisations. It involves evaluating and contesting competing proposals through deliberative processes across multiple governance venues.

(3) Implementation: This phase involves making concrete decisions about which measures to pursue, applying rules and ensuring enforcement, allocating resources, and coordinating action across different scales and sectors. This phase is particularly challenging for tipping points due to their cross-boundary nature and long-term horizons.

(4) Monitoring and adaptation: This phase encompasses tracking the effectiveness of governance measures, assessing advancing scientific understanding of tipping point dynamics, evaluating institutional performance, and adapting governance approaches based on new evidence and changing conditions. It includes feedback mechanisms that inform subsequent policy cycles.

These phases represent complex, iterative and often overlapping processes that may proceed at different speeds across issue domains, sub-topics and governance venues. For instance, we might observe rapid responses to ongoing and observable phenomena, such as coral reef decline, through international initiatives and local management measures. Yet, there might be hesitancy and slower institutional reaction to less visible and more uncertain threats such as AMOC tipping. This is in part due to the absence of clearly designated responsible actors, as well as the longer-term, seemingly less tangible nature of the risks involved.

The four main phases of the governance process outlined above are conceptually independent of the three-phase governance framework we introduced in Chapter 1.1, Figure 1.1.1 (pre-tipping, reorganisation, stabilisation). Based on the assessment in this report (see Sections 2 and 3), the initial agenda-setting phase co-occurs with the pre-tipping phase for most tipping systems.

At the current phase of **agenda-setting for a new governance problem**, particular actor functions are needed: knowledge actors to clarify risks and enable learning, international organisations to establish legitimacy, governments to translate global concerns into political traction, and civil society and media to raise salience. Other actors—such as financial institutions, funders and transnational networks—will become increasingly central as governance moves into policy design and later implementation. Below we scope the larger landscape of relevant ESTP governance actors, with a particular focus on their roles in the current agenda-setting phase of governance and the following policy formulation phase.

1.5.2 The ESTP actor landscape

Table 1.5.1 maps the range of actors relevant to ESTPs, outlining their agency and the strategies they can employ across the agenda-setting and policy formulation phases of the ESTP governance process. It also identifies challenges when engaging with ESTPs. Table 1.5.1 is indicative, not exhaustive, of the range of governance tasks and functions needed, but what is clear is that **actors in all categories have reasons to engage with ESTPs, as well as distinct capabilities to do so.**

Table 1.5.1: ESTP actors, agency and challenges

Actor category	Distinctive value for ESTPs	Phase 1 (Agenda-setting): Key activities	Phase 2 (Policy formulation): Key activities	Challenges and constraints
1. Science and knowledge actors (e.g. IPCC, IPBES, Future Earth, Earth System Governance Project)	Provide authoritative knowledge on thresholds and cascades; develop early warning indicators; translate complex Earth system science into actionable concepts.	• Define and communicate tipping elements and risks. • Build consensus on ESTPs as relevant to governance. • Engage in high-level science–policy dialogues (e.g. IPCC).	• Deliver risk typologies, decision triggers, menus of no-regret options and adaptive pathways. • Develop scenarios and early warning signals. • Support scenario exercises and risk assessments.	Gaps and inefficiencies at the science-policy interface; resource limitations; effectively communicating high uncertainty.
2. International and regional organisations & treaty bodies (e.g. UNFCCC, CBD, UNEP, WMO, UNGA, OECD, ACTO, Arctic Council)	Provide global legitimacy; convene states; mandate work programmes; embed ESTPs into existing international regimes, processes and policies.	• Put ESTPs on the agenda. • Commission reports. • Organise agenda-setting dialogues and special sessions. • Adopt tipping specific mandates. • Coordinate varying stakeholders.	• Establish work programmes, shared glossaries and task forces (e.g. on the cryosphere, forests, AMOC). • Develop reporting templates and coordination platforms.	Siloed mandates; path dependencies in unwieldy processes with low ambition expectations; lack of enforcement power; geopolitical tensions; resource constraints.
3. National governments (custodians and emitters, e.g. Brazil, Arctic States)	Exercise regulatory control over land, ecosystems and emissions; set foreign policy; signal political salience; control access to critical data.	• Participate in high-level discussions. • Identify national interests. • Support science and data collection. • Enable data access with digital public infrastructure.	• Develop national tipping risk assessments. • Revise climate mitigation and adaptation policies. • Make contingency plans (e.g. on coral reef loss, AMOC tipping). • Lead club-style initiatives (e.g. carbon removal scaling).	Competing priorities; short-term electoral cycles; political economies tied to fossil fuels; uneven state capacity.
4. Subnational and city governments (e.g. C40, ICLEI, governor alliances)	Act as laboratories for rapid innovation; manage implementation levers in land use, infrastructure and climate adaptation.	• Pilot awareness campaigns. • Join transnational city/province networks.	• Test early warning protocols. • Experiment with zoning rules and local monitoring schemes.	Limited fiscal and legal authority; multiple levels of bureaucracy can slow or hinder action.
5. Courts and legal actors	Agenda amplification; rule clarification; signalling legal risk to states and private sectors; accountability and enforcement; precautionary leverage.	• Climate litigation can force recognition of ESTPs as part of broader climate/biodiversity cases. • Can establish mandates that help to accelerate action.	• Judgments and legal opinions shape how tipping points are framed in policy design; ensure new policies are legally defensible.	Typically reactive; largely constrained by the cases and questions brought before them.
6. Civil society organisations (NGOs, advocacy groups, social movements)	Translate science into demands; mobilise public opinion; act as watchdogs against policy capture; build justice frames linking ESTPs to equity and livelihoods.	• Campaign for recognition of tipping points as urgent risks. • Link ESTPs to broader climate justice debates.	• Stress-test draft policies for legitimacy and equity. • Propose accountability scorecards. • Build coalitions across issue areas (e.g. climate, biodiversity, human rights).	Resource and financial limitations and dependencies; limited access to formal decision-making processes; vulnerable to restriction by governments.
7. Indigenous Peoples and local communities	Can be stewards of ecosystems at risk (e.g. Amazon, Arctic, boreal); embody rights and legitimacy; hold place-based knowledge; vital for long-term monitoring.	• Raise visibility of rights and stewardship roles. • Testify on local observations of change. • Join advocacy coalitions.	• Co-design safeguards, FPIC mechanisms, benefit-sharing, and community monitoring systems written into policy drafts.	Historical marginalisation and lack of secure land rights; unequal power in governance forums; barriers to accessing high-quality information; limited resources to engage in transnational arenas.
8. Media (including social media)	Amplify salience beyond expert circles; connect abstract risks to lived experience; frame issues in ways accessible to broad publics; watchdog narratives.	• Report on emerging science and campaigns. • Cover potential tipping events. • Spotlight political inaction or leadership.	• Translate draft policies into accessible narratives. • Watchdog implementation claims. • Counter misinformation/disinformation.	Difficulty in translating complex science; loss of independence (private owners' editorial influence); misinformation, bias and politicisation; short news cycles; polarised media landscape.

Table 1.5.1: ESTP actors, agency and challenges

Actor category	Distinctive value for ESTPs	Phase 1 (Agenda-setting): Key activities	Phase 2 (Policy formulation): Key activities	Challenges and constraints
9. Financial system (e.g. central banks, investors, national and MDBs)	Re-price systemic risks linked to ESTPs; shift capital rapidly away from tipping-hazard sectors; drive alignment of economic incentives.	• Conduct risk assessments. • Acknowledge tipping risks in financial discourse. • Join coalitions (e.g. Network for Greening the Financial System).	• **Develop prudential guidance, including tipping risk scenarios for supervision.** • **Apply exclusion lists.** • **Embed conditionality in MDB loans.** • **Design disclosure norms tied to tipping elements.** • **Divest from risk-increasing industries.**	Short-term profit imperatives and myopic interpretation of fiduciary duties; inertia; dependence on conventional risk models.
10. Private sector / real economy firms	Control and influence resource use, emissions, and innovation; implement supply chain controls at scale; operationalise verification.	• Build expertise. • Conduct tipping risk assessments, including supply chain risks.	• Adjust disclosure protocols to include tipping risks. • Draft sectoral protocols (e.g. deforestation-free verification), supplier audits, and data-sharing standards interoperable with public early warning systems.	Short-term profit motive and competitive pressures; business model drives tipping risks; ESG backlash.

Legend: **Orange font indicates critical actors in this governance phase.**

1.5.3 Taking action on tipping points

Here the focus is on the opportunities and abilities of actors to advance ESTP governance during the two most proximate phases of governance: agenda-setting and policy formulation.

Actors and strategies for agenda-setting

In the early phase of governance, the central challenge is to ensure that ESTPs are recognised as urgent, legitimate and politically tractable. This requires active engagement by a set of actors whose particular roles combine to generate scientific credibility, cultivate public salience, mobilise political will and catalyse action.

Science and knowledge actors provide the foundation. Scientists and science-policy engagement across multiple scales are indispensable for informing various actors, fostering learning about the problem and communicating why tipping processes matter. Knowledge brokers (Meyer, 2010; Boari and Riboldazz, 2014; Reinecke, 2015) and boundary organisations (Guston, 2001; Miller, 2001) play a vital bridging role, translating complex research into accessible insights, creating channels for information flows, and supporting meaning-making across disciplines and policy arenas. These actors together enable decision-makers to act under uncertainty and adapt as understanding evolves.

A recent rare example of science-policy engagement on tipping points is an open letter on AMOC that was submitted by a group of 43 climate scientists to the Nordic Council of Ministers in October 2024. The letter drew attention to "the serious risk of a major ocean circulation change in the Atlantic" (2024, p.1), with a request that the Nordic Council "initiate an assessment of this significant risk to the Nordic countries" and "take steps to minimise this risk as much as possible" (2024, p.2). While the effects of the letter are still unfolding (e.g. the Council is funding a workshop on AMOC impacts on the Nordic countries), Box 1.5.1 illuminates some of the challenges of such science-policy engagement.

Box 1.5.1: Research Insight: State of Governance
The AMOC scientific assessment dilemma in Denmark: Institutional legitimacy versus emerging science

National climate policymaking can face a critical dilemma when emerging scientific evidence differs from assessments from established institutions. This challenge became evident in Denmark's parliamentary response to a letter from 43 scientists warning of sudden AMOC collapse. The letter warns of sudden AMOC collapse risks and emphasises urgency, while the IPCC's latest assessment projects slow AMOC decline with limited likelihood (less than 10%) this century. These contrasting scenarios carry vastly different implications for Danish society and government responsibilities.

Climate policy relies on distinct scientific institutions with established legitimacy to inform decision-making. The IPCC provides authoritative assessments for international and national policy, while dedicated national bodies—such as Denmark's Meteorological Institute (DMI), legally designated as the country's climate science advisor—offer specialised national guidance.

Danish parliamentarians acknowledged the inherent slowness of IPCC processes compared to the fast-moving research on tipping points, expressing desire to base decisions on the best available science. However, they faced a legitimacy problem. Denmark's legal framework designates DMI, alongside IPCC assessments, as the only legitimate source of climate risk information for policymaking. The 43 signatories of the letter were operating outside established IPCC and national assessment processes. Accepting alternative scientific sources risks undermining the authority of legally designated institutions and potentially politicising science by allowing governments to selectively choose preferred scientific voices.

The government's solution—requesting the IPCC to provide an updated AMOC assessment in its next report—highlights a core challenge: maintaining institutional scientific legitimacy while potentially waiting until 2028 for crucial risk information that emerging science suggests may be urgently needed for national policy decisions.

International organisations and intergovernmental forums engage with ESTPs at the planetary scale because global recognition and coordination are required. By introducing ESTPs into agendas at the UNFCCC, CBD, UNGA and related bodies, international organisations supply legitimacy and anchor the issue as a collective challenge rather than a scientific debate. In this early phase, organisations such as the UNFCCC need to consider how ESTPs relate to their existing mandates, fit into agendas and work programmes, and how institutions and processes might need to be adjusted to account for tipping dynamics. For example, parties to the Paris Agreement need to revisit the global goal on adaptation (Art. 7) and the Global Stocktake process (Art. 14) to consider how to revise global adaptation governance to address the expected impacts of ESTPs (see Chapter 1.3). CBD negotiations need to consider the potential of tipping dynamics to create abrupt, large-scale losses of biodiversity (e.g. coral reefs, in the Amazon rainforest), and the corresponding need to revise targets and indicators to capture tipping dynamics.

National governments of major emitters and custodians of key tipping elements are critical engines of political will. Countries such as Brazil (Amazon), Arctic states (ice sheets and permafrost) and large emitters can make or break early momentum. Their buy-in signals that ESTPs are both globally significant and politically tractable. These governments also control much of the relevant data, land use policy and investment decisions, making their engagement central to shaping future governance options.

Civil society organisations, advocacy NGOs and media act as catalysts by communicating urgency, generating legitimacy and opening pathways for bottom-up collective action. In this phase, when no formal governance arrangements yet exist, their ability to raise awareness, link ESTPs to lived experience and justice concerns, and mobilise pressure on governments is crucial. Civil society organisations and individuals are already mobilising around ESTPs – these efforts can be strengthened and widened (see Box 1.5.2 below for an example). It is especially important that those who will be most affected by tipping, including Indigenous Peoples, are heard and their expertise valued, and that those likely to live in a tipped world, namely youth and future generations, are made aware and empowered to act, including via social media.

Box 1.5.2: Research Insight: State of Governance
Civil society actors raising awareness of tipping risks: Operaatio Arktis in Finland

Civil society organisations can play a significant role in raising awareness about tipping risks, as illustrated by the case of Operaatio Arktis, a youth organisation in Finland. Founded in 2022 by former Extinction Rebellion activists, Operaatio Arktis focuses on nonlinear and extreme climate risks. The organisation currently employs 12 people and is primarily funded by Finnish and international private foundations, including the Kone Foundation, Maj and Tor Nessling Foundation, LAD Climate Fund and The Navigation Fund.

Operaatio Arktis aims "to preserve the polar ice caps and prevent global tipping points". It pursues this mission by raising public awareness, advocating for political leadership to integrate tipping risk management into national strategies, and promoting research aimed at predicting, preventing and preparing for tipping impacts. Its main activities include participating in public debates, media appearances and organising events. The organisation has successfully engaged a broad range of stakeholders, including scientists, Sámi indigenous organisations, politicians and government officials.

Tipping risks are a relatively new focus for the organisation. Previously, it concentrated on advocating for increased research on climate interventions, including Solar Radiation Management (SRM), which, in their words, together with emission reductions and carbon sequestration, "may have the potential to secure a stable society and a thriving habitat for younger generations". It appears that what prompted the organisation to work on tipping risks is perceived proximity to their earlier focus on climate interventions.

Tipping points champions – opinion leaders or institutional representatives designated to lead on tipping points within their respective domains – can help to raise the profile of tipping. For example, an international tipping points champion can build momentum and catalyse actions in the global policy space. The UN Secretary-General is already drawing attention to tipping risks, and enjoys a unique platform to further inspire action and to integrate tipping into the global conversation. At the national level, policymakers can act as tipping points champions. For example, in the UK House of Lords, several Peers have taken a lead on questioning the UK government about the existential risks posed by AMOC collapse and whether this is being factored into economic planning. Tipping points champions can also exist within non-governmental organisations and collectives, and can vary from scientists and educators, to business leaders and celebrities. The example of pop band, A-ha, collaborating with environmental activists to propel uptake of electric vehicles in Norway (by both consumers and the government) shows that this can be a successful strategy.

In short, critical at this early agenda-setting phase of ESTP governance are those actors who:

- establish credible, validated and engaging scientific framings, and translate them to wider audiences (knowledge actors, science-policy processes);
- provide platforms for global recognition (intergovernmental organisations, including those at regional scales with specific capacities related to distinct tipping elements);
- create political traction (national governments of key regions, civil society mobilisers); and
- build momentum with effective reporting and narratives (media, champions).

Other actors are also important, yet their influence is likely to grow as the issue matures from agenda-setting to policy formulation and implementation. For now, the 'first movers' need to anchor tipping points in political imagination and institutional debates.

Actors and strategies for policy formulation

As ESTP governance moves from agenda-setting into the policy formulation phase, the focus shifts from recognition to design - from generating awareness and political traction to shaping concrete governance options. In this phase, the key task is to translate broad concern into workable governance architectures, incentive structures and safeguards. In this policy formulation and institutional design phase, various action proposals to address ESTP risks are debated, developed and evaluated. These proposals can include reforms of existing policies and institutions, new principles and approaches (e.g. systemic risk governance or anticipatory governance, Earth system logic), and novel policy instruments and institutions.

These activities require a somewhat different constellation of actors than in the agenda-setting phase. While science, international organisations and national governments remain central, new actors such as Indigenous Peoples and local communities take on a more prominent role. Together, they help translate recognition of tipping risks into workable policy pathways.

Science and knowledge actors remain central, but their role evolves. Rather than primarily raising awareness, scientists, knowledge actors and experts now support the co-design of policy options, providing decision-relevant insights and scenario analyses to test feasibility under uncertainty.

International organisations and intergovernmental forums continue to provide legitimacy and spaces to convene, while also now serving as incubators of emerging norms and instruments. Through forums such as the UNFCCC, CBD or the G20, they can frame principles for tipping point governance, disseminate good practice, coordinate cross-border approaches and establish platforms for negotiation.

National governments become more directly engaged in shaping options, especially major emitters and custodians of tipping elements. Their domestic policies—on land use, emissions, infrastructure or indigenous rights—will define what is politically feasible and form templates for international governance arrangements.

While targeted ESTP actions are required at the national and international levels, it is also necessary to consider governance that is scaled to individual tipping elements (Milkoreit et al., 2024, p.11). While governance capacities at this scale are currently weak, in some cases regional institutions with suitable mandates exist, including the Amazon Cooperation Treaty Organisation (ACTO), the Arctic Council (including the Arctic Monitoring and Assessment Program) and the Nordic Council of Ministers.

Indigenous Peoples and local communities are essential to the design phase, both for their situated knowledge of ecosystems and for ensuring that governance strategies recognise and respect rights, secure safeguards and build legitimacy. Including Indigenous Peoples and local communities as partners in co-design helps avoid technocratic solutions that overlook lived realities and justice concerns.

Subnational governments (e.g. cities, regions, provinces) play a growing role as testbeds for innovation. They can pioneer pilot policies, experiment with regulatory and planning instruments, network and demonstrate models that may later be scaled nationally or internationally.

Economic actors, particularly industry associations and sector bodies, play an important role in shaping policy design. They often bring resources, agility, and deep knowledge of supply chains and on-the-ground realities. By recognising the risks of tipping points to their operations, major players can mobilise their established lobbying power to shape policy responses.

Financial actors and sectoral standard-setters become particularly important in this phase. Multilateral development banks, institutional investors, commodity certification bodies and corporate standard-setters can create the incentives and disclosure frameworks that translate tipping point risks into concrete practices. Embedding tipping risks into financial norms and sectoral rules can make emerging governance structures economically credible.

Box 1.5.3: Transnational initiatives and policy development

Transnational initiatives complement intergovernmental processes by creating norms, standards and collaborative practices that influence both public and private decision-making. CDP (formerly the Carbon Disclosure Project) illustrates this potential. By mobilising investors, companies, cities and regions to disclose climate-related risks and impacts, CDP has built one of the world's largest environmental reporting systems. Its frameworks help translate complex climate science into metrics that guide policy and investment decisions, thereby lowering uncertainty and increasing accountability.

Alongside such cross-sectoral initiatives, tipping specific transnational initiatives are already emerging. The International Coral Reef Initiative (ICRI), for example, unites governments, NGOs and scientific organisations to safeguard coral reefs—one of the ecosystems most at risk of crossing tipping thresholds. ICRI coordinates monitoring and data-sharing systems, promotes early warning indicators of reef decline, and works to embed reef resilience into national and international policy frameworks. These activities illustrate how transnational initiatives can not only amplify global attention but also generate practical governance tools targeted at specific tipping elements.

Taken together, initiatives like CDP and ICRI show how transnational networks can help operationalise knowledge, align economic and political actors, and create early building blocks for governance where formal rules are not yet in place.

Judicial actors can play an authoritative role in interpreting existing laws in the light of ESTPs. Courts have shown their willingness to interpret laws in the light of climate change, even when provisions are not explicitly related to this issue. For example, the European Court of Human Rights (ECtHR) has confirmed that climate change impacts can result in violations of the European Convention on Human Rights (*Verein KlimaSeniorinnen Schweiz and Others v. Switzerland* (2024) Application No. 53600/20). While courts are generally limited to the cases that are brought before them, there is scope for them to be proactive in integrating ESTPs into law. For example, when asked to provide an Advisory Opinion on State obligations in response to the climate emergency, the Inter-American Court of Human Rights (IACtHR) explicitly mentioned tipping points in respect to the severity of climate change impacts (see Chapter 1.4 on Human Rights for further discussion). Individuals and collectives can expedite this process by bringing explicit tipping specific litigation before the courts (see Chapter 3.2).

With increased activity on ESTPs comes a need for greater coordination. The plurality of tipping point actors and activities, across varying actor types and scales, requires coordination that respects and enhances this plurality, rather than dilutes or undermines it. Yet, effective coordination in a polycentric landscape is a challenging task. Multiple centres of decision-making can relate to each other in both competitive and cooperative ways (McGinnis and Ostrom, 2012).

Polycentricity can lead to fragmentation of governance, with both positive and negative impacts on its quality (Biermann et al., 2009), and a lack of coordination can lead to various inefficiencies, including competition for attention and resources among different actors. Cooperative strategies are therefore needed to coordinate various actors while respecting the agency that each has and the multiple perspectives they bring.

Taken together, these actors form the 'policy formulation coalition', tasked with moving ESTPs from abstract concern to implementable governance options, aligning incentives and embedding safeguards that can be adapted over time.

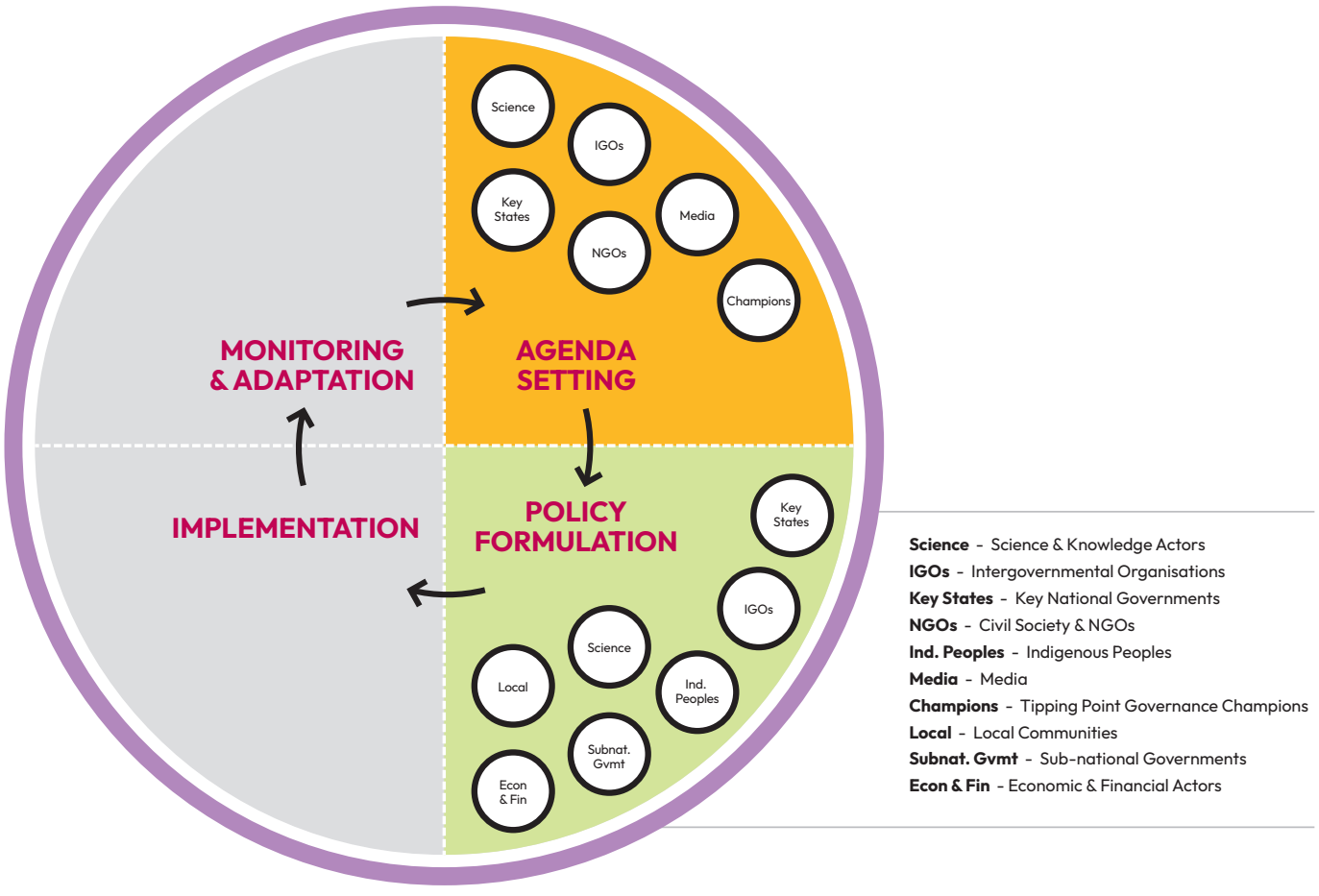


Figure 1.5.1: Key actors across phases of the ESTP governance process

1.5.4 Challenges in agenda-setting for tipping points

Setting the governance agenda for ESTPs faces a double bind: the science is both indispensable and challenging to communicate. Researchers and knowledge brokers must communicate deep uncertainty—such as nonlinear dynamics, thresholds and cascading risks—without losing urgency or credibility. If the risks are conveyed as too abstract, they can be dismissed as alarmist; if they are simplified too far, their gravity and systemic nature may be lost. Science–policy interfaces are only beginning to bridge this gap, and decision-makers remain hesitant to act on emerging evidence.

International organisations and national governments add another layer of challenge. Multilateral forums are already saturated with competing climate and development priorities, and geopolitical tensions strain collective action. At the same time, key national governments often weigh short-term economic and political pressures against longer-term systemic risks, slowing their willingness to put tipping points firmly on the agenda. The result is a governance vacuum, where ESTPs are recognised as urgent but not yet 'owned' politically.

Civil society and media can help fill this gap by raising salience, connecting tipping risks to justice concerns, and pressing governments to take notice. Yet here too there are obstacles: mobilising around uncertain or distant risks is inherently difficult, and public attention is fragmented by what are perceived as more immediate crises. Ensuring that those most affected—Indigenous Peoples, local communities and youth—are heard and valued is particularly important, however, their voices are not yet mainstreamed into global conversations.

These actor-specific hurdles are amplified by the current global political moment. Energy security concerns, economic instability and geopolitical rivalries constrain the bandwidth for new issues, while multilateral negotiations are already struggling to deliver on existing climate commitments. In this context, building momentum for ESTPs requires an 'agenda-setting coalition' that can overcome fragmentation, translate science into meaning and connect planetary risks to near-term decisions.

Cultivating trust among actors is also a challenge. There is existing mistrust in climate change governance, with trust strained by polarisation and shifts towards authoritarian leadership. Yet, trust is critically important for the success of collective climate efforts (Figueres, 2020) and for "shaping the network of policy agreement in a nascent subsystem" (Ingold et al., 2017, p.458). Building trust in ESTP governance requires distinct formats for trust-building, informal spaces for dialogue and, more broadly, the institutionalisation of social interaction (Schroeder et al., 2025). Trust can be built by shifting to collaborative forms of governance (Ansell and Gash, 2008, p.559). These are well-suited to ESTPs as they bring diverse actors together in collective forums with broad participation; collaboration "spurs a constructive use of scientific knowledge in processes of mutual learning and creative problem-solving" (Ansell et al., 2017, p.476). To stimulate collaboration, all actors need to believe their participation will have influence and produce results (Ansell et al., 2017, p.481). Given existing inequalities, effectively enabling all ESTP actors to collaborate will require a more equitable distribution of resources, as well as resource mobilisation and the strengthening of actors' capabilities. However, this brings an additional benefit for dealing with ESTPs: when affected actors are empowered and have agency and enhanced capabilities, they are better able to respond to environmental challenges and to cope with systemic risks and cascading impacts.

1.5.5 Final remarks

The governance of ESTPs is still in its infancy, and the world is only beginning to grapple with the magnitude of the challenge. ESTPs have relevance for many different actors across varying scales – all these actors have reasons to act on ESTPs and strategies available to them. The nature and scale of ESTPs is likely to overwhelm the capacity of any single actor, meaning co-operation is essential, and effective coordination is needed to ensure coherence, to harness synergies, and to realise ESTP action that is greater than the sum of its parts.

In the **agenda-setting phase**, the central tasks are to raise awareness, build legitimacy and generate political traction. This requires a coalition of scientists and knowledge brokers to translate complexity into actionable insights, international organisations to provide platforms and legitimacy, national governments to signal political will, and civil society and media to mobilise urgency and justice concerns. Together, these actors form an agenda-setting coalition that determines whether tipping points gain sustained visibility in global policy.

As attention shifts to the **policy formulation phase**, the challenge becomes one of translation – moving from recognising risks to designing workable governance structures. Here, science remains crucial, yet its role evolves towards co-design and decision support. International organisations and national governments continue to anchor negotiations, but must now partner closely with Indigenous Peoples and local communities to ensure legitimacy and safeguards. Financial actors, investors and sectoral standard-setters are essential in aligning incentives, while subnational governments offer fertile ground for experimentation. This policy formulation coalition is key to turning concern into credible pathways for action.

Both phases face formidable challenges, from scientific uncertainty and political and economic short-termism to fragmented attention and geopolitical strain. Yet, the urgency of tipping risks means that delay is itself dangerous. Early momentum will depend on building alliances that can bridge science and politics, connect planetary-scale risks to local realities, and translate abstract warnings into actionable governance options that are both legitimate and tractable. In this way, actors across levels and sectors can start to craft the foundations of a governance architecture capable of anticipating and navigating tipping points.

SECTION 2

EARTH SYSTEM TIPPING POINTS AND RISKS



Section lead authors:
Jesse Abrams, David Armstrong McKay, Joshua E. Buxton, Sina Loriani, Nico Wunderling

Chapter 2.1 Introduction to Earth system tipping points risks

Authors: Jesse F. Abrams, Steven J. Lade, Jonathan F. Donges, Paul Ritchie, Peter Ashwin, Sara Constantino, Viktoria Spaiser, Jana Sillmann, Sirkku Juhola, Yevgeny Aksenov, Laurie Laybourn

Reviewers: Ajay Gambhir, Sandy Trust, Luke Kemp

Key Messages

Earth system tipping points pose profound risks

- Tipping points threaten the stability of the Earth system, which our society and economy fundamentally rely on. Societal development, wellbeing, prosperity, and economic health are threatened by tipping points.
- Earth system tipping points create different types of risk to other climate impacts, often characterized by irreversibility, deep uncertainty, and potential for cascading failures across natural and human systems.
- **This is a national security issue as food, water and heat stresses will impact populations.**

New risk assessment and management approaches are needed for tipping points

- Traditional risk assessment fails: conventional impact-probability matrices capturing individual climate impacts are inappropriate for tipping point risk analysis, owing to uncertainty, nonlinear dynamics, and the systemic scale and scope of interactions between impacts and their cascading effects.
- New risk assessment frameworks are required: assessing tipping point risks can benefit from specialized approaches including risk registers that translate Earth system changes into policy-relevant "risk currencies" while capturing cascading effects and system interactions.

This Chapter introduces the concept of tipping points in the Earth system, their significance in climate change science, and a framework for assessing their risks and impacts. This framework provides the foundation for the assessment of Earth system tipping points presented in the remainder of this report. **Chapter 2.2** examines the biophysical science basis of individual ESTPs, providing an update on the status and likelihood of ESTPs and their interactions. **Chapter 2.3** explores overshoot scenarios and the risks of temperature overshoot for tipping points. **Chapter 2.4** translates these scientific insights into a practical risk register that quantifies impacts across our identified risk currencies, providing policymakers with actionable information for decision-making.

2.1.1. Why Tipping Points?

Tipping points represent critical thresholds in Earth's climate system where small changes can lead to significant, often irreversible consequences. Multiple tipping elements in the Earth system (Armstrong McKay et al., 2022) are already showing signs of destabilization under current warming levels. Current global warming already lies within the lower end of uncertainty ranges for several tipping points, including major ice sheets, permafrost systems, coral reefs, and various circulation patterns (Armstrong McKay et al., 2022). Several tipping points may be triggered within the range of 1.5-2°C global warming, with further increases in the likelihood of many more tipping points occurring at the 2-3°C of warming expected under current policy trajectories (Armstrong McKay et al., 2022). This creates an urgent need for systemic risk assessment that can inform policy decisions across scales from local adaptation planning to global climate governance. Understanding these tipping points is crucial for appropriate risk assessment and effective climate change mitigation and adaptation strategies.

In the Global Tipping Points Report 2023 (Lenton et al, 2023) we provided an assessment of Earth system tipping points, their risks and their implications for human societies. That report established the scientific foundation by identifying various Earth system tipping points, assessing their likelihood and timescales, and exploring potential impacts. The 2023 report demonstrated that several tipping points could be triggered in the 2030s at current rates of warming, with potentially catastrophic consequences for billions of people.

The 2023 report also highlighted critical knowledge gaps, particularly around tipping point interactions, cascading risks, and the translation of Earth system changes into policy-relevant risk assessments. While it found that empirical evidence of tipping cascades was scarce, it identified the potential for catastrophic risks from interconnected failures across natural and human systems.

Here we build on the previous assessment in several key ways. We incorporate the latest scientific evidence published since 2023 to update our assessments of individual tipping point likelihood, timing, and severity (Chapter 2.2). Building on the limited evidence of tipping cascades identified in 2023, we provide a more detailed assessment of how tipping points interact with each other and how risks cascade through interconnected natural and human systems. We then examine the critical question of temperature overshoot scenarios - whether temporarily exceeding temperature thresholds before returning below them could still trigger irreversible tipping points, and what this means for climate policy (Chapter 2.3). Finally, to make our scientific insights actionable, we translate our assessments into a detailed risk register that quantifies impacts across multiple risk domains, providing practical information for policymakers and risk managers (Chapter 2.4).

To do so, we apply and adapt established risk assessment approaches to ESTPs, translating Earth system science into policy-relevant "risk currencies" including food security, energy security, and geopolitical stability (Roberts et al, 2021).

New geography of climate change

The concept of tipping points fundamentally alters our understanding of climate change and its geographical implications. It introduces the possibility of abrupt, nonlinear and irreversible changes in regional and global climate patterns, challenging smooth projections. The impacts of tipping points are not uniformly distributed across the globe. For example, collapse of the Atlantic Meridional Overturning Circulation (AMOC) would affect the North Atlantic region most strongly. Tipping points highlight the interconnectedness of Earth's systems across different geographical scales, from local ecosystems to global atmospheric and oceanic circulation patterns.

This understanding requires a reevaluation of climate risks across different geographical regions and interconnected social and economic systems, potentially altering priorities for adaptation and mitigation strategies (as addressed in Section 1 of this report). The new geography of climate change must account for both gradual and reversible changes and the potential for sudden and irreversible shifts, necessitating a more dynamic approach to climate modeling and policy-making.

Thresholds, timescales and tipping mechanisms

Tipping points are associated with specific thresholds in key system parameters, such as the volume of ice on Greenland or the strength of the AMOC, and associated thresholds in forcing factors, such as temperature or freshwater input (**Chapter 2.2** provides a detailed analysis of these thresholds for individual tipping points). Once a tipping point is crossed the resulting transition can occur over various timescales, from abrupt changes occurring over decades to slower transitions spanning centuries. However, there is a common feature that on approaching a tipping point, linearity of response (where response scales linearly with small changes in forcing) breaks down.

For instance, a specific level of global warming might trigger the start of a melt of the Greenland or Antarctic ice sheet that may be irreversible - this represents 'bifurcation' tipping, where a system becomes unstable as key conditions slowly change, leading to a sudden transition to a new state once a critical threshold is crossed. This type of tipping is often associated with the classic notion of "tipping points" and can result in abrupt, irreversible changes. The speed at which systems approach and cross tipping points, and the rate at which these systems "tip" can vary widely, because of the physical processes involved.

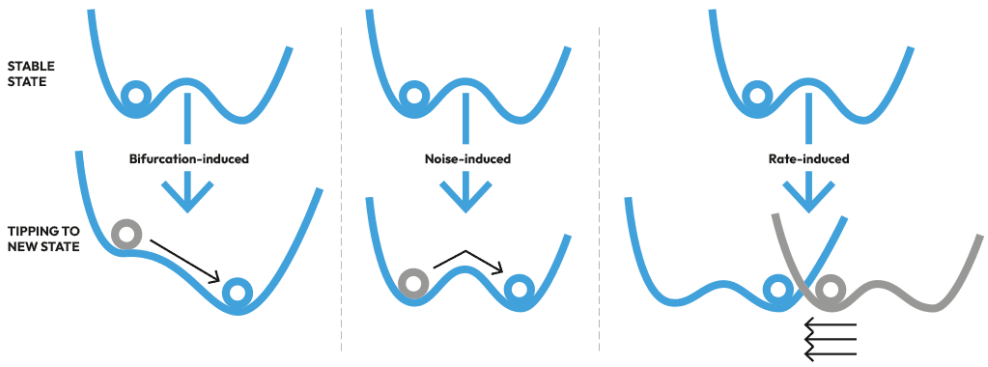


Figure 1. *Three types of tipping mechanisms in Earth systems. Bifurcation tipping occurs when a system becomes unstable as conditions slowly change, leading to a sudden transition once a critical threshold is crossed. Noise-induced tipping results from random fluctuations or extreme events pushing a system past its tipping point despite otherwise stable average conditions. Rate-induced tipping happens when the rate of change exceeds the system's ability to adapt, even before reaching absolute thresholds.*

This variation partly reflects different tipping mechanisms (Figure 1) - some systems are sensitive not just to how much forcing occurs, but how quickly it happens. 'Rate-induced' tipping happens when the rate of change in a system parameter exceeds the system's ability to adapt, even if the absolute change hasn't reached a critical threshold. This type of tipping highlights the importance of not just the magnitude of change, but also its speed. In Earth systems, rapid changes in factors like greenhouse gas concentrations or land use could potentially trigger rate-induced tipping events. The AMOC, for example, appears to be sensitive not just to how much warming occurs, but how quickly it happens - suggesting it could shut down from rapid warming even before critical temperature limits are crossed.

A third mechanism, 'noise-induced' tipping, can occur when random fluctuations or perturbations push a system past a tipping point even when average conditions might otherwise be stable. In the climate system, natural variability or extreme weather events can act as this "noise." For example, marine heatwaves can push already-stressed coral reefs past their recovery capacity, triggering widespread bleaching and ecosystem collapse even if average conditions might otherwise be tolerable (see **4.3 Coral Case Study**).

Understanding these different types of tipping is crucial for accurately assessing and predicting potential changes in different components of the Earth system (Figure 2). Bifurcation tipping may be more predictable given sufficient data on system thresholds, while rate-induced and noise-induced tipping present additional challenges for forecasting and risk assessment. Each type of tipping requires different approaches for detection, modeling, and prevention or mitigation strategies.

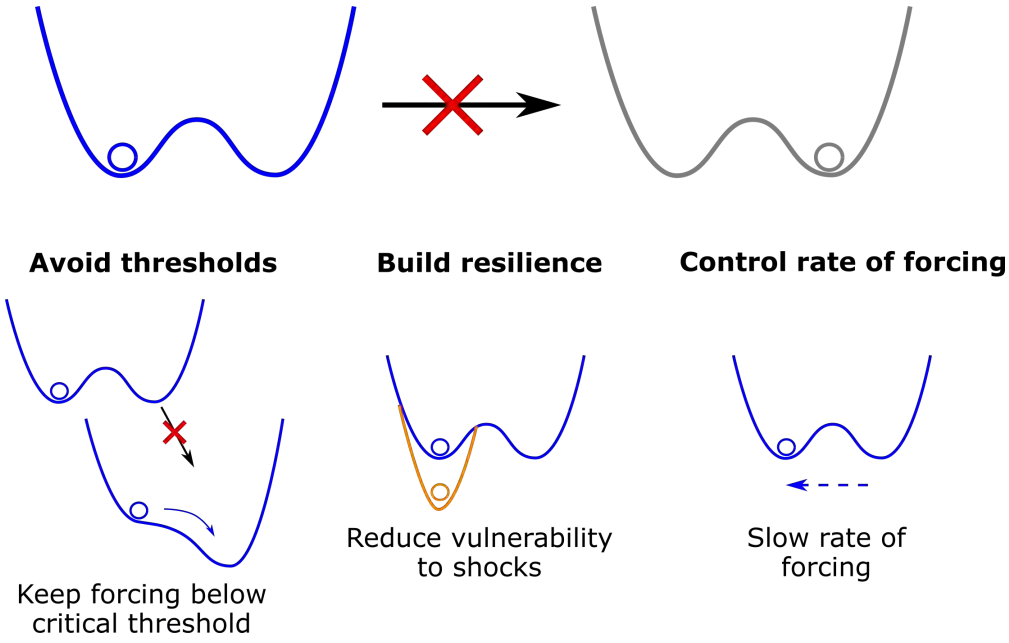


Figure 2. Prevention strategies for different tipping mechanisms. Bifurcation tipping can be prevented by avoiding critical thresholds through limiting the magnitude of forcing (e.g., keeping warming below specific temperature limits). Noise-induced tipping can be mitigated by strengthening system resilience and reducing background stresses that make systems vulnerable to extreme events and natural variability. Rate-induced tipping requires controlling the rate of change, such as limiting how quickly warming occurs.

Extremely fast changes could occur after passing tipping points for processes such as the collapse of monsoons. These present a challenge in that the speed of changes may exceed possible mitigation and adaptation. For more slowly evolving systems, such as deep ocean circulation, the effect of crossing a tipping point may unfold much more slowly (but still inexorably) over decades or centuries. In such cases, there remains the possibility that the consequences of crossing a tipping point can be avoided, if there is a return below the tipping point immediately after "overshooting" it. This reversibility is fleeting, however: if the tipping element completes its tipping then the known constraints on irreversibility for that tipping point apply and the opportunity is lost. This is explored in **Chapter 2.3**.

Bifurcation tipping may be prevented by keeping forcing below critical thresholds, while rate-induced tipping may be prevented by controlling rates of change, such as limiting how quickly warming occurs. Noise-induced tipping can be mitigated by strengthening system resilience and reducing background stresses that make systems vulnerable to extreme events. The governance of tipping point risks and strategies for prevention, adaptation and mitigation are covered in **Section 1** of this report.

It is therefore important to understand the processes involved in any tipping point. If the change in forcing is sufficiently slow and the system's behavior follows regular, consistent patterns, we may be able to detect statistical changes that serve as early warning signals of approaching tipping points (covered in Chapter 1.6 of the 2023 Global Tipping Points Report).

2.1.2. Risk framework for Earth system tipping points

Our framework builds on established approaches for environmental risk assessment that integrate climate science with impact assessment (Jones, 2001) and more recent developments in climatic impact-driver frameworks that systematically link physical climate changes to sectoral impacts (Ruane et al., 2022). The IPCC definition of climate change risk can be adopted to assess risks from Earth system tipping points (ESTPs). Risks therein are defined as the "potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems" (IPCC 2021). The complex nature of risk was central in the IPCC AR6, which pointed out the immense relevance of including feedbacks, cascades, nonlinear behavior and the potential for surprise (e.g. low likelihood high impact outcomes) in the risk assessment.

The IPCC Special Report on 1.5° Global Warming introduced compound risk as "the interaction of hazards, which can be characterized by single extreme events or multiple coincident or sequential events that interact with exposed systems or sectors" (IPCC 2018). However, this definition did not acknowledge the complex interaction between hazards, exposure and vulnerability shaping risks. Other studies have defined cascading risks as an "event or trend triggering others; interactions can be one way (e.g., domino or contagion effects) but can also have feedbacks; cascading risk is often associated with the vulnerability component of risk, such as critical infrastructure" (Simpson et al. 2021). This includes risks from cascading shocks, such as those causing irreversible changes in climate or impacts on a human timescale, tipping points, and indirect impacts.

However, the definition of risk is only one component of a functioning risk management framework. Key risk management principles are identified as (King et al, 2015):

- **Assess risks in relation to objectives, or interests**
  Start from an understanding of what it is that we wish to avoid, then assess its likelihood.
- **Identify the biggest risks**
  Focus on finding out more about worst-case scenarios in relation to long-term changes, as well as short-term events.
- **Consider the full range of probabilities**
  Bearing in mind that a very low probability may correspond to a very high risk, if the impact is catastrophic.
- **Use the best available information**
  Whether this is proven science or expert judgment. A best estimate is usually better than no estimate at all.
- **Take a holistic view**
  Assess systemic risks as well as direct risks. Assess risks across the full range of space and time affected by the relevant decisions.

Regrettably, these risk management principles have not typically been adhered to by policymakers when considering climate change and tipping points. For example, high-profile climate change assessments – including through the TCFD (Task Force on Climate related Financial Disclosures) - significantly underestimate risk, as they exclude many of the most severe risks we could face. Widely used economic assessments of climate impacts show relatively benign economic impacts which are inconsistent with science as they exclude tipping points, nature risks, and risk cascades such as displacement and conflict, thereby significantly understating risks. Policymakers who use these model outputs to guide decisions may therefore be implicitly accepting far higher levels of risk than they think. Although there is no precise globally-agreed risk appetite, it is reasonable to assume that most decision-makers want to minimise the risk of significant societal disruption, including from ESTPs.

A well recognised risk management principle is the precautionary principle, which is not consistently applied to climate change. The precautionary principle emphasises caution if it is possible that a given course of action may cause significant harm, particularly where there is high uncertainty. One of the most important expressions of the precautionary principle internationally is the Rio Declaration from the 1992 United Nations Conference on Environment and Development (United Nations, 1992). It is in common use as a concept by national governments including the EU (European Commission, 2000) and UK (DEFRA, 2023).

It is illustrative to compare societal approaches to climate change to that used in other areas of human endeavour with mature risk management approaches, which in many cases are regulated. For example, insurance companies hold capital to meet the liabilities they expect to meet in the future, as well as to cover adverse events so they can avoid becoming insolvent. In Europe the amount of capital insurers are required to hold is set at a level designed to withstand an extreme loss scenario that would occur only once in 200 years. Put another way, the amount of capital held is calculated to give a 0.5% chance that an insurance company would fail in any one year. Nuclear facilities have an even higher threshold for failure, designed to cope with hazards on a 1 in 10,000 basis. The contrast with the probabilities of success we have accepted with carbon budgets is stark.

A final consideration from a risk management perspective is the impact of partial tipping. Tipping points do not have to finish tipping to significantly impact weather patterns, with consequent impacts on key socio-economic systems including food, water, energy and transport.

For assessing Earth system tipping points (ESTPs), we adopt and build on the IPCC's understanding of risk complexity, particularly the AR6 framework's recognition that climate responses can themselves become sources of risk and that feedback loops and cascading impacts are central to comprehensive risk assessment. However, tipping points require additional considerations due to their potential for abrupt, irreversible changes and their capacity to trigger cascading failures across interconnected systems - exactly the kind of high-impact events that can have system-wide consequences. The framework addresses a critical gap in current climate-society-economy models, which often inadequately represent the feedback mechanisms and system interactions that are crucial for understanding tipping point risks. By incorporating systemic risk considerations and translating impacts into policy-relevant currencies, our approach ensures that scientific insights about tipping points can inform practical decision-making across different scales and sectors.

Our ESTP risk framework incorporates three main components (Figure 3). This approach addresses critical gaps identified in integrated models of natural and human Earth systems, particularly the need to better represent cascading effects and telecoupling processes that can amplify tipping point impacts across scales and sectors (Franzke et al., 2022):

1 **ESTP hazards and direct risks:** Individual ESTPs are assessed for their likelihood of occurrence (very unlikely to certain) and potential severity of impact (low to catastrophic) using established scientific evidence. This includes evaluating threshold temperatures, triggering mechanisms (bifurcation, rate-induced, or noise-induced tipping), and timescales of system transitions. We assess our confidence in these evaluations using a standardized scale (very low to very high confidence) that reflects the current state of scientific understanding and observational evidence. **Chapter 2.2** provides detailed assessments of the physical science of individual tipping points, while temperature overshoot scenarios and their implications for triggering irreversible changes are examined in **Chapter 2.3**.

2 **Systemic risk analysis:** Systemic risks arise when individual tipping points interact through cascading failures that spread across interconnected natural and human systems. We examine three types of cascading processes: tipping cascades (where one tipping point triggers another), impact cascades (chains of socioeconomic impacts), and emergent feedbacks (self-reinforcing cycles that amplify effects). The categories are not mutually exclusive: for example, cascades can also be connected through feedbacks. These interconnected processes can lead to severe outcomes, such as system collapse, over various time horizons (Sillmann et al. 2022). Current climate-society-economy models often inadequately represent these feedback mechanisms (e.g. Schaumann & Alastrué de Asenjo 2025), creating critical gaps in risk assessment. Globalization amplifies systemic risk, making it a worldwide concern that affects populations across the globe.

3 **Risk currencies: In Chapter 2.4**, risks arising from Earth system changes are interpreted in terms of policy-relevant "risk currencies" that decision-makers intuitively understand, including food security, energy security, water security, human security, economic stability, and geopolitical stability. This translation process captures both direct impacts from individual tipping points and systemic effects from cascading interactions.

We use these three components to construct a risk register that provides quantitative assessments across multiple domains, enabling policymakers to compare risks, set priorities, and develop targeted response strategies. **Chapter 2.4** presents the detailed risk register with regional and sectoral impact assessments across nine key risk currencies.

By adopting this framework, we seek to bridge the gap between scientific understanding of tipping points and the practical needs of risk management and policy formulation. It allows for a more nuanced treatment of uncertainty and systemic risk while still providing actionable insights for decision-makers.

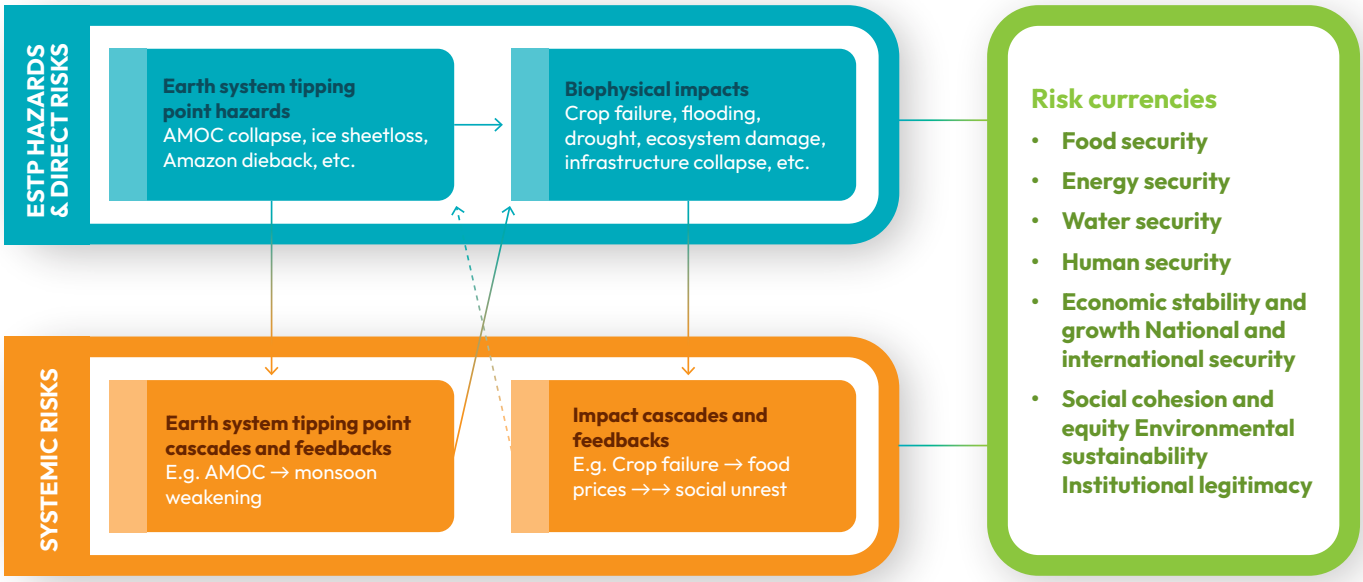


Figure 3. Direct risks (blue) show the linear pathway from tipping points through biophysical impacts to risk currency domains (green). Systemic risks (red) involve cascades and feedbacks related to Earth systems and impacts. Dashed lines indicate social-ecological feedbacks not fully assessed in this report.

Earth system tipping point hazards and direct risks

ESTPs hazards refer to the immediate and primary consequences of a tipping point being crossed. These might include rapid sea level rise from ice sheet collapse or sudden shifts in regional climate patterns. Direct risks, in contrast, encompass the direct effects that emerge as a result of these ESTPs hazards. For instance, the ESTP hazard of increased drought frequency might lead to direct risks, such as agricultural failures. When assessing ESTP hazards and direct risks, we categorize these in terms of their likelihood of occurrence (very unlikely / unlikely / likely / very likely / certain), and severity (low / moderate / major / critical), while also stating our confidence in those assessments (very low, low, medium, high and very high). Chapter 2.2 employs a standardized confidence framework using a +/- system to evaluate the scientific evidence for each tipping system. This framework assesses whether multiple independent lines of evidence support the presence of self-perpetuating feedback loops that can drive state shifts beyond critical thresholds, with high confidence (+++) indicating consistent support across paleoclimate records, models, and observations, while lower confidence levels (+, ++) reflect greater uncertainties in timing, magnitude, or feedback strength.

Systemic and cascading risks

Systemic risk occurs when the functioning of an entire system could be compromised due to the interactions among its components (Sillmann et al., 2022; Arnscheidt et al, 2025; Renn et al, 2017). The complex, interconnected nature of these risks can be visualized through network approaches that show how multiple risk factors interact and reinforce each other. In the context of Earth system tipping points, systemic risk encompasses the potential for ESTP impacts to propagate through interconnected natural and human systems, threatening the stability and functioning of broader Earth-human systems. Critically, responses to risks can themselves become risk factors, creating additional layers of complexity. When governments, institutions, or communities respond to ESTP impacts, their actions could inadvertently generate new vulnerabilities that propagate through interconnected systems (see Section 1 for a detailed exploration of governance). For example, emergency resource restrictions implemented in response to climate impacts might force communities into unsustainable practices that create longer-term risks.

Systemic risks are assessed in the following domains:

Earth system: Earth system tipping point causes changes to other Earth system components.

Societal: Direct impacts of Earth system tipping point on people causes other impacts on people

Social-ecological: Direct impacts of Earth system tipping point on people leads to acceleration or mitigation of other Earth system tipping points

Cascading risk is a specific type of systemic risk characterized by chains of impacts where one event triggers the next in a broadly domino-like fashion (Figure 4), although sometimes with feedback between the 'dominoes' to accelerate tipping (Simpson et al. 2021). The interconnected nature of cascading risks has been recognized across multiple disciplines as a fundamental challenge for risk assessment (Helbing, 2013), particularly in environmental systems where multiple interacting hazards can compound impacts in nonlinear ways (Pescaroli & Alexander, 2018; Zscheischler et al., 2018). Cascading regime shifts can occur both within ecological systems and across social-ecological scales (Rocha et al., 2018), making them especially relevant for understanding tipping point interactions. For example, the melting of the Greenland Ice Sheet could lead to increased heat absorption by the darker ocean surface, accelerating regional warming. This, in turn, could trigger further tipping points such as permafrost thaw or changes in atmospheric circulation patterns. Each step in this cascade can exacerbate the original impact and potentially push other systems closer to their own tipping points (Wunderling et al, 2024).

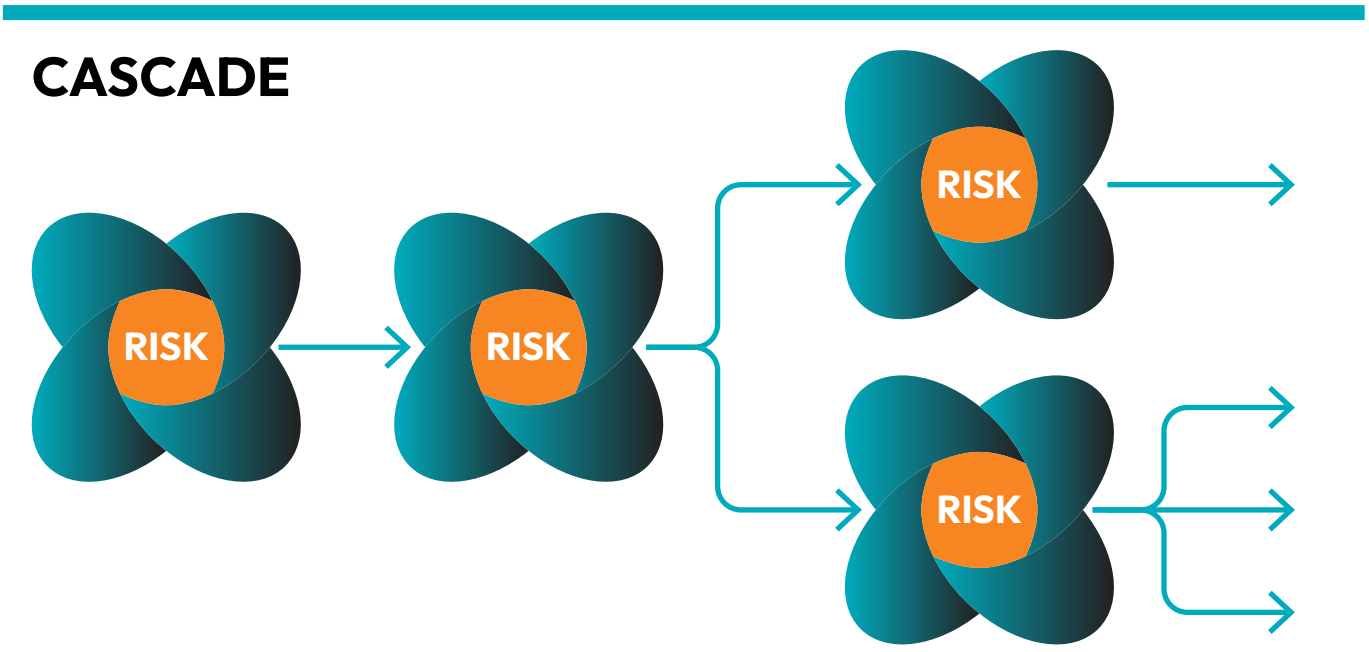


Figure 4. Cascading risk pathways showing how initial triggers can propagate through interconnected systems. Source: Adapted from Simpson et al. (2021).

The 2023 Global Tipping Points report found that empirical evidence of tipping cascades is currently scarce, with most research focused on climate change, coastal flooding and marine species tipping cascades. Significantly less is known about cascades from biophysical to socio-economic systems compared to cascades between biophysical systems. However, extrapolating from known feedbacks in complex human-natural systems suggests that tipping points in social and natural systems could plausibly form tipping cascades, with catastrophic risks for human wellbeing. This previous analysis underscores both the potential severity of cascading risks and the critical need for improved assessment frameworks. Here we differentiate between the following types of cascading risk

- **Tipping cascades:** chains of Earth system and/or societal tipping points where triggering of each tipping point causes the next to tip. For example, AMOC collapse could reduce northward heat transport and shift the Intertropical Convergence Zone southward, weakening the West African and Indian Summer Monsoons, which reduces regional precipitation and triggers vegetation loss that further destabilizes the monsoon systems through reduced evapotranspiration.
- **Impact cascades:** chains of impacts where each impact causes the next impact. These impacts may ultimately be the consequence of a tipping point, but the impacts themselves do not display tipping characteristics. For instance, regional drought leads to crop failure, which causes food price spikes, triggering social unrest and political instability.
- **Emergent feedbacks:** circular chains of Earth system or societal tipping points or impacts that could amplify impacts. For example, forest fires release CO2 causing further warming, which increases fire risk, creating a self-reinforcing cycle.

For each ESTP we assess these different systemic risks, as well as the interplay between these. The interplay between systemic risks can create complex domino effects, feedback loops and amplification processes. For instance, a tipping point in the Amazon rainforest leading to its dieback could trigger a cascade of impacts on regional water cycles, biodiversity, and carbon storage. These cascading effects could then translate into systemic risks for global climate regulation, international trade in agricultural commodities, and geopolitical stability in the region (see **4.1 Amazon Case Study**).

Risk currency

"Risk currency" is a term used to describe the fundamental concerns that drive policy decision-making across all levels of governance: risks of primary importance which are understood intuitively by people and decision-making cultures and systems (Roberts et al 2021). These currencies include the objectives and interests pursued by states and other system-scale actors: food security, energy security, water security, human security, economic stability and growth, national and international security, social cohesion and equity, environmental sustainability, and institutional legitimacy (**Chapter 2.4**). Policymakers think in terms of protecting lives, maintaining economic competitiveness, ensuring energy and food security, preventing social unrest, safeguarding critical infrastructure, and preserving the effectiveness of governance systems. They are concerned with measurable impacts on GDP, employment rates, public health metrics, migration pressures, and the functioning of essential services. In this context, information about the climatic changes and biophysical impacts of tipping points might not be by themselves enough to engage decision-makers, as these do not directly relate to risk currencies. Risk currency thus refers to the translation of Earth system impacts (direct, systemic, cascading) into metrics and language that resonate with policy and decision-makers. The translation of Earth system changes into these risk currencies requires a systematic approach that captures both direct impacts and their strategic implications (Figure 5).

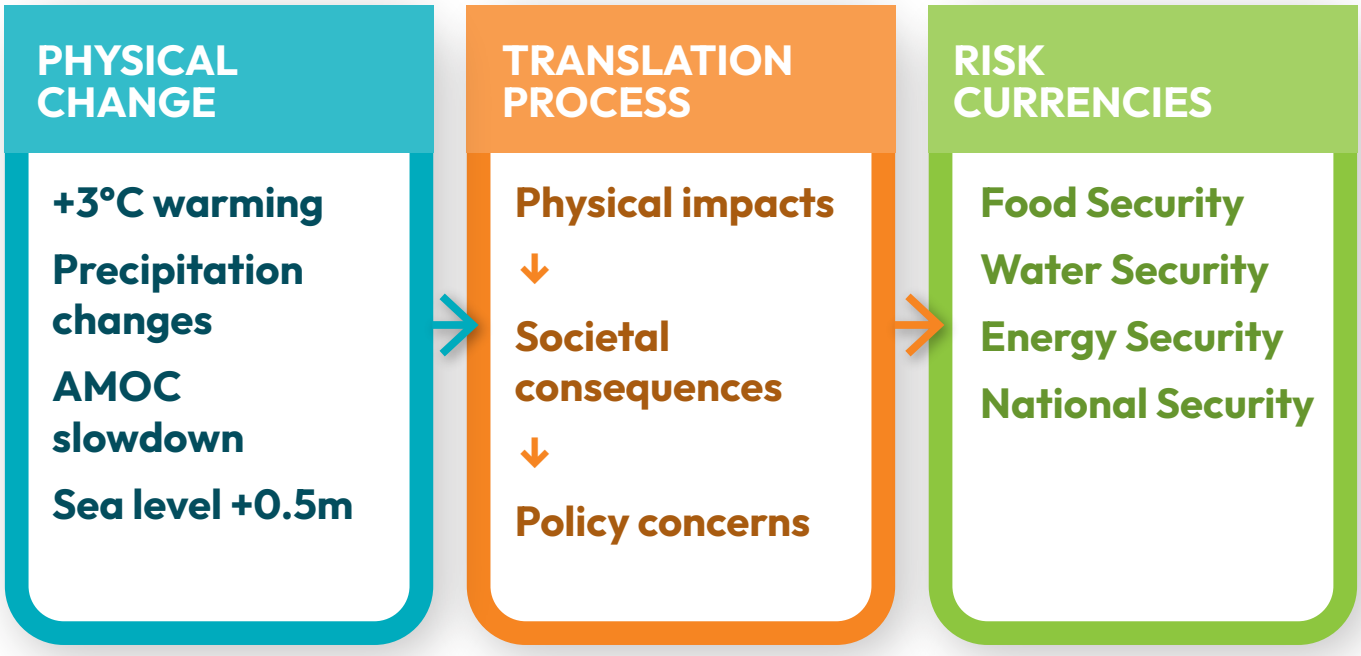


Figure 5. Risk currency translation framework, showing how Earth system tipping point impacts are converted into policy-relevant security concerns across different domains.

Understanding tipping point risks in terms of these policy-relevant currencies is crucial for several reasons. First, it translates complex Earth system science into the language of policy impact assessment that decision-makers use daily. Second, it demonstrates why tipping points cannot be treated as simply environmental issues but must be recognized as fundamental threats to societal stability (Monnin & Hiebert, 2023). Climate change has a clear systemic dimension: its consequences are not only widespread across all sectors and regions, but potential concentrations, spillovers and interlinkages risk amplifying its impacts further (Monnin & Hiebert, 2023). Third, it provides a framework for prioritizing policy responses based on which risk currencies are most threatened and which populations are most vulnerable (Milkoreit et al., 2024). Finally, it reveals why traditional risk assessment approaches, designed for single-currency risks, are inadequate for the multi-currency, systemic nature of tipping point impacts (European Commission JRC, 2025). Due to their long timescales, multi-hazard, cross-boundary and systemic risk nature, risk and impact assessments of crossing tipping points go beyond conventional disaster and climate risk analysis, and adaptation solutions will be needed (UNDRR, 2022).

The AMOC collapse example illustrates this translation process clearly (Figure 6). Physical changes in ocean circulation translate into concrete impacts on food security, energy demands, economic costs, and geopolitical stability - each representing different currencies that policymakers can understand and act upon (see **4.2 Atlantic Ocean circulation case study**).

The currency of risk in this framework converts changes in Earth system parameters - such as temperature increases, precipitation pattern shifts, or extreme weather event frequency - into terms directly relevant to societal concerns. For instance, alterations in regional climate patterns are expressed in terms of their implications for food security, considering impacts on crop yields, agricultural productivity, and global food supply chains. Similarly, changes in hydrological cycles are framed in the context of water security, highlighting potential challenges in water availability for human consumption, agriculture, and industry.

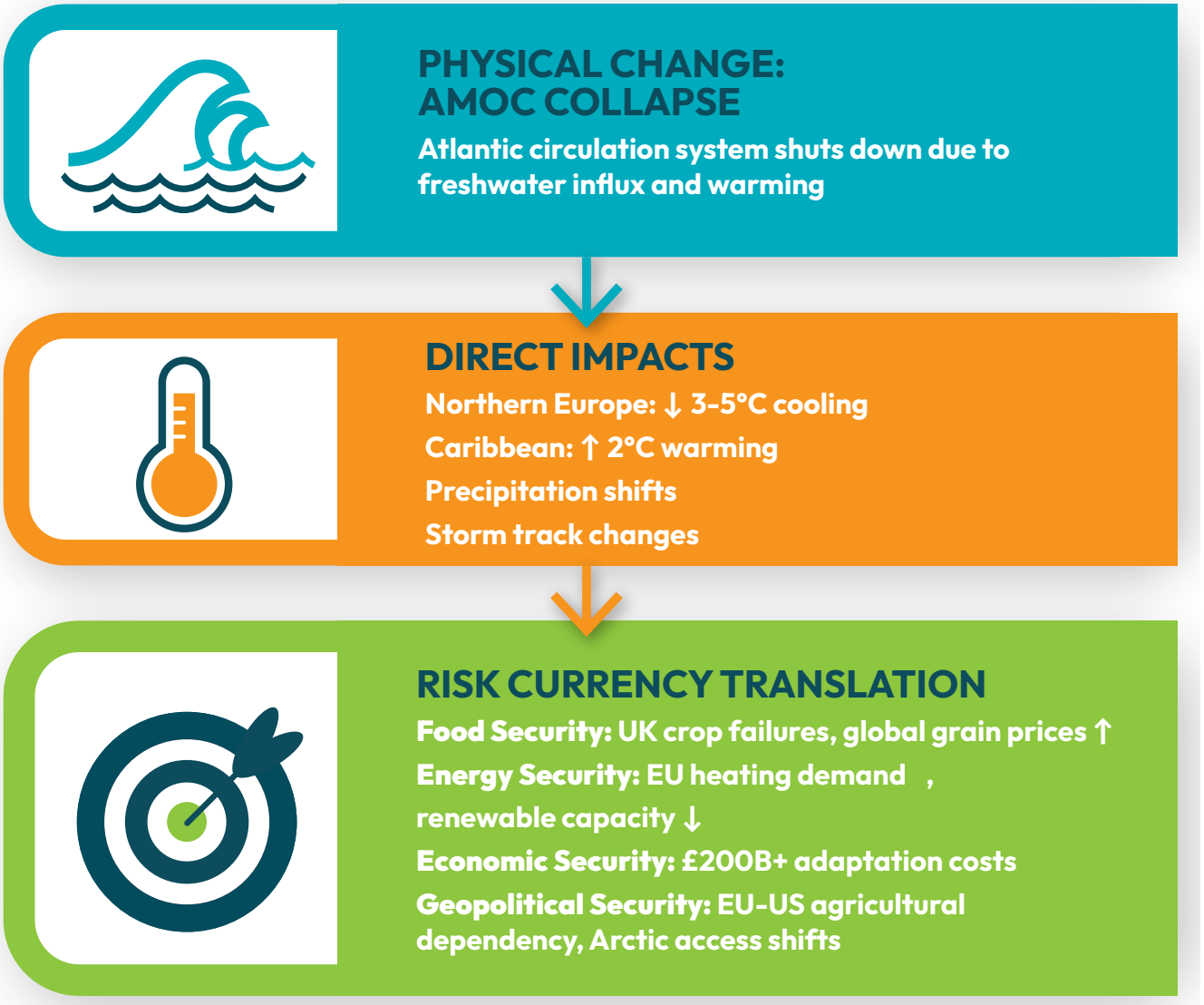


Figure 6. AMOC collapse risk currency example, demonstrating how physical ocean circulation changes translate into specific policy-relevant impacts across food security, energy security, economic security, and geopolitical domains.

This approach extends to other critical areas of concern for decision-makers. Climate-induced alterations in ecosystems and resource availability are presented in terms of their potential impacts on national security, including the risk of resource conflicts or climate-driven migration. Energy security is another crucial 'currency', with the framework articulating how climate tipping points might affect energy production, distribution, and consumption patterns.

Risk register

Earth system tipping points represent some of the most significant and poorly understood risks in climate science, yet they remain inadequately integrated into policy and risk management frameworks (Armstrong McKay et al., 2022; Lenton et al., 2019). Unlike conventional risks that follow predictable patterns, tipping points involve the change in behaviour of a system beyond a threshold, where small changes in forcing can trigger large, often irreversible changes that fundamentally alter Earth system functioning (Lenton et al., 2008). These systems are characterized by deep uncertainty, meaning precise probabilities cannot be determined with current knowledge, even as scientific understanding advances (Kriegler et al., 2009). Assessing such deep uncertainty requires specialized approaches that move beyond traditional probabilistic risk assessment toward frameworks designed specifically for high impact-low likelihood events where precise probabilities cannot be determined (Wood et al., 2023). This uncertainty is compounded by the cascade potential inherent in these systems, as individual tipping points can interact through complex feedback mechanisms to trigger others, creating the possibility of cascading failures across the Earth system (Wunderling et al., 2021; Wunderling et al., 2024; Klose et al, 2021; Wunderling et al, 2023; Spaiser et al (2024).

The temporal dimension of tipping point risks presents additional challenges for traditional risk management. Many changes associated with tipping points are irreversible on policy-relevant timescales of decades to centuries, meaning that once triggered, these changes cannot be undone through conventional mitigation strategies (Steffen et al., 2018). Furthermore, even regionally-focused tipping points can have global implications, with worldwide consequences for human societies, economies, and ecosystems far from the original source of change (Wang et al., 2023).

Governments use risk registers to provide practical examples of how complex, interconnected risks are assessed and communicated to policymakers and the public, such as the UK's National Risk Register (HM Government, 2025; Figure 7). A risk register is a tool used to identify, assess, and support the management of risks within a given context. It provides a structured way to record potential threats. The main purpose of a risk register is to support better decision-making via the qualitative or quantitative assessment of the severity and likelihood of an impactful event. By providing a clear overview of current and emerging risks, a risk register can help those with responsibility for risk management to prioritise actions, allocate resources, and remain accountable. As such, risk registers are also a key part of transparency and governance. Overall, a risk register should enable proactive, rather than reactive, management, reducing the chance of being caught off guard and improving the likelihood of achieving objectives.

Risk registers are typically presented as a table, spreadsheet, or a matrix that focuses on quantities relevant to assessment and management. For example, a risk register used by a government to identify major threats at the scale of a society is typically constructed using a matrix plotting the potential impact of a risk against a calculation of the likelihood.

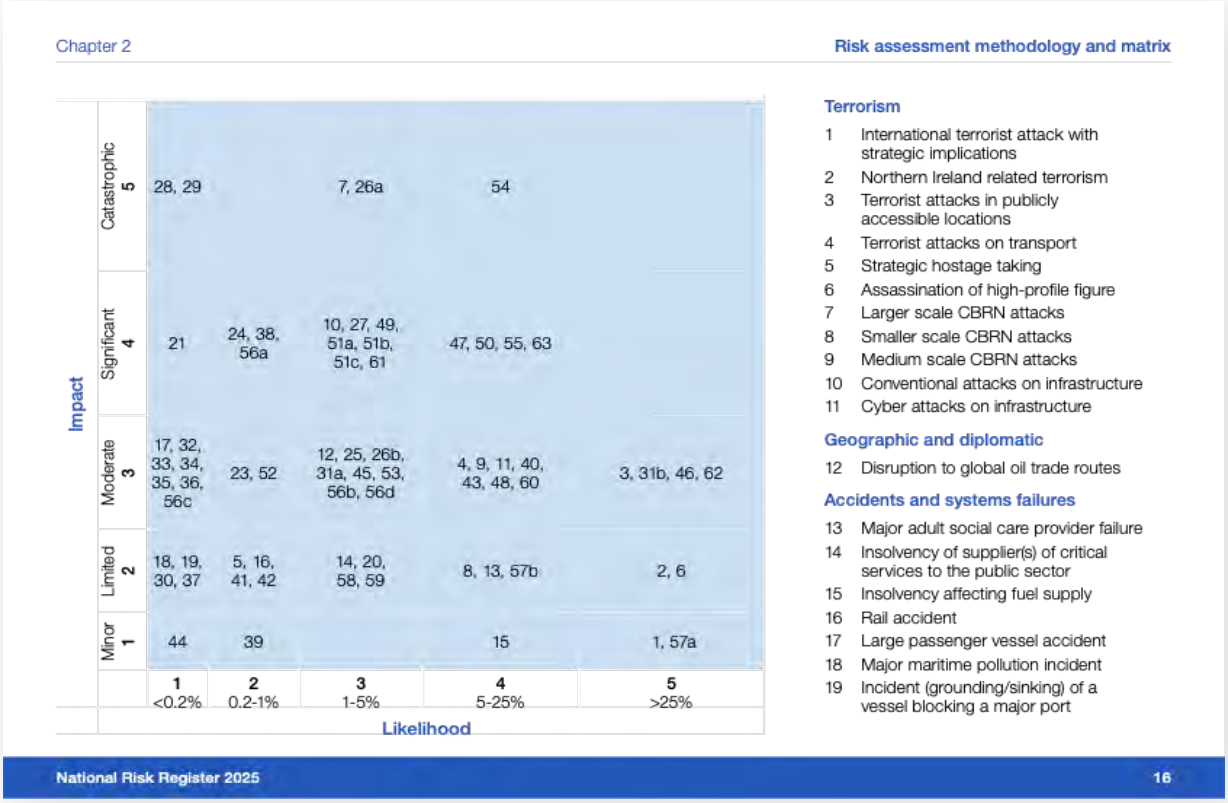


Figure 7. Example from the UK Government's National Risk Register showing systematic risk assessment methodology, including likelihood-impact matrices and consideration of cascading effects that inform our adapted framework for Earth system tipping points. Source: HM Government (2025) National Risk Register 2025, Cabinet Office.

These registers demonstrate systematic approaches to categorizing risks by likelihood and impact, while also considering cascading effects and dependencies between different risk types. Our ESTP framework builds on these established risk assessment methodologies, adapting them specifically for the unique challenges posed by Earth system tipping points.

Traditional risk register approaches face significant limitations when applied to tipping point systems characterised by deep uncertainty, as precise probability estimates are often misleading or impossible to determine reliably. To illustrate how these approaches could be better adapted for tipping points, we have developed a mock Earth system tipping points risk register (Figure 8) that uses temperature thresholds as a proxy for the timing of when different tipping points may be triggered, rather than using conventional likelihood categories.

This approach recognizes that while we cannot assign precise probabilities to tipping events, we can identify the temperature ranges at which different systems become vulnerable based on current scientific understanding. While this temperature-based risk register provides a systematic approach for communicating ESTP risks to policymakers, Chapter 2.4 explores this approach alongside alternative methods including impact-focused assessments that emphasize consequence severity rather than probabilistic estimates. These methods provide more robust foundations for policy decision-making under conditions of deep uncertainty, where the focus shifts from predicting when tipping points will occur to understanding what happens if and when they do.

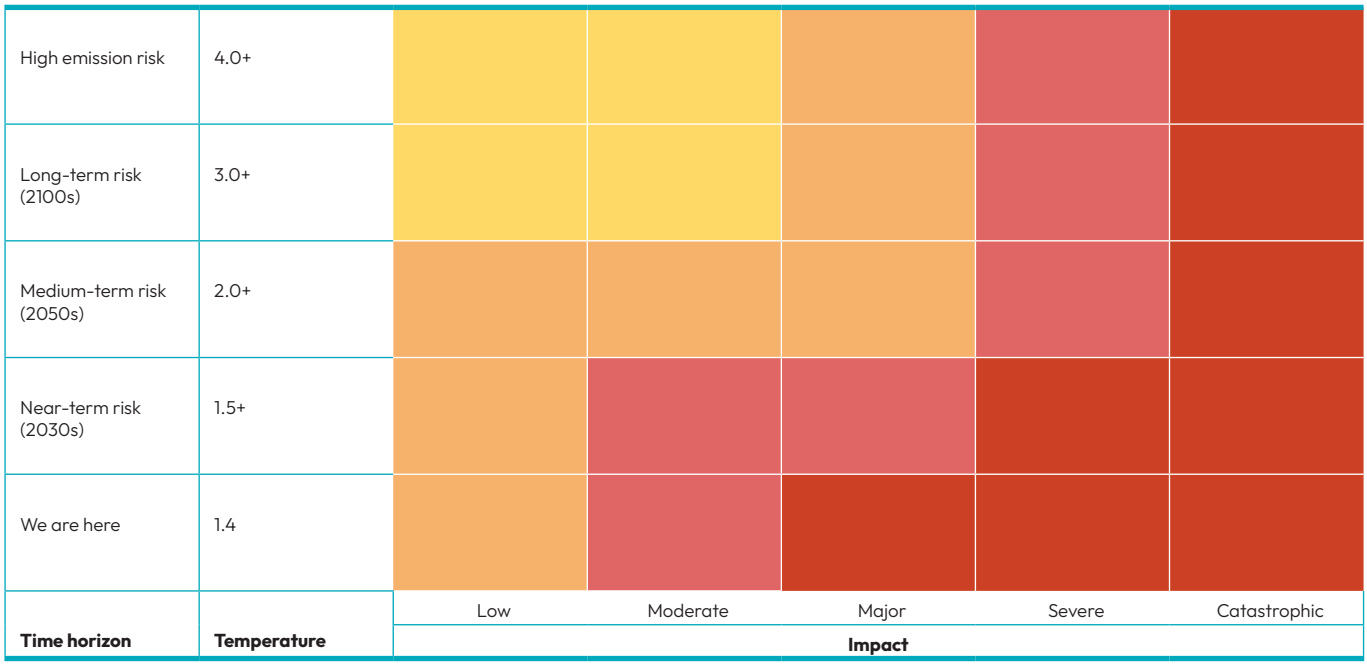


Figure 8: Earth system tipping points risk register. Temperature-threshold based risk assessment showing when different tipping points may be triggered under various warming scenarios, with impacts categorized by severity.

Looking ahead

The following chapters apply this framework. **Chapter 2.2** provides detailed scientific assessment of individual tipping points, their thresholds, timescales, and interactions with each other. **Chapter 2.3** examines the critical question of temperature overshoot scenarios and their implications for tipping point risks. **Chapter 2.4** implements our risk register approach through regional and sectoral impact assessment, translating Earth system science into actionable risk information across nine policy-relevant risk currencies.

Chapter 2.2 Status of Earth system tipping points: What's new?

Authors: David I. Armstrong McKay, Joshua E. Buxton, Sina Loriani, Nico Wunderling, Beniamino Abis, Jesse F. Abrams, Yevgeny Aksenov, Beatriz Arellano Nava, Maura Brunetti, Cristiano M. Chiessi, Vasilis Dakos, Donovan P. Dennis, Norman C. Duke, Matthew H. England, Bernardo M. Flores, Julius Garbe, Kathryn Gunn, Dag O. Hessen, Anna von der Heydt, Andreas Kääb, Sonia Kéfi, Petra M. Langebroek, Valerio Lucarini, Gabriele Messori, Helen Millman, Jan Nitzbon, Isobel Parry, Benoît Pichon, Marie-Aude Pradal, Boris Sakschewski, José A. Sanabria-Fernández, Jörg Schwinger, Sacha Sinet, Bryan M. Spears, A. Carla Staver, Norman J. Steinert, Ivan Sudakow, Thejna Tharammal

Reviewers: Robbin Bastiaansen, Sebastian Bathiany, John Dearing, Swinda Falkena, Ed Gasson, Goran Georgievski, Kai Kornhuber, Nicole C. Laureanti, Tim Lenton, Carlos López-Martínez, Catherine Lovelock, Ben Marzeion, David Obura, Paul Pearce-Kelly, Juan Rocha, Jonathan Rosser, René van Westen,

Acknowledged: Daniel Mayor, Arie Staal, Els Weinans

Key messages

Cryosphere

- We have high confidence that ice sheets - from Greenland to West Antarctica - have tipping points leading to irreversible collapse, locking in long-term multi-metre sea level rise, and have been at risk since at least 1°C of global warming.
- While Arctic summer sea ice is unlikely to reach tipping points, we cannot rule out a tipping point for Antarctic sea ice which could already be underway, although this is highly uncertain.
- We have medium confidence in potential regional tipping in permafrost and glaciers, which would respectively amplify emissions and commit some regions to total deglaciation.

Biosphere

- The Amazon rainforest has faced two years of intense El Niño-induced drought, and the combined effects of deforestation and climate change put it at risk below 2°C of global warming.
- Warm-water coral reefs have experienced the worst bleaching event on record over 2023-25, and the central estimate of their thermal tipping point of 1.2°C global warming has been crossed.
- We now recognise river deltas and peat bogs as potential tipping systems, identify the potential for localised mangrove tipping with high confidence, and the potential for local-scale temperate forests tipping with low confidence.

Ocean/Atmosphere circulations

- Recent modelling supports convection in the Atlantic Meridional Overturning Circulation (AMOC) and subpolar gyre being capable of tipping, which cannot be ruled out at current warming levels, but limited models and observations means how likely they are to tip on current trajectory remains uncertain.
- In the Southern Ocean, dense shelf Water formation may be declining and could reach a tipping point, but understanding of its interactions with ice remains limited.
- Evidence has strengthened for no tipping dynamics in the 'jet stream', while recent modelling supports monsoons having tipping dynamics, but evidence remains limited.

Interactions

- Out of 20 climate tipping system interactions assessed, most are destabilising, but a few (e.g. AMOC on Amazon, West Antarctic Ice Sheet on AMOC) may have a stabilising effect.
- A vicious cycle may form where permafrost thaw could lead to amplified Arctic sea ice retreat, which may lead to enhanced inland permafrost degradation and so on.
- The AMOC is the key global mediator of tipping point interactions, featuring in 45 per cent of all assessed tipping point interactions.

2.2.1 Executive summary

Many parts of the Earth system can reach a point beyond which change in response to pressure can become self-sustaining, resulting in an often irreversible and abrupt shift to a very different state - what we refer to as a 'tipping point'. In this chapter we briefly summarise each proposed tipping system covered by the last Global Tipping Points Report, and reassess each based on relevant new scientific research published since the last report.

In the **cryosphere** - Earth's frozen reaches - we (the Global Tipping Points community) maintain high confidence in ice sheet tipping points, two of which have been at risk since around 1°C of warming, with potentially substantial consequences for future sea level rise. We also maintain medium confidence in local to regional tipping in permafrost and glaciers, with implications for amplified emissions and regional deglaciation. While Arctic summer sea ice decline is unlikely to reach a tipping point, we cannot rule out tipping for it in the winter, or around Antarctica, where sea ice has recently dropped for the first time.

In the **biosphere** - the living world - we are more confident in the potential for tipping in the Amazon at various scales, and note that combined with ongoing deforestation as little as 1.5°C of warming could trigger widespread dieback. Both the Amazon and coral reefs have suffered during the 2024-25 El Niño event, seeing the worst coral bleaching event on record and signs of die-off in many regions. We also have higher confidence in localised mangrove tipping, and now include peat bogs and river deltas as potential freshwater tipping systems.

In the **circulations of the ocean and atmosphere**, recent research strengthens the case for North Atlantic convection being capable of tipping, potentially at current warming levels, but large uncertainties remain on if and when they may tip in practice. Convection around Antarctica may also be weakening towards a tipping point, driven by warming and meltwater, but we are not sure how this in turn interacts with ice melt. We now include the East Asian summer monsoon as a potential tipping system, but remain confident that despite changes in response to warming the northern polar 'jet stream' as well as the El Niño Southern Oscillation (ENSO) and large-scale tropical circulations are unlikely to have a tipping point.

Tipping points do not exist in isolation - they **interact** in ways that can change the likelihood of their tipping. We have extended our previous analysis to cover more than twenty climate tipping system interactions, adding in for example interactions with subglacial basins in East Antarctica or interactions with the permafrost. Our newest science updates maintain the finding that the majority are destabilising. For example, a vicious cycle may form where permafrost thaw releases greenhouse gases, driving further warming and more Arctic sea ice retreat, which by making the Arctic darker amplifies warming, amplifying inland permafrost degradation, and so on. The AMOC emerges as a key global mediator of tipping point interactions, featuring in nearly half of all assessed tipping point interactions, including a few that may potentially have a stabilising effect, such as AMOC collapse's impact on the southern Amazon rainforest, and West Antarctic Ice Sheet impact on the AMOC.

2.2.2 Summary table

Table 2.2.1: Tipping assessment for each system considered, highlighting changes since GTPR23. Key: +++ (high confidence yes), ++ (medium yes), + (low yes), ? (uncertain), – – – (high no), – – (medium no), – (low no).

Domain	Tipping system (& tipping dynamics)	GTPR25 tipping system assessment (bolded if changed vs. GTPR23)
Cryosphere	**Ice Sheets (collapse)**	Greenland: +++ **[threshold updated]** West Antarctica: +++ Marine basins East Antarctica: +++ Non-marine East Antarctica: ++
	Sea Ice (loss)	Arctic summer: - - - **Arctic winter: ?** [was: - -] Barents Sea: - Antarctic / Southern Ocean: ?
	Glaciers (retreat) See 4.4 Mountain glaciers case study	++ (regional) - - (global)
	Permafrost (thaw)	++ (regional, land) - - (global, land / subsea)
Biosphere	**Tropical Forests (dieback)** See 4.1 The Amazon rainforest case study	Amazon: +++ (local) **[threshold updated]** ++ (regional) + (continental) Congo: + (local), **? (regional)** [regional added] SE Asia: ? (local), - - (regional)
	Boreal Forests (dieback / expansion)	Dieback: ++ (regional) + (continental) Northern Expansion: + (regional)
	Temperate Forests (dieback)	**+ (local)** [local added] ? (regional)
	Savannas & Grasslands (regime shifts)	++ (local to landscape) ? (regional)
	Drylands (regime shifts)	++ (local to landscape) + (regional)
	Freshwater (regime shifts)	Eutrophication-driven lake anoxia: +++ (widespread localised) Lake DOM loading ('browning'): ++ (widespread localised in boreal) Lake (dis)appearance: – (widespread localised in tundra) Lake N to P-limitation switch: – (localised in high N-deposition regions) Lake salinisation: – (localised in arid regions) Lake invasive species: – (widespread localised) **River deltas: + (localised)** [system added] **Peat bogs: ++ (localised)** [system added]
	Coastal ecosystems (regime shift)	**Mangroves: +++ (local)** [local added] ++ (regional) Seagrass meadows: ++ (regional) Kelp forests: +++ (local)
	See 4.3 Warm-water coral reefs case study	+++ (localised) +++ (regionally clustered)

Table 2.2.1: Tipping assessment for each system considered, highlighting changes since GTPR23. Key: +++ (high confidence yes), ++ (medium yes), + (low yes), ? (uncertain), – – – (high no), – – (medium no), – (low no).

Domain	Tipping system (& tipping dynamics)	GTPR25 tipping system assessment (bolded if changed vs. GTPR23)
	Marine (benthic & pelagic) ecosystems (regime shifts)	Cod fisheries: +++ (regional) Large fish fisheries: + (regional) Small fish fisheries: – (regional) Marine communities: + (local) Biological (lipid) pump: ? (regional) Biological (gravitational) pump: – – (regional) Marine hypoxia: + (local), ? (regional to global)
Ocean & atmosphere circulations	**Ocean overturning (collapse)** See 4.2 Atlantic Ocean circulation case study	Atlantic Meridional Overturning Circulation (AMOC): ++ Deep convection in North Atlantic Subpolar Gyre (SPG): ++ Southern Ocean: ++
	Monsoons (abrupt collapse / intensification)	West African: + Indian Summer: ? South American: ? **East Asian Summer: ?** [system added]
	Tropical clouds & circulation (reorganisation)	– –
	ENSO (extreme / permanent)	– –
	Mid-latitude jet (wavier)	–

2.2.3 Introduction

The Earth system describes the interconnected complex system at the surface of the planet that sustains life, including the cryosphere (ice-related systems, including ice sheets, sea ice, glaciers and permafrost), biosphere (all living things), atmosphere, hydrosphere (water-based systems, including oceans, rivers and lakes), and the lithosphere (the Earth's solid surface) [Kump, Kasting, & Crane, 1999; Lenton, 2016].

Evidence has accumulated from models, palaeorecords, and observations that change in many parts of the Earth system can under certain circumstances become self-sustaining once forced beyond a threshold, leading to a state change driven by positive (i.e. amplifying) feedback loops, and/or the weakening of negative/balancing feedback loops [Lenton et al., 2008; Armstrong McKay et al., 2022; Wang et al., 2023; GTPR23]. We refer to this situation as a 'tipping point', and the systems that this dynamic occurs in as 'tipping systems' (see Introduction of the report).

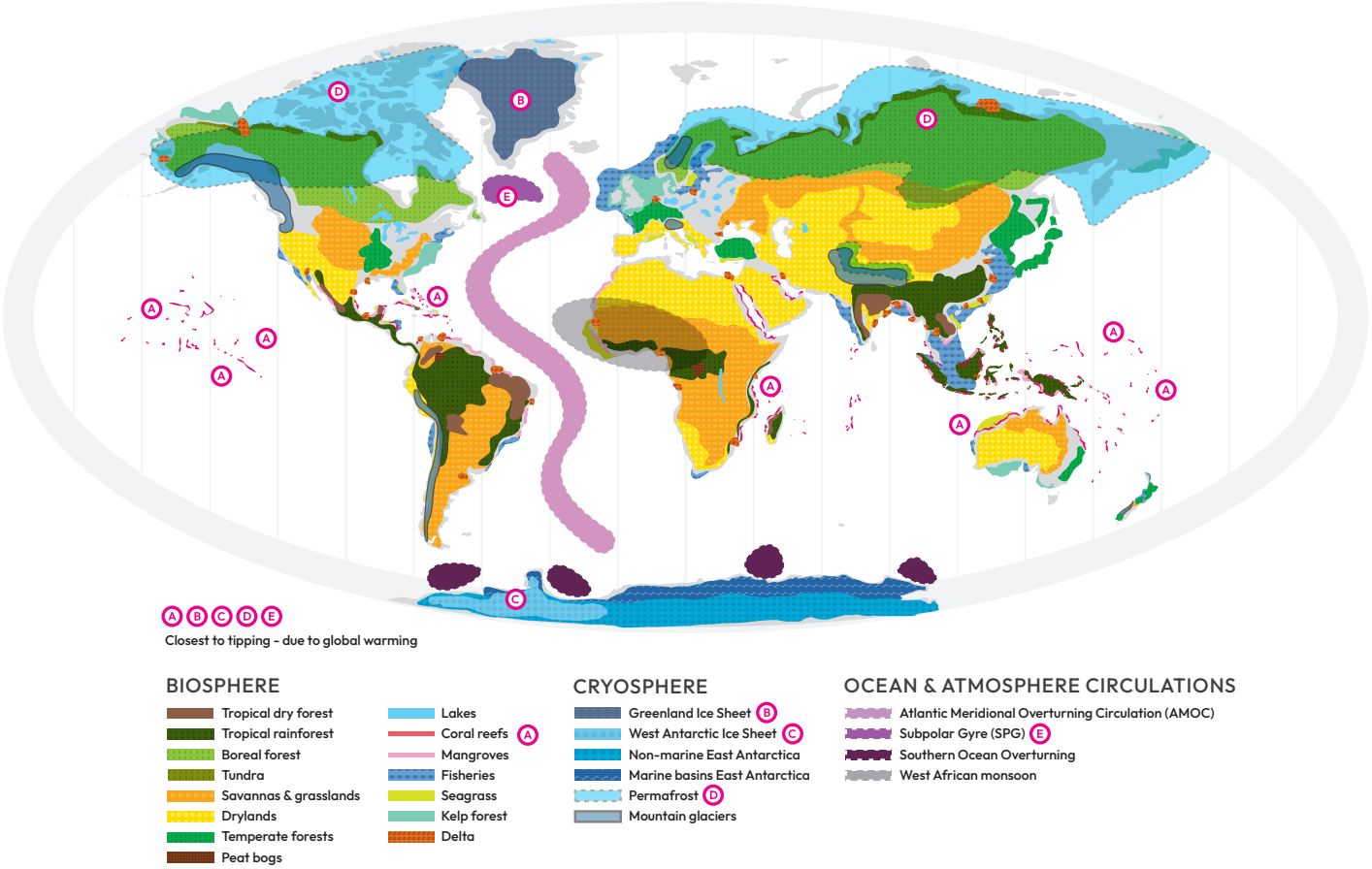


Figure 2.2.1: Map of potential tipping systems across the biosphere, cryosphere, and circulations in oceans and atmosphere.

In the first Global Tipping Points Report [GTPR23], over 120 Earth and environmental scientists assessed the biophysical evidence for tipping dynamics across the Earth system. We assessed the scientific literature for each proposed tipping system, and using collective expert judgement then judged if sufficient evidence exists for tipping dynamics in that system along with an associated confidence level (following the IPCC system; Mastrandrea et al. [2010]), and identified knowledge gaps to be targeted with further research. Based on this, we found evidence for potential tipping in many parts of the Earth system, across the cryosphere, biosphere, and ocean/atmosphere circulations, several of which may already be close to tipping thresholds due to a variety of anthropogenic pressures (Figure 2.2.1).

Since the last Global Tipping Points Report was published, new research has deepened our understanding of many of these systems. In this chapter, we briefly describe each system and our previous assessment of its tipping dynamics, before summarising insights from new research on it, and presenting any changes to the assessments made in GTPR23 (summarised in Table 2.2.1).

2.2.4 Methodology

There are many sources of information that Earth system science draws from. Broadly classified, there are direct observations (in-situ measurements and remote sensing), proxy records on historic or palaeo timescales (indirect reconstructions, e.g. inferring past temperatures via certain isotope concentrations) and models of differing complexity. The latter range from conceptual (e.g. box models) over component models (e.g. ice sheet models representing the relevant physical processes) to fully coupled Earth system models (e.g. the models participating in the Coupled Model Intercomparison Project, CMIP). All these lines of evidence come with their respective strengths and drawbacks, and can help construct a consistent understanding of a system [Boers, Ghil & Stocker, 2022].

In line with the tipping point definition above and as described in Loriani et al. [2025], our assessment reviews evidence for the presence of feedback loops that can drive self-perpetuating change beyond a threshold, leading to a state shift in that system. The confidence in our assessment increases with both robustness and agreement of evidence, following the IPCC system [Mastrandrea et al., 2010]. Table 2.2.2 summarises the criteria for different confidence levels.

Critically, this confidence rating concerns merely whether a system can tip under plausible future conditions (within coming centuries to millennia), not that it will tip in future, or could tip under any circumstances. Although these questions are tightly related, estimating whether a system is likely to tip requires quantification of the critical threshold and an assessment of whether that threshold will be transgressed, including a discussion of overshoots and timescales. All of these aspects are surrounded by considerable uncertainties for different systems.

Table 2.2.2: Summary of confidence level criteria for ESTP assessments in this chapter.

Confidence	Criteria (from Loriani et al. [2025])
High (+++)	Multiple, independent lines of evidence consistently indicate the presence of feedback loops that can drive self-perpetuating change beyond a threshold on plausible future trajectories, leading to a state shift in that system. Strong palaeo analogues, consistent tipping behaviour in models across the hierarchy. If applicable, proxy and direct observations are compatible with the expected tipping dynamics.
Medium (++):	Multiple, independent lines of evidence indicate the presence of such feedback loops. However there are uncertainties in timing, magnitude or feedback strength. e.g. there are tipping dynamics in some models, and palaeo records hint at dynamics compatible with tipping. Support from observations is limited or contested.
Low (+):	Singular lines of evidence indicate the presence of such feedback loops. Tipping dynamics only emerge in specific models or under constrained assumptions. e.g. tipping is in principle conceivable via conceptual models, but there are no clear or only weak palaeo analogues. Limited demonstration of tipping dynamics in numerical models.
Not a tipping system	There is evidence indicating the lack of feedback loops that can drive self-perpetuating change beyond a threshold (with low/medium/high confidence).
Unclear	There is conflicting or limited evidence about the existence of such feedback loops.

2.2.5 Potential tipping points in the cryosphere

The cryosphere includes all of the ice-bound parts of the Earth, including ice sheets (separated into the Greenland and Antarctic ice sheets, the latter also subdivided into West Antarctic and East Antarctic ice sheets), mountain glaciers, sea ice, and permafrost.

In this section, we describe each of these systems, their evidence for tipping dynamics, and relevant new research in turn. Based on this, we have reassessed the status of several systems, including the threshold range for the Greenland Ice Sheet, updating Arctic winter sea ice from not a tipping system (low confidence) to uncertain, and discussing the potential implications of recent drop in Antarctic sea ice (Figure 2.2.2).

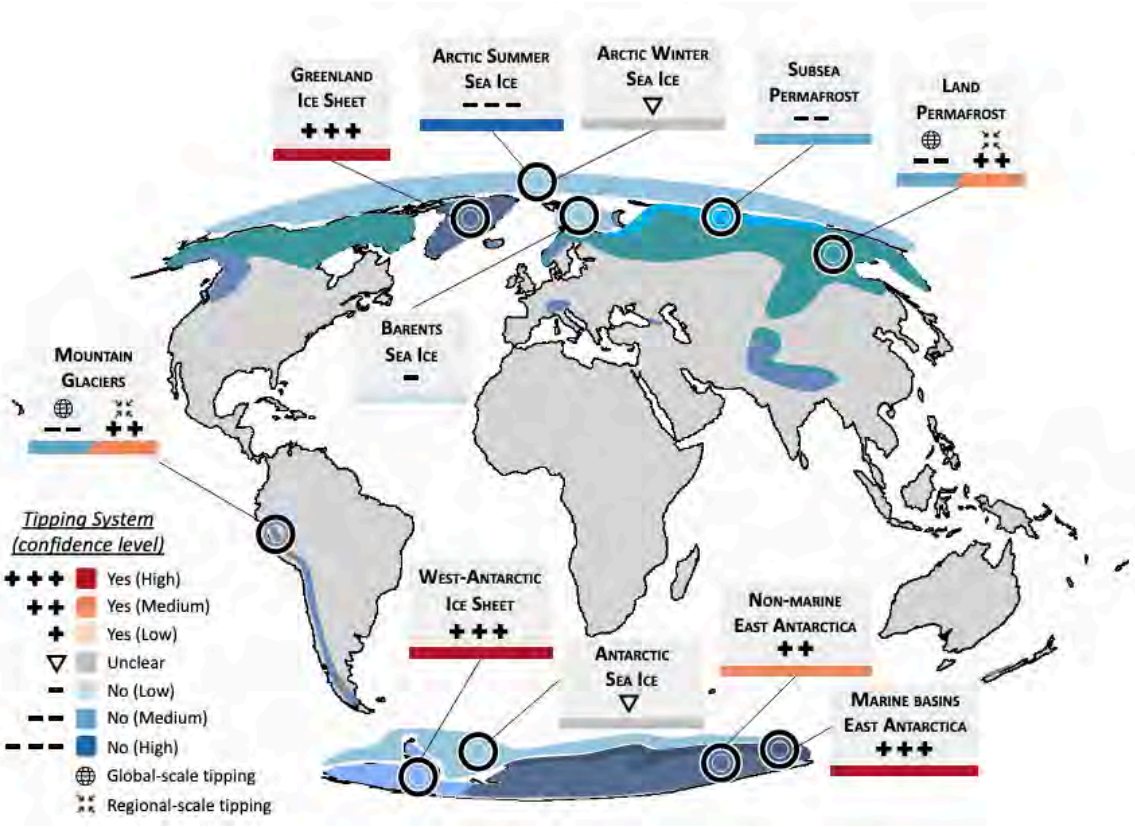


Figure 2.2.2: Map of cryosphere systems considered in this chapter (shading). The markers indicate which of the systems are in this report considered a tipping system (+++ high confidence, ++ medium confidence and + low confidence) and which are not (– – – high confidence, – – medium confidence and – low confidence), ▽ indicates systems for which a clear assessment is not possible based on the current level of understanding.

Greenland Ice Sheet

What it is

The Greenland Ice Sheet (GrIS) consists of the ice sheet covering the island of Greenland, and contains the equivalent of circa 7 metres of sea level equivalent (SLE) [Aschwanden et al., 2019]. Palaeoclimate evidence suggests that while it survived many recent interglacials (i.e. warm interludes between cold 'Ice Age' glacials, of which the current Holocene is the latest), it partly collapsed during the last interglacial 130,000 to 115,000 years ago (a.k.a. the 'Eemian', or 'MIS5e'), and may have collapsed during the 'MIS11' interglacial ~420,000 to 395,000 years ago when sea levels were likely 6 to 13 m higher than present [Alley et al., 2010; Schaefer et al., 2016; Rachmayani et al., 2017; Robinson et al., 2017; Christ et al., 2021]. While MIS11 may have reached a warmer peak than MIS5e (with up to ~2°C in the former and up to ~1.5°C in the latter relative to pre-industrial, albeit with high uncertainty and differing orbital configurations and regional patterns [Rachmayani et al., 2017; Fox-Kemper et al., 2021]), the larger estimated ice loss during the older interglacial is likely due to a longer duration of warmer climate [Robinson et al., 2017]. This sensitivity to only marginally higher warming than preindustrial indicates the presence of a tipping dynamic. Some models also support this, indicating that this is largely driven by melt-elevation feedback, in which ice mass loss leads to the ice sheet surface dropping to warmer altitudes, accelerating ice loss. Below a critical elevation, this process leads to inevitable collapse even if global warming were to halt or reverse [Boers & Rypdal, 2021]. If triggered, GrIS collapse would play out over millennia (1-10ky; A. McKay et al. [2022]), but would lock in a multi-metre sea level rise that would prove catastrophic to coastal areas. Early warning signals of tipping points in the Greenland Ice Sheet have been identified in empirical data [Boers & Rypdal, 2021], and ~30 cm sea level rise from Greenland may already be locked in, regardless of emissions scenario [Box et al., 2022].

What's new

In GTPR23, GrIS was assessed as a tipping system with high confidence, with high confidence too in it involving abrupt / large rate change and irreversibility over decadal/centennial timescales, and a threshold range of 0.8-3°C of global warming [Winkelmann, Steinert & Armstrong Mckay et al., 2023].

Since GTPR23, there have been several new publications relevant to this system. Recent observations have shown ongoing mass loss from the GrIS, with 196 ± 37 km3/yr of volume lost between 2010 and 2022 [Ravinder et al., 2024] and widespread accelerated calving across the GrIS from 1985 [Greene et al., 2024], as well as increased crevassing associated with an acceleration of ice flow at the marine-terminating sectors of the GrIS [Chudley et al., 2025]. There has also been an increase in extreme melting event frequency and intensity across the GrIS since 1950 [Bonsoms et al., 2024].

The irreversibility of ice loss from the GrIS in a fully coupled Earth system model of intermediate complexity is highlighted in Höning et al. [2024], which finds that once the southern GrIS has melted with a mass loss of greater than 0.4 m SLE, total regrowth would require atmospheric greenhouse gas concentrations below pre-industrial and timescales in the order of 10,000s years. While carbon dioxide removal technologies would be required to bring global warming levels down to below +1.0°C, such technologies at scale are hypothetical and strong ambitions to curb emissions are the most important way to prevent the GrIS from crossing a tipping threshold. Another recent study [Petrini et al., 2024] suggests that a global mean warming of 3.2-3.4°C above pre-industrial levels could result in a near full melt of the GrIS. Again this would unfold over 1,000s-10,000s of years. The higher the temperature forcing, the shorter the timescale of collapse. This analysis also suggests that the topography of the central west of Greenland may play a role in stabilising the GrIS [Petrini et al., 2024].

Based on this new research, the GTP community maintains its assessment of GrIS being a tipping system with high confidence, with an updated threshold range of 0.8-3.4°C.

Antarctic Ice Sheet

What it is

The Antarctic Ice Sheet (AIS) can be divided into the mostly marine-based West Antarctic Ice Sheet (WAIS), the marine-based sectors of East Antarctica, and the non-marine regions of the East Antarctic Ice Sheet (EAIS), on account of the differing dynamics and temperature thresholds associated with their tipping. The response of the Antarctic Ice Sheet—the largest source of long-term sea-level rise—to global warming remains poorly constrained, and large uncertainty regarding its future contribution to global sea-level rise remains [Seroussi et al., 2024; Levermann et al., 2020]. The AIS responds extremely slowly to changes in its surrounding climate, so that the full consequences of past and ongoing warming may take centuries or longer to fully unfold [Clark et al., 2016; Klose et al., 2024]. Nevertheless, Antarctica is already today losing mass and contributing to sea-level rise [IMBIE team, 2018], with losses projected to accelerate even if global temperatures were stabilised at today's levels [Reese et al., 2023].

The WAIS is separated from the EAIS by the Transantarctic Mountains and holds enough ice to raise sea levels by ~5 m. Unlike the EAIS, which largely rests on bedrock above the sea level, the majority of the WAIS rests on a bed well below sea level, making it especially vulnerable to ocean warming (either directly or by changes in ocean circulation). In contrast to the GrIS, much of the coast of Antarctica is fringed by floating ice shelves, which create a vulnerable point of contact with the ocean. These connections to the ocean, as well as the fact that most of its ice is resting below the sea level, make the WAIS much more vulnerable to climate warming than the EAIS. A collapse of the WAIS would lock in long-term sea-level rise on the order of 3-5 meters, depending on collapse extent [Garbe et al., 2020]. At current temperatures, a partial WAIS collapse may already be unavoidable in the long term [Reese et al., 2023]. Evidence exists for the collapse of the WAIS during past warm periods, such as the last interglacial [DeConto and Pollard, 2016; Sutter et al., 2016; Turney et al., 2020; Thomas et al., 2020; Weber et al., 2021] and the Pliocene when temperatures were ~2-3°C warmer than pre-industrial [Naish et al., 2009; Grant et al., 2019; DeConto et al., 2021]. Several potential mechanisms for WAIS tipping have been proposed. One likely candidate for WAIS loss is Marine Ice Sheet Instability (MISI), when the grounding line sits on a slope that deepens into the ice sheet interior. When the ice retreats inland the greater ice thickness means that more ice flows into the ocean This causes additional thinning and retreat, resulting in a self-accelerating loss until the ice reaches a stable point (often a higher bedrock elevation) [Weertman, 1974; Schoof, 2007; Mengel and Levermann, 2014; Feldmann and Levermann, 2015; Garbe et al., 2020]. Another proposed feedback mechanism is Marine Ice Cliff Instability (MICI), whereby ice shelf collapse creates inherently unstable tall marine-terminating ice cliffs, which in turn rapidly collapse and cause a self-reinforcing feedback of ice recession, which only terminates when ice cliff is buttressed or the water shallows [DeConto et al., 2021]. However, this feedback has not been observed in Antarctica (yet) and there is much less scientific consensus on this instability than MISI.

Marine-based ice-sheet sectors (like much of the WAIS) also exist in East Antarctica, including in the Wilkes, Aurora, and Recovery subglacial basins. They are potentially vulnerable to the same tipping dynamics as WAIS, including the MISI and the MICI [Morlighem et al., 2020; Stokes et al., 2022]. However, unlike the WAIS, palaeorecords of previous interglacials as well as models still carry large uncertainty with regard to their vulnerability. However, most studies suggest that the critical temperature threshold of EAIS marine-based sectors is above that of the WAIS or the GrIS.

Beyond its marine basins, the majority of the EAIS lies above sea level, containing an ice amount equivalent to ~34 meters of global sea level rise [Pritchard et al., 2025]. As they have no connection to the ocean, these parts of the ice sheet are not vulnerable to the instabilities of marine-based ice. However, although less vulnerable than the GrIS due to its thermal isolation and its location over the pole, the EAIS is susceptible to the melt-elevation feedback, which might cause self-sustained and irreversible ice loss in the long term (perhaps multiple millenia) if temperatures exceed 6°C of global warming [Garbe et al., 2020]. Under current projected warming scenarios, only modest ice loss is expected from this part of the ice sheet, and models suggest an excess of 10°C warming might be needed to lead to complete ice sheet loss [Garbe et al., 2020]. Crucially, if the ice sheet were to be lost, there would likely be strong hysteresis, requiring far greater cooling for the ice sheet to be restored.

What's new

WAIS was previously identified as a tipping system with high confidence, with a high likelihood of abrupt / large rate change and irreversibility on a decadal/centennial timescale, with an associated temperature threshold of 1-3°C. Marine-based East Antarctica was identified as a tipping system with high confidence, with a high confidence in abrupt / large rate change and irreversibility on a decadal/centennial timescale, with an associated temperature threshold of 2-6°C. Non-marine based East Antarctica was identified as a medium confidence tipping system, with a high confidence in abrupt / large rate change and medium confidence in irreversibility on a decadal/centennial timescale, with an associated temperature threshold of 6-10°C [Winkelmann, Steinert & Armstrong Mckay et al., 2023]. Since GTPR23, there have been numerous publications which are relevant to the science of ice sheet tipping points for the WAIS, marine-based and non-marine based EAIS, and across the whole Antarctica. We shortly highlight these new studies below for the AIS as a whole, and for West and East Antarctica separately.

Across the whole of Antarctica

On potential thresholds, an ice sheet model forced by different climate model simulations of the warm mid-Pliocene (3-3.3 million years ago) compared with warming stabilised at current levels indicates that WAIS collapse occurs with a modest 0.5-1°C of ocean warming above pre-industrial, while the East Antarctic Wilkes Subglacial Basin retreats at a higher level of around 3°C oceanic warming (depending on precipitation changes) [Blasco et al. 2024]. Using an ice-sheet model, Coulon et al. [2024] identify a threshold of +7.5°C warming above pre-industrial to amplify melt–elevation feedback across the Antarctic, leading to a complete collapse of the WAIS and retreat of the marine EAIS. Recent simulations in a coupled climate-ice-sheet model also support strong hysteresis of the Antarctic Ice Sheet driven by melt-albedo feedback with associated critical thresholds of atmospheric CO_2 levels for Antarctic Ice Sheet loss [Leloup et al., 2025]. Lastly, considering evidence from previous warm periods, ice sheet mass balance observations, and models, Stokes et al. [2025] recently argued that the current warming level is high enough to see substantial loss of ice sheets, and that a long-term limit of 1°C, or lower, above pre-industrial levels is necessary to avert substantial ice sheet loss.

On potential tipping dynamics, further modelling studies have supported the committed nature of sea level rise from Antarctic Ice Sheet loss [Alevropoulos-Borrill et al., 2024], including some degree of committed sea level rise from having potentially passed a tipping point in the Amundsen Sea sector of West Antarctica [Bett et al., 2024] (although a modelling study by Hill et al. [2023] found that a tipping point has not yet been crossed). The sensitivity of ice sheets to intrusion from warmer sea water is identified as an underestimated cause of tipping points in one model [Bradley & Hewitt, 2024]. Ice sheet modelling shows that basal water conditions can bring forward tipping points by up to 40 years [Zhao et al., 2025]. Atmospheric extreme events - often associated with atmospheric rivers, which are responsible for 50–70 per cent of extreme snowfall events in Antarctica, as well as being involved in the Larsen A and B ice shelf collapses during surface melting events - are not resolved by current-generation models, and could potentially result in faster melting than expected [Kolbe et al., 2025; Wille et al., 2025].

West Antarctica

There is further evidence that the WAIS is committed to long-term collapse at current or near current temperature levels [Van den Akker et al. 2025; Chandler et al., 2025], with each additional fraction of warming increasing the likelihood that collapse could be initiated much sooner. Recent studies show that the WAIS is particularly vulnerable to ocean warming and grounding line retreat [Hill et al., 2024; Rignot et al. 2024]. In the ISMIP6 ensemble of 16 ice flow models up to 2300, Seroussi et al. [2024] found a retreat of the WAIS leading to a rapid increase in sea level rise after 2100, reaching up to 4.4 m SLE by 2300 under high-emission scenarios. Offshore sediment cores also indicate that West Antarctica remained ice-free during the initial formation of the Antarctic Ice Sheet following the Eocene-Oligocene Transition around 34 million years ago, implying lower temperatures are required for WAIS formation as well as loss [Klages et al., 2024].

Recently, a study using three ice sheet models showed that the WAIS might be less vulnerable to MICI than previously thought [Morlighem et al., 2024]. Additionally, ice core data suggests that the West Antarctic Ronne Ice Shelf survived the Last Interglacial (approximately 125,000 years ago) when regional Antarctic temperatures were higher than today [Wolff et al, 2025], thus suggesting the WAIS may be less sensitive to MICI than previously suggested. Conversely, a study currently under review uses empirical data to suggest that MICI may be sensitive to parameters other than cliff height, such as ice thickness gradients, and if these parameters were better resolved in models more future cliff-calving may be projected [Needell, Walker and Bassis, under review]. Additionally, other mechanisms could still lead to a tipping point, and there is still uncertainty around the timing of this [Fricker et al., 2025].

East Antarctica

Hydrological feedbacks, associated with meltwater flowing beneath the ice sheet, which could accelerate ice loss in East Antarctica, are identified in a recent coupled ice sheet-subglacial hydrology model [Pelle et al., 2024]. This suggests that models without these feedbacks could underestimate future sea level rise. EAIS vulnerability is shown through the recent sudden disintegration of the Conger-Glenzer Ice Shelf, which is mapped with remote sensing data in Walker et al. [2024].

Summary

Based on this new research, the GTP community maintains its assessment of the WAIS being a tipping system with high confidence (with high agreement across robust evidence). We also assess that the current lower-end threshold estimate for WAIS of 1°C may be too high to be considered a safe long-term limit [Arthern & Williams 2017; Seroussi et al., 2017; Garbe et al., 2020; Golledge et al., 2021; Reese et al., 2023; Van den Akker et al., 2025; Stokes et al., 2025], and while the exact lower limit is hard to determine, a precautionary limit of 0.5°C would be appropriate. We also maintain our tipping system assessments for marine-based EAIS as high confidence, and non-marine based EAIS with medium confidence.

Sea ice

What it is

When seawater cools below the freezing point in each hemisphere's autumn to spring, it begins to form a layer of floating sea ice. Large areas of highly reflective (i.e. high albedo) white sea ice helps amplify regional cooling, and conversely reduced sea ice extent with global warming is one of the drivers of the 'Arctic amplification' of warming. This feedback was originally thought to lead to a tipping point beyond which sea ice loss becomes self-sustaining [e.g. Lenton et al., 2008], but more recent work instead expects quasi-linear sea ice loss with warming as a result of counteracting negative feedbacks serving to dampen ice loss [e.g., Gregory et al., 2002; Winton, 2006; Winton, 2008; Notz, 2009; Tietsche et al., 2011; Mahlstein and Knutti, 2012: Wagner and Eisenman, 2015]. However, there remains some possibility of sea ice tipping in certain regions and circumstances, such as around Antarctica [Winkelmann, Steinert & Armstrong Mckay et al., 2023].

What's new

In GTPR23, Arctic summer sea ice was assessed as not a tipping system with high confidence, Arctic winter sea ice as not a tipping system with medium confidence, and Barents sea as not a tipping system with low confidence. In contrast, Antarctic sea ice was assessed as unclear, with more evidence required to make an assessment [Winkelmann, Steinert & Armstrong Mckay et al., 2023].

Since GTPR23, several new publications have advanced understanding of sea ice tipping dynamics. Heuzé & Jahn [2024] showed through model simulations that the Arctic Ocean could experience its first entirely ice-free summer day before 2030 under scenarios of continued warming, emphasising that while ice loss is accelerating, it remains largely linear and influenced by acute warming events rather than tipping points. Selivanova et al. [2024] confirmed significant ongoing reductions in Arctic summer sea ice extent and thickness, projecting nearly ice-free summer conditions by the 2040s, indicating a regime shift to a thinner, more transient summer ice cover, but without identifying irreversible thresholds. However, species and ecosystems dependent on sea ice are less recoverable.

In the Barents Sea, Onarheim et al. [2024] documented recent localised thickening due to temporary cooler conditions, emphasising regional variability and responsiveness to short-term climatic fluctuations rather than sustained recovery or tipping behavior.

This is a mixed picture on whether Arctic winter sea ice might reach a tipping point or not. Recent winter ice reductions in the Barents–Kara Seas have resulted largely from anthropogenic forcing rather than feedbacks, though significantly amplified by internal climate variability [Siew et al., 2024]. Wunderling et al. [2024] reviewed potential tipping interactions, noting winter Arctic sea ice might exhibit threshold-like behavior linked to ocean–ice feedbacks and the Atlantic Meridional Overturning Circulation. However, they noted that current evidence does not yet support an irreversible collapse of Arctic winter sea ice. At the same time, abrupt reductions remain plausible at certain warming thresholds, even if these are not feedback-driven tipping events, as indicated in recent CMIP6 analyses [Terpstra et al., 2025].

Other recent work suggests the potential for tipping behaviour in winter sea ice. In a sea ice model, Hankel & Tziperman [2023] show a clear bifurcation: beyond a critical forcing the winter-ice equilibrium vanishes, driving an abrupt, hysteretic transition to a permanently ice-free Arctic. Observationally-constrained detection studies further show that CMIP6 still underestimates greenhouse-gas control on sea-ice loss, implying the threshold for year-round ice collapse lies closer to today's climate than CMIP5 suggested [Kim et al. 2023]. Finally, carbon-removal ensemble experiments indicate that even after CO_2 is drawn back to pre-industrial levels, most models retain an approximate 1 million km² winter-ice deficit — evidence of incomplete recovery and long-lived hysteresis [Yu et al. 2025].

Antarctic sea ice has shown alarming trends recently, with a gradual increase up to 2014 broken by a precipitous decline beyond natural bounds of variability since, rivalling Arctic losses [Abram et al., 2025]. 2023 saw a record-low extent, attributed to anomalously warm ocean conditions and unusual wind patterns [Espinosa et al., 2024]. Raphael et al. [2025] found compelling evidence of a structural regime shift in Antarctic sea ice since the mid-2010s, characterised by unprecedented consecutive low-ice events and decreased recovery capability, signaling potential tipping behavior. Recent improvements in satellite observations have also revealed a reversal in surface freshening in the Southern Ocean, with increasing salinity since 2015 associated with reduced stratification, which could accelerate sea ice loss through increased ocean heat loss [Silvano et al., 2025]. Abram et al. [2025] proposes that the Antarctic sea ice regime shift may feature self-perpetuating dynamics even below 2°C, but it is not yet clear if future projections of decline reflect this or lagged ocean warming.

Recent analysis of abrupt shifts in CMIP6 model results suggest abrupt shifts in Arctic summer sea ice occur in some simulations between 1.0 and 4.6°C, in winter sea ice between 2.4 and 5.4°C, and in Barents sea ice between 1.3 and 2.3°C [Terpstra et al., 2025; Angevaare & Drijfhout, in review] (see Table A2.2.1 in Appendix for details). Similarly, abrupt shifts are also detected around Antarctica in a number of simulations between 0.5 and 5.3°C. However, these abrupt shifts are not necessarily tipping points without confirming self-perpetuating dynamics.

Based on this new research, the GTP community maintains its assessment of Arctic summer sea ice and Barents Sea ice as not tipping systems. Arctic winter sea ice is assessed as uncertain regarding tipping point behavior, as while recent studies suggest there are possible threshold effects and rapid ice loss from significant warming, there is not yet strong proof that this would be irreversible due to self-perpetuating feedbacks. Improved modelling and longer observations of sea ice will help to clarify potential tipping dynamics. We also maintain our assessment of Antarctic sea ice potentially exhibiting tipping behavior as uncertain, reflecting that while there is mounting evidence of a fundamental and possibly irreversible shift in Antarctic sea ice conditions [Raphael et al., 2025], and there are feedbacks that could potentially sustain this shift [Silvano et al., 2025], there is insufficient research confirming the dynamics involved and the likely endpoint.

Mountain glaciers

For more on tipping points in glaciers, see the Mountain glaciers case study

What it is

Outside of the ice sheets of Greenland and Antarctica, ice bodies occur as mountain glaciers, gaining ice in higher altitudes before flowing to lower altitudes where they lose mass. In general glaciers are shrinking and projected to shrink further with global warming, but this mass balance is subject to various feedbacks with the potential for nonlinear responses to a changing climate as a result [Marzeion et al., 2018; Hock et al., 2019; Meredith et al., 2019; Rounce et al., 2023]. These feedbacks include changing flow rates from increased meltwater generation, increased retreat of calving glaciers from a warming ocean, drop of glacier surface elevation increasing melt rates and possibly also decreasing snow accumulation, and increased dustiness and surrounding vegetation reducing local albedo. Under certain circumstances the above feedbacks can result in self-sustained mass loss of individual glaciers [Winkelmann, Steinert & Armstrong Mckay et al., 2023]. Although these feedbacks act mainly on local scales, there is on average a tendency for regional similarities and thus synchronous transitions between different states of glaciers and their downstream impacts.

What's new

In GTPR23, mountain glaciers were assessed as a tipping system at the regional scale with medium confidence, but as not a tipping system at the global scale with medium confidence [Winkelmann, Steinert & Armstrong Mckay et al., 2023]. This assessment has since been confirmed by a number of further considerations and studies. The most recent global-scale compilation of glacier mass loss [The GlaMBIE team, 2025] found that glaciers worldwide lost 273 ± 16 gigatonnes annually from 2000 to 2023, with an increase of 36 ± 10 per cent from 2000–2011 to 2012–2023. These numbers correspond to a loss of between 2 and 39 per cent of regional glacier ice mass, about 5 per cent globally. The glacier mass loss found has already passed the IPCC AR6 lowest mass-loss projections over the period from 2000 to 2040. Glacier mass loss 2000–2023 is about 18 per cent larger than the mass loss from the Greenland Ice Sheet and more than twice that from the Antarctic Ice Sheet. A recent global glacier modelling intercomparison [Zekollari and Schuster et al., 2025] highlights the substantial regional diversity of already committed and further equilibrium response of glaciers worldwide, supporting the GTPR assessment of glaciers being tipping systems at regional scale, rather than global.

While GTPR23 focused mainly on processes of glacier dynamics and mass balance, also the atmospheric forcings behind glacier mass changes underlie nonlinear behaviour, that in turn can then cause nonlinear glacier development. Temperature-precipitation relations are weakly understood and quantified [Ding et al. 2014]. While in some glacier regions the increased humidity of the warming atmosphere leads to increased snowfall and accumulation, in other cases precipitation undergoes a transition to a higher percentage of the liquid phase [Hock et al., 2019]. In addition to changes in the regional atmospheric forcing, glacial landscape changes such as glacier area loss, exposure of rock and debris, formation of lakes, or increased vegetation cover will change temperature and wind patterns [Shaw et al. 2023]. The feedback of these changes on the glaciers themselves is poorly understood, including for instance the transition between sublimation-dominated to melt-dominated glacier ablation regimes [Marshall 2021]. The shift of polythermal glacier regimes (a mixture of ice zones at and zones below the pressure melting point) to temperate thermal regimes (all ice at pressure melting point) is also expected with atmospheric warming, but associated processes and consequences, for instance on meltwater refreezing, runoff, glacier dynamics and even mechanical glacier stability [Gilbert et al. 2018], are little understood [Marshall 2021].

Bolibar et al. [2022] suggest a number of nonlinearities in the relation between temperatures and snowfall, melt and in particular their positive and negative extremes that impact glacier mass balance. The combined impacts of these nonlinear changes in individual forcings can compensate each other towards quasi-linear behaviour. The latter overall forcing combines then with feedbacks related to glacier topography. In that context, Bolibar et al. [2022] point out the particularly important differences between mountain glaciers, which can retreat to higher average elevations where melt rates are reduced (negative, self-stabilising feedback, GTPR23), and flat glaciers (on global average the ones with largest ice volumes), where mass loss reduces average surface elevation and enhances melt rates (positive feedback, GTPR23). Studies for Alaska glaciers confirm GTPR23 findings that topographic controls, in particular elevation distributions, on surface mass balance of ice fields and glaciers can lead to tipping behavior on local to regional scales [Davies et al., 2022; Davies et al, 2024]. The causes and impacts of glacier tipping at the local- to regional scale are explored in the case study on tipping dynamics in an Alaskan (USA) glacial system.

Based on these considerations and new research, we maintain our assessment of mountain glaciers being a tipping system at the regional scale with medium confidence, but as not a tipping system at the global scale (medium confidence).

Permafrost

What it is

Permafrost consists of ground frozen for at least two consecutive years [Harris et al., 1988], and underlies about 14 million km^2 (15 per cent of the land surface area) in the Northern Hemisphere [Obu, 2021; Steinert et al. 2023]. Freezing prevents organic matter from tundra or boreal forest ecosystems entering the soil from decomposing, resulting in the buildup of over ~1000 GtC in the top 3m of permafrost soils on land [Hugelius et al., 2014]. However, global warming is leading to some of this permafrost beginning to thaw, allowing the preserved organic matter to degrade and emit greenhouse gases in the process, primarily as CO_2 but with a proportion as high-warming methane where permafrost is waterlogged [Walter Anthony et al., 2014]. Much of the carbon loss is likely irreversible due to the slow formation timescales of permafrost and sustained microbial decomposition of previously frozen organic matter, leading to continued carbon emissions over centennial to millennial timescales and reinforcing warming through a positive feedback loop [Schwinger et al. 2022; de Vrese & Brovkin et al. 2021; Park et al. 2025; Ji et al. 2025]. Furthermore, permafrost thaw does not occur uniformly, as some areas experience localised abrupt thaw, leading to rapid carbon loss and landscape destabilisation, i.e., degradation of ice-rich permafrost, and subsequent rapid slope slumping, ground subsidence and the formation of thermokarst landscapes. These processes could amplify emissions by 40 per cent under high emission scenarios but are not currently represented in Earth system models [Turetsky et al. 2020]. While large-scale permafrost thaw is gradual, these regional abrupt thaw processes involve positive feedbacks such as thermokarst formation that can lead to self-sustained thawing processes, allowing for localised tipping to take place [Nitzbon et al., 2020]. However, at the regional to global scale permafrost thaw is expected to aggregate to a quasi-linear response to global warming [Nitzbon et al. 2024].

What's new

In GTPR23, land-based permafrost was assessed as a tipping system at the regional scale (medium confidence), but not as a tipping system at the global scale (medium confidence). Equally, subsea permafrost was not identified as a tipping system (medium confidence) [Winkelmann, Steinert & Armstrong Mckay et al., 2023]. Since GTPR23, several new publications have advanced understanding of permafrost thaw in the context of tipping dynamics.

Evidence suggests that permafrost thaw remains characterised by multiple regional-scale tipping processes, including abrupt thermokarst lake formation and slope slumping, rather than exhibiting a single global tipping threshold [Nitzbon et al., 2024]. A recent analysis of CMIP6 model results identified individually small but widely distributed (collectively aggregating to over >1M km^2) abrupt shifts in land permafrost frozen soil moisture content in eight models between 1.0 and 3.8°C of global mean warming, and in soil frozen water content in 19 models between 1.2 and 3.3°C [Terpstra et al., 2025] (Table A2.2.1). Localised, abrupt thaw events [Webb et al. 2025] contribute cumulatively but gradually at the global level, thus reaffirming that permafrost degradation progresses incrementally and heterogeneously. The presence of multiple steady states in permafrost systems indicates the potential for local tipping of ecosystems and soil carbon storages on centennial timescales [Brovkin et al. 2025]. Further, Earth System simulations suggest that changes in permafrost hydrology can gradually, rather than abruptly, impact hydroclimate in the tropics and subtropics. The permafrost soil state and consequential carbon fluxes of such processes have the potential to be underestimated in low-resolution climate models [Schickhoff et al. 2024].

Recent findings from NOAA's 2024 Arctic Report Card [2024] revealed that Arctic tundra ecosystems have shifted to net carbon sources earlier than projected, driven by intensified permafrost thaw and record wildfire seasons. This transitioning of Arctic ecosystems from carbon sinks to sources is amplifying climate feedbacks at regional scales. A previously overlooked feedback mechanism linking permafrost thaw to reduced cloud cover, amplifying Arctic warming and its global impacts was identified by de Vrese at al. [2024].

Localised abrupt thaw expose deeper layers of organic material to microbial decomposition, significantly increasing emissions in a short period, and significantly contributing to methane emissions from inundated areas [Park et al. 2025], while emissions from deep Arctic lake sediment could be more substantial than previously thought [Freitas et al. 2025]. As such, abrupt thaw hotspots across the Arctic highlight the vulnerability of permafrost regions even under present-day conditions. Using the CESM2 model coupled with CLM5, Park et al. [2025] further determined that permafrost carbon emissions will persist for centuries even under scenarios of aggressive climate mitigation and net-negative emissions. Their model simulations indicate irreversible commitments to continued carbon release from thawed permafrost, further reinforcing the long-term implications of regional tipping processes.

A warming Arctic enhances the risk of causing localised abrupt thaw and increases its magnitude and therefore also increases the risk of tipping cascades, where permafrost degradation - in addition to its carbon-climate feedback - interacts with other Earth system components, such as boreal forest dieback [Alfaro-Sánchez et al. 2024], including wildfire occurrence [Kim et al., 2024] or a modified ocean circulation [Schwinger et al. 2022, Park et al. 2025, Steinert et al. 2025] and carbon uptake efficiency [Nielsen et al. 2024], potentially accelerating global climate change. Further, adaptive emission driven MPI-ESM simulations show that, while average annual permafrost carbon emissions of ~0.3–0.7 GtC/yr are small compared to present-day fossil fuel emissions (~10 GtC/yr), permafrost thaw can still reduce the carbon budget by ~11–13 per cent by 2300 under 2°C or 3°C warming scenarios [Georgievski et al., 2025].

Based on this new research, the GTP community maintains its assessment of land-based permafrost as a tipping system at the regional scale with medium confidence, reflecting ongoing evidence of localised tipping processes. It also maintains medium confidence that subsea permafrost is not a tipping system, as well as that land-based permafrost is not a tipping system globally, given the absence of a unified global threshold.

2.2.6 Potential tipping points in the biosphere

The 'biosphere' consists of all life on Earth and includes the major biomes of tropical, temperate, and boreal forests, more open ecosystems across grasslands, savannas, and drylands, and aquatic ecosystems across freshwater, coastal, and marine environments.

In this section, we describe each of these biomes, their evidence for tipping dynamics, and relevant new research in turn. Based on this, we have reassessed the status of several systems, including lowering the minimum warming threshold for the Amazon, adding river deltas and peat bogs as potential tipping systems, and clarifying local- to regional-scale dynamics in the Congo and temperate forests (Figure 2.2.3).

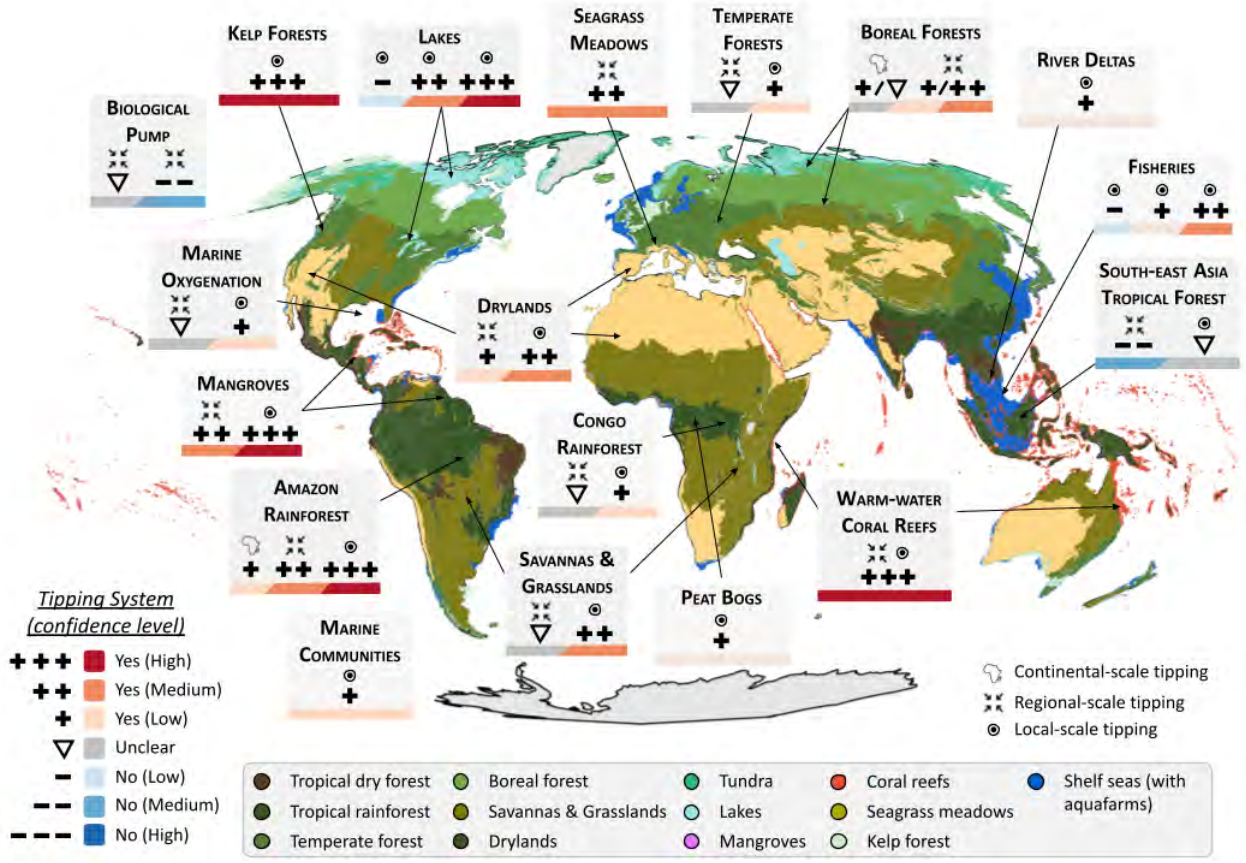


Figure 2.2.3: Map of biosphere systems considered in this chapter. Systems are marked by the coloured areas, with terrestrial biomes and mangroves based on biogeographic biomes [Dinerstein et al., 2017], and lakes and ocean biomes on IUCN functional biomes [Keith et al., 2022] (lakes are shown over other biomes for tundra only; fisheries are spread across the global ocean, but are marked only on key coastal seas for simplicity [Steinert, 2023]). Labels indicate which of the systems are in this report considered a tipping system (+++ high confidence, ++ medium confidence and + low confidence), which are not (- - – high confidence, – – medium confidence and – low confidence), and which are currently uncertain (▽).

Tropical forests

What it is

Known for their high levels of biodiversity [Slik et al., 2015; Pillay et al., 2021; Aguirre-Gutiérrez et al. 2025], tropical forests cover ~1.95 billion hectares and store substantial amounts of carbon within their biomass and soils (circa 471 +/- 93 GtC) [Pan et al., 2011; SPA, 2021; Ornetto et al., 2022]. They form a key part of the interconnected Earth system and have far reaching impacts on the climate through evapotranspiration and cloud formation. They are mainly threatened by deforestation, for example to create pastures, land-cover change, for example to plantations, and droughts and wildfires being worsened by climate change [Sternberg, 2001; Franco et al., 2025]. There are many tropical forest feedbacks, but two key positive feedback mechanisms, acting at different spatial scales, have been identified which may drive tipping points in tropical forests: the forest-rainfall feedback at regional scales and the fire-vegetation feedback at local scales [Flores & Staal, 2022; A. McKay, Sakschewski & Roman-Cuesta et al., 2023]. The forest-rainfall feedback operates at a regional level, with moisture being recycled throughout tropical forests, thus reducing the impact of rainfall variability on forest health; however deforestation and climate change-induced drought extremes can reduce this moisture recycling and force the forest towards a tipping point [Staal et al., 2020]. This feedback is present in the Amazon [Zemp et al., 2017; Staal et al., 2018] and Congo forests [Staal et al., 2020], however it is less important in Southeast Asian and Australasian rainforests where ocean-derived rainfall is plentiful. At a local level, the fire-vegetation feedback can cause a transition from tropical forests to a more open state (such as savanna or degraded dry forest). Less dense tree cover can lead to increased likelihood of fires due to the spread of grasses and local drier air, thus further reducing tree cover [Cochrane et al. 1999].

What's new

Global

Remote sensing by satellites of major forest disturbances (mainly wildfires and droughts) were recently used to calculate a hydrologic sensitivity index, establishing critical thresholds beyond which forest loss drives drastic changes in water yield and climate conditions [Domínguez-Tuda & Gutiérrez-Jurado, 2024]. In tropical rainforests, a threshold near 16 per cent tree cover reduction at local-to-landscape scales was identified, beyond which water yields notably decrease and warming trends intensify.

Amazon rainforest

For more on tipping points in the Amazon rainforest, see the Amazon case study

In GTPR23, the Amazon rainforest was assessed as a tipping system with high confidence at the local scale, medium confidence at the regional scale and low confidence at the continental scale, with medium confidence in it involving abrupt / large rate change, medium confidence in irreversibility over decadal/centennial timescales, and a threshold range for dieback of 1000-1250 mm mean annual rainfall, ~400 to ~450 mm maximum accumulated water deficit, a dry season length of 7-8 months, deforestation levels of 20-40 per cent and ~3.5°C (2-6°C) of global warming [A. McKay, Sakschewski & Roman-Cuesta et al., 2023].

Since GTPR23, the Amazon has faced droughts and extreme warmth associated with the 2023-24 El Niño event, which has led to water stress, increased fires, and reduced greenness [Jiménez et al., 2024]. A major recent synthesis of research on the potential for critical transitions (such as dieback) in the Amazon forest found that by 2050 the potential effects of compounding disturbances on Amazonian systemic resilience could see around 10-47 per cent of Amazon forests facing combined stresses beyond critical thresholds, potentially triggering irreversible regime shifts and exacerbating regional climate change [Flores et al., 2024]. Based on this, Flores et al. [2024] suggested precautionary limits of 1.5°C and 10 per cent deforestation (requiring restoration of 5 per cent of the biome) to avoid broad-scale ecosystem transitions, the latter reduced from the 20-25 per cent precautionary limit of Lovejoy & Nobre [2018].

Similarly, under review modelling suggests that while regional dieback would occur at 3.7-4.0°C without deforestation (in line with A. McKay et al. [2022]), deforestation reaching 22-28 per cent of current forest extent would reduce the warming threshold to 1.5–1.9°C of global warming and make dieback more widespread [Wunderling et al., in review]. Recent analysis of abrupt shifts in CMIP6 model results detected some abrupt shifts in Amazon vegetation between 0.9 and 5°C [Terpstra et al., 2025] (Table A2.2.1), but they were not consistent across models, and do not necessarily represent tipping dynamics. Running CMIP5/6 models until 2300 and including slower transitions reveals localised to regional scale dieback in nine out of twelve models, with location and thresholds (global warming 1.5-10.2 °C, local surface air temperatures >32.2 ± 4.8°C, precipitation <1394.3 ± 306.0 mm/yr) highly model-dependent [Melinkova et al., 2025].

A simpler land-surface-atmosphere model has found that under projected rainfall decreases deforestation of 45 and 55 per cent could trigger dieback, but this model did not feature spatial variation or more complex vegetation dynamics [Hajdu et al., 2025]. Conversely, Yoon & Hohenegger [2025] found that better representing atmospheric convection in a storm-resolving model limited rainfall's sensitivity to deforestation, although only in a short simulation. Under high emission scenarios, it has been estimated that more than 25 per cent of the forest in Central Amazonia could become a net carbon source under high emission scenarios, with drying trends reducing biomass and triggering regime shifts particularly if eastern Pacific temperatures rise >1.5°C (globally, >2.3°C) [Nath et al., 2024], while based on estimates of root zone moisture storage the area of forest at risk of regime shifts jumps by ~1.7–5.8 times (relative to <2°C warming) [Singh et al., 2024].

Potential 'early warning signals', in the form of 'slowing down' in system response to disturbances which can indicate resilience loss prior to a tipping point, have previously been identified in the Amazon in empirical data [Boulton et al., 2022] and models [Boulton et al., 2013; Bochow & Boers 2023]. However, recent studies have found a more heterogeneous or unclear response of forest resilience than earlier estimates, while other co-drivers of resilience loss can mask slowing down [Blaschke et al., 2024; Grodofzig et al., 2024; van Passel et al., 2024]. Despite this, more widespread resilience loss is still expected due to climate change in the future, and areas with greater deforestation or disturbance are already less resilient [Wang et al., 2024] and leading to greater seasonality in rainfall in those regions [Qin et al., 2025].

In GTPR23 the potential impacts of AMOC slowdown or collapse on the Amazon Rainforest were unclear, but several new studies have shone new light on this (see the Interactions & Cascades section).

Based on this new research, the GTP community maintains its assessment of the Amazon rainforest being a tipping system with low confidence at the continental-scale, medium confidence at the regional-scale, and high confidence at the local-scale (with robust evidence but low to medium agreement). While evidence has grown for larger-scale tipping, particularly on the basis of the assessment of Flores et al. [2024], and we now have high confidence in irreversibility over decadal/centennial timescales, continued model limitations and disagreements over location and thresholds limits current confidence level. However, we lower the minimum warming threshold from 2 to 1.5°C based on recent assessments of warming/deforestation synergies [Flores et al., 2024; Wunderling et al., in review; Melinkova et al., 2025], with the lower end of this range more likely when considering both warming and deforestation.

Congo rainforest

In GTPR23, the Congo rainforest was assessed as a tipping system with low confidence at the local scale, but unlikely to tip as a result of climate change, with low confidence in it involving abrupt / large rate change, low confidence in irreversibility over decadal/centennial timescales, and a threshold range of ~1350 mm mean annual rainfall [A. McKay, Sakschewski & Roman-Cuesta et al., 2023]. Since then, remote-sensing based assessments of local-scale bistability of high and low tree cover in the Congo have been refined [Zwaan et al., 2024]. While the hypothesis of local-scale bistability is supported [Staver et al., 2011; Aleman et al., 2020], the results indicate that transitions between closed forest and open savanna could instead pass through a state of coexistence, which would likely smoothen out tipping points between these states over larger spatial scales. In contrast, estimates based on root zone moisture storage project that the Congo Basin forest area at risk of critical transitions grows by ~0.7–1.7x under higher warming scenarios (relative to <2°C warming) [Singh et al., 2024].

Based on consistent evidence for bistability but continued limited agreement and evidence for wider scale tipping dynamics under future climate projections, we maintain our assessment of it being a low confidence tipping system at the local scale, and add that it is uncertain at regional scales. Overall, tipping may be more localised in comparison to the Amazon [Zwaan et al., 2024].

Southeast Asian rainforest

The Southeast Asian rainforest was assessed in GTPR23 as an uncertain tipping system at the local scale and not a tipping system with medium confidence at the regional scale, with low confidence in it involving abrupt / large rate change, low confidence in irreversibility over decadal/centennial timescales, and a threshold range of ~1550 mm mean annual rainfall [A. McKay, Sakschewski & Roman-Cuesta et al., 2023]. In the absence of substantial new research on this area, we maintain this assessment here.

Boreal forests & tundra

What it is

Boreal forests occupy ~1.14 billion hectares in the high latitude regions of the northern hemisphere [Pan et al., 2011]. They face disturbances from fire and insect outbreaks, as well as logging [Kuuluvainen & Gauthier, 2018]. Situated in an area with amplified climate change, there are two potential tipping points associated with boreal forests - one at its northern edge, where forest may expand into the tundra, and the other at the south, where the forest may dieback and transition to an open steppe/prairie landscape. Southern boreal forest dieback could be driven by the fire-vegetation feedback [Joos et al., 2001; Lucht et al., 2006; Lenton et al., 2008; Abis and Brovkin 2017; Rotbarth et al. 2023]. With high latitude temperatures increasing, there is evidence of increased survival rate of seedlings in the tundra and an advancing shrubline, with potential positive feedbacks (such as albedo and soil moisture feedback) leading to further forest expansion [Myers-Smith et al., 2011].

What's new

Dieback

In GTPR23, boreal forest dieback was assessed as a tipping system with medium confidence at the regional scale and low confidence at the continental scale, with medium confidence in it involving abrupt / large rate change, low confidence in irreversibility over decadal/centennial timescales, and a threshold of ~4°C (range 1.4-5°C) [A. McKay, Sakschewski & Roman-Cuesta et al., 2023].

Recent simulations found that boreal forests may be shifting from the current multi-stable state towards a unimodal semi-open state with 30-50 per cent tree cover in the coming decades [Rotbarth et al., 2025]. Such a shift would likely increase the risk of forest fires, leading to potentially substantial releases of stored carbon. However, these results are based only on the inferred relationship between tree cover change and mean annual temperature, with added stochasticity to represent process noise, and do not consider other important factors affecting the boreal forest dynamics, such as permafrost thaw or water and nutrient availability.

Warming will likely have consequences for boreal forest biodiversity and the likelihood of dieback. An average increase in tree species diversity by 12 per cent has been observed across boreal forests between 2000 and 2020 [Xi et al., 2024]. However, a negative impact was observed in areas of extreme warming (>0.065 °C /yr), suggesting that exceeding a certain threshold of warming could have detrimental effects. Repeated cycles of clear-cutting in boreal forests are also reducing old and large trees, deadwood diversity, and altering soil composition, causing a long-term decline in species richness [Lunde at al., 2025].

A recent satellite observations-based hydrologic sensitivity index [Domínguez-Tuda & Gutiérrez-Jurado, 2024] indicates that areas impacted by forest loss with a tree cover reduction higher than 18 per cent exhibited more pronounced warming trends and a rapid rise in hydrologic responses compared to areas with smaller losses. Similarly, it has been shown that tree growth in Eurasian larch forests is being increasingly limited by rising temperatures and the associated drought stress, leading to negative response to warming [Li et al., 2023]. Recent findings also show that across northwestern North America warming and disturbances are affecting vegetation resilience, which declined significantly in the southern boreal forest, including some regions exhibiting overall greening, but increased in much of the Arctic tundra [Zhang et al., 2024].

Based on this new research, we assess that while there is some increased evidence for dieback at the regional scale, we maintain our assessment at medium confidence in the absence of more evidence, and maintain low confidence at the continental scale.

Northern expansion

Boreal forest northern expansion was assessed in GTPR23 as a tipping system with low confidence, with low confidence in it involving abrupt / large rate change, low confidence in irreversibility over decadal/centennial timescales, and a threshold of ~4°C (range 1.5-7.2°C) [A. McKay, Sakschewski & Roman-Cuesta et al., 2023]. Since GTPR23, there have been several new publications relevant to this tipping system.

On the boreal forest's northern edge, transitional forests located between boreal forests and tundra are experiencing consistent increases in vegetation height and density [Montesano et al., 2024]. These changes are driven by Arctic amplification and are expected to continue through 2100 across all climate scenarios. Furthermore, a population of white spruce (*Picea glauca*) across an Arctic basin in North America has been documented advancing at rates that cannot be sustained by warming alone [Dial et al., 2022]. However, significantly reduced tree growth has also been found on thawing permafrost in the higher latitudes of North America [Alfaro-Sánchez et al., 2024], as trees need to invest more into remaining upright on destabilised grounds. Recent analysis of abrupt shifts in CMIP6 model results detected some abrupt shifts in boreal vegetation between 0.8 and 4.9°C, mostly for northward expansion [Terpstra et al., 2025] (Table A2.2.1), but they were not consistent across models, and do not necessarily represent tipping dynamics.

Based on this new research, while there is some agreement that climate change will likely induce tipping points in the expansion of the boreal forest, the still limited evidence base means the GTP community maintains its assessment of this being a tipping system with low confidence at the regional scale.

Temperate forests

What it is

Temperate forests make up 16 per cent of the global forest area [Hansen et al., 2010; Pan et al., 2011]. The majority of temperate forests are spatially fragmented and are managed, low biodiversity ecosystems [Potapov et al., 2017; Sabatini et al., 2021]. These management practices are likely to lead to large areas of forests with a lower resilience to perturbations, with forests exposed to droughts, heatwaves and pest outbreaks [Allen et al., 2010; Buras et al., 2019; Billing et al., 2020; Senf et al., 2020; Zhang et al., 2021; Carnicer et al., 2021; Benyon et al., 2023; Forzieri et al., 2022], with a potential of widespread dieback from these. Temperate forests may experience localised feedback dynamics from fire and bark beetle attacks in common with boreal forests (see above). Further investigation is required to establish the strength of the forest-moisture feedback in temperateforests. Large uncertainties remain around whether temperate forests may experience tipping points across a large scale [A. McKay et al., 2022], with some assessments suggesting this is unlikely at present [Thom, 2023].

What's new

In GTPR23, temperate forest dieback was assessed as a tipping system with low confidence due to limited evidence, with medium confidence in it involving abrupt / large rate change, low confidence in there not being irreversibility over decadal/centennial timescales, and uncertainty around any threshold ranges [A. McKay, Sakschewski & Roman-Cuesta et al., 2023].

Since GTPR23, there have been several new publications relevant to this tipping system. A recent satellite observations-based hydrologic sensitivity index [Domínguez-Tuda & Gutiérrez-Jurado, 2024] identified a threshold of around 46 per cent tree cover reduction for temperate coniferous forests, which leads to cooler climate conditions and higher water yield once surpassed. For Mediterranean woodlands, a threshold of roughly 54 per cent emerged, indicating relatively higher resilience but also rapid hydrologic shifts once that critical point is crossed. However, the degree to which these hydrological shifts involve tipping dynamics is unclear.

Several recent studies show new evidence of localised resilience loss and potential tipping points in different regions of temperate forests. In northwestern China, ecosystem productivity and photosynthetic efficiency have decoupled since 2010 [Zhang et al, 2024]. This indicates a loss of ecosystem resilience in these forests, which under rapid warming/drying flags a near-term dieback threshold in water-stressed regions. In Europe, the 2018-20 drought event led to a breakdown in standard forest dynamics in a German Beech forest [Mathes et al., 2023]. The drought's intensity potentially induced a nonlinear weakening of dominant trees, and future drought events of this or greater intensity could lead to a regime shift in such Beech forests.

Recent analysis of the relationship between forest fragmentation and ecosystem resilience revealed a clear nonlinear decline in resilience once forest connectivity dropped below critical thresholds (e.g. when number of patches per unit area increases beyond 0.89) [Fu et al., 2024]. In other words, when forest areas become too fragmented, their ability to recover from disturbances, such as droughts, fires, or storms, is significantly reduced. Notably, the study found that agricultural expansion had a more detrimental impact on forest resilience than urban development. While some degree of fragmentation may promote habitat diversity, exceeding certain fragmentation levels leads to a sharp and lasting decline in ecosystem stability, underscoring the importance of preserving large, contiguous forest areas.

While this new research supports the presence of tipping points in some temperate forest systems, and several temperate ecoregions have been subject to increasingly extreme heatwaves [Barriopedro et al., 2011; Sutanto et al., 2020; Lucarini et al., 2023], due to the evidence remaining limited the GTP community maintains its assessment of temperate forest dieback was assessed as an uncertain potential tipping system at the regional scale. However, we now assign low confidence to temperate forest tipping at the local scale.

Savannas & grasslands

What it is

Savanna and grassland are ecosystems dominated by grass cover intermixed, in savannas, with variable tree cover [Bond et al., 2008; Staver et al., 2018]. They face threats from conversion to agriculture [Stevens et al., 2022; Strömberg & Staver, 2022], woody encroachment [Stevens et al., 2017; Rosan et al., 2019], afforestation for carbon mitigation [Parr et al., 2024], and climate change via e.g. changes in rainfall variability [D'Onofrio et al., 2019], with major associated losses in ecosystem functions especially on the ground [Ding & Eldridge, 2024]. Savannas are distinct, biodiverse ecosystems, not degraded forest systems [Veldman & Putz, 2011; Veldman et al., 2013; Nerlekar & Veldman, 2020] or candidates for afforestation [Parr et al., 2024]. In some regions, savannas and forests represent potential alternative stable states [Hirota et al., 2011; Staver et al., 2011; Aleman et al., 2020], with open savanna states leading to a buildup of flammable grass material which can cause wildfires and limit tree growth. This open savanna-fire feedback loop can be disrupted by active and passive suppression of fires [Durigan & Ratter, 2016; Andela et al., 2017], which enables forest expansion into savannas [Stevens et al., 2017]. Palaeoecological evidence and fire studies have shown that this savanna to forest transition can be irreversible [Shanahan et al., 2008; Karp et al., 2023]. In some arid regions, savannas and grasslands also represent an alternative stable state to low vegetation cover with substantial bare ground [Hirota et al., 2011], discussed more fully in the Drylands section below.

What's new

In GTPR23, savannas and grasslands were assessed as a tipping system with medium confidence at a local-to-landscape scale. Tipping dynamics likely emerge over decades, resulting in low confidence in the possibility of abrupt / large rate change but with medium confidence in irreversibility over decadal/centennial timescales. Mechanisms involve decreases below ~60 per cent flammable cover that could prevent fire percolation, regionally variable and highly localised rainfall thresholds, and the influence of of CO_2 fertilisation. It is unknown to what extent savanna and grassland tipping points might scale up to emergent and synchronised events at larger regional scales, so this potential was assessed as uncertain.

Since GTPR23, there have been several new publications relevant to this tipping system. Higgins et al. [2024] synthesised several past studies arguing for widespread savanna-forest bistability, showing that a range of different approaches all produce savanna-forest bistability but that there is a substantial uncertainty in the climate thresholds associated with tipping points, consistent with our previous assessment. Several publications have also examined the possible contributions of spatial patterning and mosaics to avoiding tipping at larger scales in these systems [Zwaan et al., 2024; van der Voort et al., 2025]. Finally, a range of work showed that afforestation is accelerating potentially irreversible losses of savanna ecosystems [Loft et al., 2024; Parr et al., 2024] and has elaborated the potential for lost ecosystem services as a result of savanna encroachment [Ding & Eldridge, 2024].

Based on this new research, the GTP community maintains its assessment of savannas and grasslands being a tipping system with medium confidence at a local to landscape scale, and uncertain at the regional scale.

Drylands

What it is

Drylands consist of numerous vegetation types, including deserts, grasslands, shrublands, woodlands, savannas, Mediterranean forests and tropical dry forests, all defined by their aridity level (where the rainfall is lower than 65 per cent of the 'potential evapotranspiration', including hyper-arid, arid, semi-arid and pre-sub-humid climate zones) [Maestre et al., 2016; D'Odorico et al., 2013]. Some of these land cover types are covered in more depth in dedicated sections for 'tropical forests' and 'savannas', as well as the relevant feedback loops of vegetation-fire feedback and vegetation-rainfall feedback. Other feedbacks are possible, including at a small scale, e.g. microbial communities in soil influence the level of soil carbon stocks by decomposing organic. This aids moisture retention in dry soils which is in turn necessary for the decomposition of organic matter, thus forming a feedback loop. Interactions between plants can form important feedbacks in dryland, including around the formation of regular patterns which can occur from plants affecting local soil conditions, such as water and nutrient retention, which create 'islands of fertility' [Eldridge et al., 2024] and can create ecohydrological feedbacks at a large scale through plant connectivity. Additionally, excessive grazing by herbivores can drive changes in plant communities. Evidence exists for vegetation cover bistability in drylands around an aridity level (calculated as one minus the ratio of precipitation to potential evapotranspiration) of between 0.75 and 0.8 [Kefi et al., 2024], with different states of soil fertility, nutrient capture and nutrient recycling [Berdugo et al., 2017]. Studies have identified hysteresis in drylands through palaeorecords [Xu et al., 2020], remote sensing [Zhao et al., 2020] and field studies [Berdugo et al., 2017].

What's new

In GTPR23, land degradation in drylands was assessed as a tipping system with medium confidence at the local to landscape scale and low confidence at the regional scale, with medium confidence in it involving abrupt / large rate change, low confidence in irreversibility over decadal/centennial timescales, and three potential thresholds at aridity levels of 0.54, 0.7 and 0.8. Since GTPR23, there have been several new publications relevant to this tipping system.

On mechanisms, self-organised spatial vegetation patterns in drylands can enhance resilience to increasing aridity by facilitating resource redistribution. However, this ability is often lost in degraded ecosystems, with recent work showing this ability may break down beyond an extreme aridity level of 0.8 [Kéfi et al., 2024]. Land-atmosphere feedbacks involving existing drylands can also contribute to their own expansion. Warming and drying of air flowing over drylands can lead to reduced precipitation and increased atmospheric water demand in downwind humid regions, causing aridification [Koppa et al. 2024].

On the drivers of stress & thresholds, climate variability and seasonality were identified as significant environmental factors explaining abrupt changes in dryland Normalised Difference Vegetation Index (NDVI; a measure of vegetation greenness derived from satellite observations) [Berdugo et al., 2022]. Higher rainfall interannual variability is associated with increased vulnerability to abrupt shifts, while long-term trends in rainfall are a major driver of future abrupt shift susceptibility, with decreasing trends increasing the risk [Bernardino et al. 2025].

Aridity values reaching around 0.8 appears to be a threshold separating zones with contrasting dynamical behaviors for positive and negative abrupt shifts in NDVI [Berdugo et al., 2022]. Negative abrupt changes in NDVI are less likely after crossing this aridity threshold, while positive abrupt changes are more likely [Berdugo et al., 2022]. Kéfi et al. [2024] found bimodality in vegetation cover in a global dryland data set, which is consistent with the bistability predicted by dryland models and also supports a threshold at an aridity value of 0.8 (consistent with Berdugo et al. [2020]). Human activities, such as grazing, can amplify the effects of aridity on ecological thresholds. For example, grazing in China's drylands can act in synergy with aridity on dryland structure and functioning, and can therefore lower the aridity thresholds at which abrupt decreases in productivity, soil fertility, and plant richness occur [Li et al., 2023].

On the recent dynamics of dryland responses, while gains in vegetation productivity were more frequent than losses in the last two decades, 50 per cent of the areas experiencing significant changes in productivity showed abrupt (rather than gradual) changes in time [Berdugo et al., 2022]. Abrupt changes were more common among negative than positive NDVI trends and could be found in global regions suffering recent droughts, particularly around critical aridity thresholds.

On potential indicators of dryland tipping, in a study of global drylands lower functioning was found to be associated with impaired ability of the vegetation to self-organise into patchy spatial structure [Kefi et al., 2024]. Trends in spatial patterns observed along large scale dryland gradients matched model prediction, strengthening the idea that patterning is a mechanism of resilience and a possible indicator of ecosystem degradation. Similarly, a machine learning-based approach to detect early warning signals of abrupt shifts in ecosystem functioning was used in one of the world's largest dryland regions, the Sudano–Sahelian zone, and showed its applicability to identify regions that are more likely to undergo a future abrupt shift [Bernardino et al., 2025].

On projections of global dryland expansion, the contribution of reduced precipitation and increased evapotranspiration from existing drylands to ongoing dryland expansion was recently quantified, differentiating it from influences originating in other regions [Koppa et al., 2024]. This established that vegetation-climate feedbacks contribute to 50 per cent of the recent desertification of drylands areas, illustrating how existing dry regions contribute to the intensification and spread of aridity worldwide through feedbacks. However, an investigation of the effects of future climates on dryland productivity found that climate change might promote desertification in less than 4 per cent of current dryland areas, with the fertilisation effect from CO_2 emissions likely overcoming the projected increase in arid conditions in other areas [Zhang et al., 2024].

Based on this new research, the GTP community maintains its assessment of drylands being a tipping system with medium confidence at the local to landscape scale and low confidence at the regional scale.

Freshwater ecosystems

What it is

Freshwater ecosystems include lakes, ponds, wetlands, and rivers, all subject to major climate impacts. Lakes are present across much of the world and represent an iconic early example of ecosystem tipping points, hysteresis and resilience [Holling, 1973; Scheffer et al., 1993; Scheffer & van Nes, 2007]. Closely intertwined with the wellbeing of communities connected with them, lakes form part of a socio-ecological system which may be affected by rapid changes in lake state. Empirical evidence exists for tipping points in shallow lake systems [Scheffer et al., 2001; Tátrai et al., 2008], the most common type of lake globally. Anthropogenically driven eutrophication in lakes can be persistent, and difficult to reverse due to internal phosphorus-loading, whereby phosphorus stock-piled during periods of high pollution is mobilised from the sediment to surface waters following pollution reduction [Jeppesen et al., 1991; Spears & Steinman, 2020]. Lake warming enhances this effect, which together with nutrient pollution can also lead to an increase in greenhouse gases released from the lake, thus feeding back to global warming, but this may be countered to an extent by increased carbon burial processes [Anderson et al., 2020]. Critical phosphorus concentrations in shallow lakes are known to be highly variable with lake depth, retention time and fetch [Janse et al., 2008]. Modelled and empirical studies suggest thresholds in the range of 80–120 and 40–60 mg total phosphorus per m^{-3} lake water, respectively, for forward and reverse switches in both temperate and tropical systems [Wang et al., 2014; Springmann et al., 2018], though limitations in contemporary empirical data to explain non-linear relationships between chlorophyll a and nutrient concentrations in lakes requires further attention [Davidson et al., 2023].

Another potential tipping point for shallow lake systems involves increased levels of dissolved organic matter (DOM) from terrestrial sources due to land cover changes, such as afforestation, and a changing climate [Creed et al., 2018]. This process, also known as 'browning', occurs in boreal systems and can lead to increased stratification, net heterotrophy and anoxia, and ultimately increased greenhouse gas release [Jeppesen et al., 1991; Spears & Steinman, 2020], thus suggesting a potential positive feedback loop. The timescale of this 'browning' feedback loop is still uncertain [Hessen et al., 2024]. In permafrost regions, appearance or loss of waterbodies is tightly linked to permafrost thaw (e.g. thermokarst formation), and as such what could be considered a lake system tipping point is in fact a result of an underlying permafrost thaw tipping point [Hessen et al., 2024]. Rivers are not addressed in detail in this report, yet both extreme flood and droughts have major impact on wetlands, deltas, coastal areas and a renga of human activities. Glacial fed rivers clearly will be affected by disappearing glaciers [Milner et al 2008].

What's new

In GTPR23, eutrophication-driven anoxia in lakes was assessed as a tipping system with high confidence at the localised scale, with high confidence in it involving abrupt / large rate change and medium confidence in irreversibility over decadal / centennial timescales. DOM-loading, also known as 'browning', in lakes was assessed as a tipping system with medium confidence at the local scale, with low confidence in it involving abrupt / large rate change, medium confidence in irreversibility over decadal / centennial timescales, and a threshold range of >10 mg DOC/l. Other potential abrupt changes in lake ecosystems were identified in GTPR23, including disappearance / appearance of freshwater bodies, switch between Nitrogen and Phosphorus limitation, salinisation and the spread of invasive species. Some of the transitions to saline ecosystems are permanent and give rise to losses of biodiversity and changes in functions and services [Cunillera-Montcusí et al., 2022], but these were not classified as tipping points due to an absence of clear self-sustaining feedbacks. Several of these tipping points will imply positive feedback in terms of increased GHG emission [Rosentreter et al. 2021].

Since GTPR23, there have been several new publications relevant to this tipping system. Hessen et al. [2024] discussed candidate tipping points for lakes, while the concept of tipping points vs. 'tipping sets' have been explored using lake eutrophication as a case study [Mathias et al., 2024]. Lake drainage has been studied as a tipping point case [Liu et al., 2024], while the use of remote sensing for assessing lake tipping points has also been discussed [Gilarranz et al., 2022; Lenton et al., 2024]. Meanwhile, recent analysis found that compound weather extremes (heatwaves and extreme rainfall) in 2022 drove abrupt 'browning' shifts across multiple West Greenland lakes, altering biological and biogeochemical structure [Saros et al., 2025].

Recent works also address the link between permafrost thaw and expansion (or loss) of permafrost ponds linked to this. The widespread increase in thermokarst ponds has been linked to topography [Abolt et al., 2024], while other regions are prone to substantial loss of surface waters due to permafrost thaw, with Northern Sweden for example seeing thermokarst pond area and number decreasing by 6 and 27 per cent per decade, respectively, between 2003 and 2021 [Seeman & Sannel, 2024]. Of particular relevance is the work by Brovkin et al. [2025], arguing that permafrost and freshwater systems in the Arctic are inextricably linked in their tipping dynamics, and that hydrological changes in the permafrost region could have impacts on global hydroclimate.

GTPR23 only dealt with lakes, but given the prevalence of wetlands, their susceptibility to climate change (and other anthropogenic forcings), and not least their role as major greenhouse gas sources, they, should also be considered as potential freshwater tipping systems. For deltas, a number of drivers have been identified, also including cases of positive feedbacks, that may profoundly and rapidly change the physical and ecological properties of large deltas [Törnqvist et al. 2020; van de Vijsel et al. 2024]. The use of remote sensing has also been used for detecting regime shifts and loss of resilience in coastal wetlands, covering a salinity gradient from fresh to marine ponds and wetlands [Martinez et al. 2024]. For many wetlands, change in hydrology, water saturation and thus redox conditions due to degradation will shift systems from sinks to sources of CO_2, and determine the ratio between methanogenesis and methanotrophy. Zou et al. [2024] estimated a strong increase in greenhouse gas release from wetlands due to drought, and redox state of wetlands can be seen as a tipping point in the context of redox processes. However, tipping points for these systems implies irreversible losses of ecosystems with their key properties (rather than continued functioning with altered dynamics), and it is not always clear that positive feedback loops and hysteresis are as prevalent in all of these systems as for lakes.

Bogs, and notably peat bogs are globally important long-term sinks of carbon acting as major conduits of greenhouse gases, depending on temperature and water saturation. Waddington et al. [2025] recently argued that peatland ecohydrological resilience is a nonlinear function of water storage dynamics, with implications for carbon storage and fluxes when critical tipping points have been exceeded. Peatland in the Congo may have a rainfall-linked threshold, and has been suggested as a potential tipping system if drying led to carbon release [Crezee et al., 2022; Garcin et al., 2022]. Ombrotrophic (only precipitation-fed) peat bogs are highly vulnerable to rainfall and catchment properties, and have bistable properties linked to water table both in terms of carbon storage, greenhouse gas emissions and community composition [Lamentowicz et al. 2019; Loisel & Bunsen 2020]. The extent to which this bistability can reach tipping points to self-sustaining change is not always clear, but especially when it comes to carbon balance and hydrology, there is evidence that regime shifts can be driven by within-system feedbacks [Milner et al. 2020].

Based on this new research, the GTP community maintains its assessment of lakes being a tipping system with high confidence for eutrophication-driven anoxia (i.e. internal loading of phosphorus from sediments under anoxia) and maintains medium confidence for browning-related anoxia, noting growing evidence for the latter [Saros et al., 2025]. Loss or gain of permafrost-water bodies has a confidence level closely linked to permafrost thaw. We also add river deltas and peat bogs as potential local tipping systems, with low confidence for the former, and medium confidence for the latter.

Coastal ecosystems (mangroves, tidal wetlands, seagrass meadows, & kelp forests)

What it is

Despite their globally small area, coastal ecosystems such as mangrove forests, tidal saltmarshes, seagrass meadows, and kelp forests are highly biodiverse, and provide critical ecosystem services to many coastal areas [Nordlund et al., 2016; Menéndez et al., 2020; Cooley et al., 2022; doAmaral-Camara et al., 2023, James et al., 2023]. They face widespread degradation, primarily from habitat loss but increasingly from climate change impacts including increased weather extremes, severe storms & flooding, sea level rise, moisture and heat stress, and shifting climatological niches [Saunders et al., 2014; Bergstrom et al., 2021; Dunic et al., 2021; Cooley et al., 2022; Duke et al., 2022; Hagger et al., 2022]. For tidal wetland systems, there is strong evidence for bistability, with alternate states including mangrove or saltmarsh-dominated. Increased and compound pressures, strongly influenced by annual rainfall, are recorded as triggering the loss of one habitat form at the expense of the other [Feller et al., 2017; Duke et al., 2019; Duke et al., 2021; Hesterberg et al., 2022]. With more extreme and repeated damaging a point has been reached where re-establishment is threatened in some areas, leading to ecosystem collapse [Bergstrom et al., 2021]. Evidence is more limited for seagrass meadows, but also suggests that feedbacks can drive irreversible regime shifts to algal or unvegetated states in temperate and subtropical regions [Maxwell et al., 2017; Duarte et al., 2018; Kendrick et al., 2019; Cooley et al., 2022; Bartenfelder et al., 2022; Marba et al., 2022; Temmink et al., 2022]. Kelp forests can experience feedback-driven regime shifts to a barren state due to trophic cascades resulting from sea urchin dominance or climate-change intensified marine heatwaves [Ling et al., 2015; Filbee-Dexter & Werberg, 2018; Filbee-Dexter et al., 2020].

What's new

Mangrove forests & tidal wetlands

In GTPR23, mangrove forests and tidal wetlands were assessed as regional-scale tipping systems with medium confidence, with thresholds estimated to be reached by 1.5-2°C and late century alongside potential pollution and sea level rise rate thresholds.

Since GTPR23, research on mangroves and tidal wetlands has further established the extent to which mangroves are threatened. While mangroves overall have seen a greening trend since 2001 [Zhang et al., 2024], regionally there have been some large dieback events, with recent research analysing the El Niño-linked 2015-16 dieback event in the Gulf of Carpentaria [Duke et al., 2017], extreme events driving dieback in Australia, the Sundarbans, and Brazil [Sippo et al., 2018], and hailstorm-induced dieback in Mozambique [Machava-António et al., 2024]. The capacity of mangrove forests to re-establish has been compromised by rapidly rising sea levels coupled with increased severe weather and El Niño Southern Oscillation (ENSO) events, including ENSO impacts on sea level [Duke et al., 2022; Chung et al., 2023; Zhang et al., 2025], category 3+ cyclones [Duke et al., 2024], drought-hurricane compound events [Amaral et al., 2023], and unprecedented severe flood events and bushfires [Glasby et al., 2023]. In the future, one recent study estimated that the combination of climate-change intensified tropical cyclones and sea level rise would put around half of global mangrove area at high to severe risk of loss, and in particular those providing key services to people [Hülsen et al., 2025]. Mangroves and tidal wetlands can keep up with relative sea level rise rates up to a threshold of 4-7 mm per year through accretion, but at 2°C of global warming nearly all mangroves would be exposed to 4 mm per year and one third to 7 mm per year, and all nearly tropical and subtropical coastlines would reach 7 mm per year at 3°C [Saintilan et al., 2020; 2022; 2023].

Mangrove habitat is constrained within a very narrow elevational range between mean sea level and the highest tide levels. For the habitat to survive the vegetative structural elements must relocate, a process that can only be achieved over at least a decade, as the time needed for seedling establishment and growth to mature trees is essentially fixed [MacLeod et al., 2023; Duke et al., 2024]. As such, this capability can be overwhelmed, and this appears to be being surpassed in some regions [Duke et al., 2022]. Furthermore, the indirect impacts of climate change are also negatively affecting key functional groups in mangrove ecosystems, further reducing mangrove resilience [Ferreira et al., 2024]. However, landward mangrove expansion is still occurring in some regions, with for example the 2015-16 dieback event in northern Australia happening within a longer-term expansion [Asbridge et al., 2019], while some mangroves demonstrate continued resilience to tropical cyclones [Asbridge et al., 2025].

Based on this research, the GTP community maintains its assessment of mangroves being a tipping system at regional scales with medium confidence, while adding localised mangrove tipping at high confidence. While observations of particular mangroves failing to recover from increasingly extreme events are accumulating, there is strong regional variation in mangrove vulnerability [Rogers et al., 2019], and uncertainty globally in where sediment supply and landward migration can compensate relative sea level rise [Schuerch et al., 2018].

Seagrass meadows

In GTPR23, seagrass meadows were assessed as regional-scale tipping systems with medium confidence, with thresholds estimated to be reached by 1.5°C and mid-century, alongside potential pollution and sea level rise rate thresholds. Since then, new research has shown that in a conceptual mechanistic model of seagrass ecosystems, passing mortality thresholds results in a tipping point from seagrass meadow to a bare state, exposing the sediment to erosion, and reversing the meadow from carbon sink to source [Dakos et al., 2025]. This mirrors previous research indicating that seagrass meadows feature feedbacks that can drive self-sustaining regime shifts [Maxwell et al., 2017]. Research in the Gulf of Mexico has also shown how even in relatively undisturbed meadows, sea level rise can drive rapid seagrass loss [Capistrant-Fossa & Dunton, 2024]. Together this supports the confidence assessment of GTPR23, with further empirical research needed to assess regional variations in tipping thresholds and likelihood.

Kelp forests

GTPR23 assessed kelp forests as a local-scale tipping system with high confidence, with a timescale of months to decades. This assessment is supported by recent research focused on the effects of climate change on kelp ecosystems along the southeastern coast of Australia, particularly highlighting the invasion of overgrazing sea urchins that are expanding poleward due to warming waters [Ling & Keane, 2024]. The population of sea urchins has significantly increased here over the past 15 years, leading to the rapid emergence of incipient barrens, areas where kelp has been overgrazed. This suggests that half of the kelp beds within the affected region could collapse by around 2030, posing serious ecological concerns. Further work has also shown the increasing role of marine heatwaves in driving physiological tipping points [Leathers et al., 2024], while a sea urchin outbreak since 2014 on the Californian coast has led to a shift to a patchy mosaic of forest and barrens due to spatial heterogeneity in environmental conditions [Smith et al., 2024].

Other coastal systems

There are several other coastal ecosystems - such as mussel beds, oyster reefs, and salt marshes (cordgrass) - for which evidence exists for potential tipping dynamics (including bistability and self-sustaining regime shifts [Temmink et al., 2023]), that would benefit from targeted assessment here in future.

Warm-water coral reefs

For more on tipping points in coral reefs, see the coral reef case study

What it is

Shallow coral reefs in tropical and subtropical waters (hereafter 'warm-water coral reefs') are highly complex ecosystems built around the symbiotic relationship of reef-building corals and photosynthetic algae [Wilkinson et al., 2004]. Increasingly though, global warming means warm-water coral reefs are experiencing 'coral bleaching' events, during which sustained marine heatwaves triggers corals to expel their symbiotic algae due to heat stress [Hughes et al., 2017; 2018a; 2018b; Houk et al., 2020]. While natural bleaching events do occur, after which most corals recover, the increasing frequency and intensity of marine heatwaves - which has recently estimated to have increased by circa five times in frequency and intensity in the tropical Atlantic since 1982 [Rodrigues et al., 2025], and the 2023-24 global marine heatwave triggering catastrophic bleaching in previously less affected southern Great Barrier Reef [Byrne et al., 2025] - is increasingly preventing recovery between heatwaves, triggering mortality.

The loss of hard coral structure can trigger a wider ecological regime shift to an algae-dominated state, creating a localised tipping dynamic by which hard coral recovery would be impeded even if global warming were to be halted or reversed [Bland et al., 2018; Darling et al., 2019; Sheppard et al., 2020; Perry et al., 2013; Vercelloni et al., 2020]. Globally widespread die-off is expected by 1.5-2°C [IPCC SR1.5 2018; Cooley et al., 2022; Dixon et al., 2022; Setter et al., 2022; McWhorter et al., 2021; Frieler et al., 2013], but regional-scale coral reef mortality is already being observed as localised tipping becomes regionally synchronous [Le Nohaïc et al,.2017; Amir, 2022; Muñiz-Castillo et al., 2019; Obura et al., 2022]. Additionally, coral reefs face many other anthropogenic pressures, including pollution from nutrient and sediment runoff, increased weather extremes, overfishing and invasive species and diseases, which can also contribute to localised tipping [Ban et al., 2013; Edmunds et al., 2014; Darling et al., 2019; Cramer et al., 2020].

What's new

In GTPR23, warm-water coral reefs were assessed as a tipping system at the local and regionally-clustered scales with high confidence, with thresholds region- and reef-dependent but a global warming level of ~1.2°C (1.0-1.5°C) estimated for globally widespread losses. Since then, there has been a multi-year coral bleaching event, which has not been declared closed at the time of final text editing. Observations confirmed that 2023-2025 experienced the fourth global coral bleaching event on record, and the second within the past decade (following events in 2014-17, 2010, and 1998) [NOAA, 2024]. In this event, coral bleaching affected every ocean basin, with 83.7 per cent of corals experiencing bleaching-level heat stress by April 2025 (the greatest extent recorded, compared with 65.7 per cent in 2014-17) [NOAA CRW, 2025]. In 2024 catastrophic bleaching occurred in the previously less affected southern Great Barrier Reef, with mortality also affecting genera that are considered resilient [Byrne et al., 2025], while Coral Sea heat extremes were the worst for 400 years, putting the Great Barrier Reef at risk of near-annual bleaching [Henley et al., 2024]. Final global mortality figures are not yet available while the event continues, but around 14 per cent of coral reef was lost in the 2009-2018 period spanning the previous two global bleaching events [Souter et al., 2020].

Following GTPR23, Pearce-Kelly et al. [2025] explored the potential for coral tipping dynamics in response to various different stressors and their interactions, concluding that a warming threshold of 1.2°C (1–1.5 °C) as well as the long-term impacts of atmospheric CO_2 beyond 350 ppm were appropriate, noting these thresholds have already been passed, and warning that a comprehensive assessment of stressors and interactions has not yet been conducted and would likely result in lower threshold estimates. Cornwall et al. [2024] assessed the potential for ocean acidification to trigger tipping dynamics, and concluded that while evidence for direct physiological-level tipping dynamics is lacking, indirect ecosystem-level tipping is likely beyond 500 ppm of CO_2, particularly due to the differential impacts of acidification on calcification and growth to the detriment of calcifying (e.g. corals, molluscs, foraminifera) and benefit of non-calcifying (e.g. diatoms, fish, non-calcareous seaweed) organisms. Conversely, future decline in coral reef calcification due to climate change could increase the overall ocean carbon sink by around 7 per cent [Kwiatkowski et al., 2025].

Questions have been raised as to whether current coral decline projections are potentially overestimated. In a systematic review of the methods used to make projections of coral responses to climate change, Klein et al. [2024] found that most used deterministic rather than probabilistic approaches, limiting the ability to assess uncertainty, and that methods showing higher impacts (generally simpler 'excess heat' threshold models, often linked to estimated thresholds in 'Degree Heating Weeks', DHW, for which globally consistent values are difficult to establish) were disproportionately cited. Lab-based results also suggest that a broad range of coral species in the Indo-Pacific show sufficient heritability to allow for adaptation to both warming (with some coral species' DHW thresholds potentially increasing to those expected at c. 1-1.7°C) and acidification levels (c. -0.2 pH units) broadly consistent with the Paris Agreement, but would be insufficient for higher emission scenarios [Jury & Toonen, 2024]. However, these analyses do not explicitly account for interacting non-climate co-drivers, which could reduce adaptive capacities at the ecosystem level in the field, nor of in-situ applicability of lab results like these, while recent modelling has found that coral range expansion is too slow to counter future declines [Vogt-Vincent et al., 2025].

Based on the latest information, the GTP community maintains its assessment of warm-water coral reefs having localised to regional tipping points with high confidence [medium agreement, robust evidence]. This is based on well-documented evidence for coral reefs being vulnerable to regime shifts to various alternative states, and observations of increasingly widespread mortality in responses to increasingly frequent and intense marine heatwaves. We also maintain the warming threshold estimate of ~1.2°C (1-1.5°C), noting that widespread mortality is already being observed at current warming levels of ~1.4°C [WMO, 2025]. While laboratory tests suggest some coral species might have the adaptive capacity to cope with Paris Agreement-compliant warming [Jury & Toonen, 2024] this is not validated in in situ contexts. We also note that CO_2 levels above 500 ppm could directly trigger ecosystem tipping points via acidification [Cornwall et al., 2024], while in the long run CO_2 levels remaining beyond 350 ppm also threaten corals through long-term commitment to climate change [Pearce-Kelly et al., 2025].

Marine (benthic & pelagic) ecosystems

What it is

Marine ecosystems - from shelf sea to deep ocean, and sea floor to water column - face substantial pressures from multiple anthropogenic drivers, which has the potential to trigger irreversible regime shifts [Heinze et al., 2021; Jouffray et al., 2020; Bindoff et al., 2019]. Overexploitation combined with climate change could cause some fisheries to collapse [Sguotti et al., 2019; Beaugrand et al., 2022]. Similarly, warming, habitat loss, and pollution could result in community-wide shifts in wider marine ecosystems in benthic as well as pelagic environments [Conversi et al., 2015; Beaugrand et al., 2019; Möllmann et al., 2021; Ban et al., 2022; Sguotti et al., 2022]. Warming is also expected to result in a reduction in the biological pump - the transport of organic carbon from surface to deep waters - as ocean layers become harder to mix, although barring the polar seasonal lipid pump this is currently expected to be a relatively linear process [Jonasdottir et al., 2015; Armstrong McKay et al., 2021; 2022]. Finally, low oxygen 'dead zones' are expanding as a result of warming and nutrient pollution, with excess algae growth leading to deoxygenation and further amplified by sediment phosphorus release feedback [Diaz & Rosenberg, 2008; Breitburg et al., 2018; Heinze et al., 2020]. However, while many marine regime shifts have been observed and evidence exists for these ongoing changes and the potential for them to reach local to regional-scale tipping points in some cases, confidence is currently mixed due to limited understanding of potential thresholds and hysteresis in these systems.

What's new

In GTPR23, fisheries were assessed as a local-scale tipping system for some larger fish species with low confidence, and high confidence specifically for cod, with a tipping timescale of around a decade. Marine community shifts were assessed as a low confidence local-scale tipping system. The overall biological pump was not considered a tipping system (medium confidence), but specifically the seasonal lipid pump in the Arctic could be a regional-scale tipping system (unclear, decades). Finally, ocean hypoxia was assessed as a low confidence tipping system at the local scale (and unclear at regional-scale), with timescale varying from months to centuries.

Since GTPR23, there have been several new publications relevant to these systems. Vasconcelos et al. [2024] investigated the impacts of climate change on small pelagic fish communities in the Madeira Archipelago over a 40-year span (1980-2019). The research highlights how global warming has led to a regime shift in the small pelagic community, accounting for 88.9 per cent of the observed fluctuations in fish landings and life-history traits of two key species, *Scomber colias* and *Trachurus picturatus*. Cecapolli et al [2025] were able to identify contrasting regime shift dynamics across the three substocks of Atlantic cod in the North Sea, namely that the Southern North sea populations are now in a depleted state following a regime shift, whereas the other two substocks are either recovering or have not experienced a regime shift. Lastly, an analysis of three global datasets of 667 fish populations has identified abrupt shifts in productivity in almost 20 per cent of them [Cano et al., 2025], confirming and expanding on similar findings a decade earlier [Vert-pre et al., 2013]. Although the documented regime shifts of these papers support the GTPR23 assessments for marine systems, they also highlight the need for further research on the confidence for the extent of tipping point responses in benthic and pelagic marine systems.

2.2.7 Potential tipping points in ocean & atmosphere circulations

The ocean and atmosphere's circulations consist of the major flowing, fluid portions of the Earth system that transport water, air, and heat around the planet, and drive daily weather patterns. This includes the major overturning circulations in the ocean, as well as monsoon systems, mid-latitude atmospheric dynamics like the 'jet stream', tropical circulation patterns, and interannual 'oscillations' like the El Niño Southern Oscillation. In this section, we describe each of these systems, their evidence for tipping dynamics, and relevant new research in turn.

Based on this, we have reviewed the status of several systems, concluding that the Atlantic meridional overturning circulation (AMOC), convection in the North Atlantic Subpolar Gyre (SPG) and the circulation in the Southern Ocean are tipping systems with medium confidence, the West African Monsoon as tipping system with low confidence, and all other considered systems as uncertain or no tipping system with varying confidence levels (Figure 2.2.4). With respect to GTPR23, the East Asian Summer Monsoon has been added as an uncertain potential tipping system.

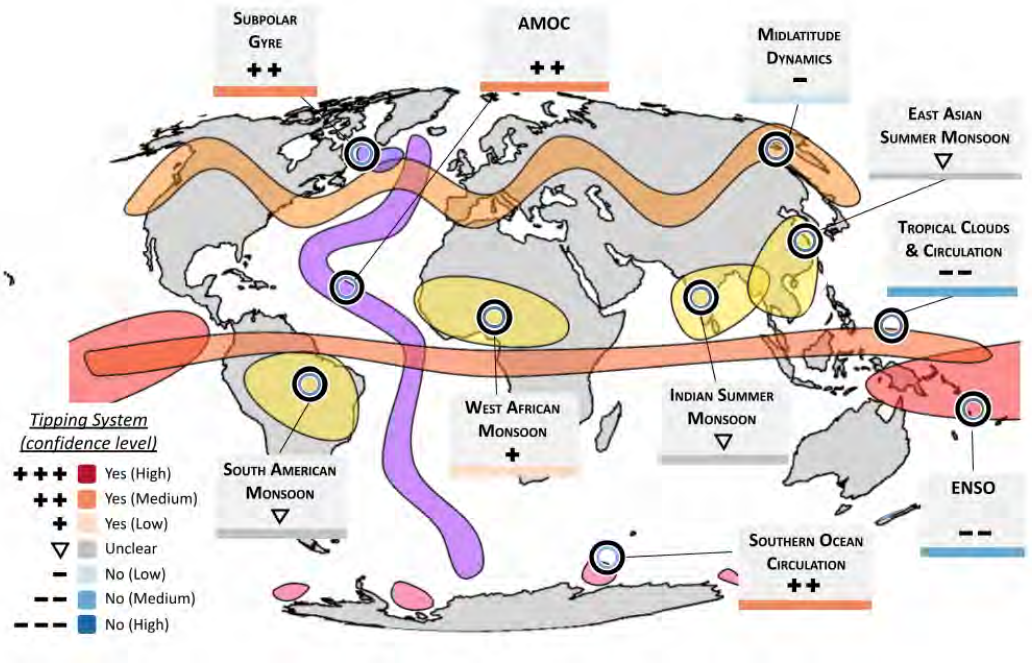


Figure 2.2.4: Potential tipping systems in ocean and atmosphere circulations considered in this chapter. The markers indicate which of the systems are in this report considered a tipping system (+++ high confidence, ++ medium confidence and + low confidence) and which are not (− − − high confidence, − − medium confidence and − low confidence), ▽ indicates systems for which a clear assessment is not possible based on the current level of understanding.

Atlantic meridional overturning circulation (AMOC) & deep convection in the North Atlantic subpolar gyre (SPG)

For more information on the AMOC and SPG tipping points, please see the AMOC case study

What it is

The Atlantic meridional overturning circulation (or 'AMOC') is the component of the Earth's ocean circulation driven by buoyancy loss at the surface in the north polar region. It describes the movement of warm surface water northwards in the Atlantic, followed by its cooling and densification, and subsequent sinking ('deep convection') in the seas around Greenland, helping to drive the circulation of the global ocean over the course of hundreds of years [Buckley & Marshall, 2015]. There are two main regions of deep convection: in the Greenland-Iceland-Norwegian Seas and in the Labrador-Irminger Seas. Climate change, however, can disrupt this circulation by warming and freshening water in the North Atlantic (via increased ice sheet runoff and precipitation), making it harder for it to get dense enough to sink [Arias et al., 2021, Liu et al., 2017]. Most model projections show a gradual decline initiated this century [Weijer et al., 2020; Bonan et al., 2025; Drijfhout et al., 2025], which is unprecedented at least in the last 6000 years [Gerber et al., 2025]. Palaeoclimate evidence suggests that the AMOC has more abruptly switched to weak or collapsed modes before that [Rahmstorf, 2024].

Some models also show weak AMOC states in future projections for extreme and intermediate forcing scenarios [Drijfhout et al., 2025], leading to strong North Atlantic cooling and substantial weather disruption in Europe and the Tropics [van Westen et al., 2025a; van Westen et al., 2025b], and the IPCC assessed in AR6 that many models are currently overly stable [Fox-Kemper et al., 2021; also Arumí-Planas et al. 2024, Dima et al., 2025 and Vanderborght et al., 2025]. The AMOC may already have weakened by ~15 per cent over the past 50 years [Caesar et al., 2018; Li and Liu, 2025; Michel et al., 2025], and some studies have detected statistical and physics-based 'early warning signals' (EWS) that could mean AMOC collapse begins within decades [Ditlevsen and Ditlevsen, 2023; van Westen et al., 2024], but whether tipping timings can be projected based on EWS has also been questioned [Latif et al., 2022; Ben-Yami et al., 2024, Terhaar et al., 2025].

Furthermore, the convection branch in the Labrador and Irminger Seas west and south of Greenland (forming part of the Subpolar Gyre, or 'SPG'), has been found to collapse separately to the rest of the AMOC (however being a precursor for AMOC weakening or tipping). This is suggested by palaeoclimate evidence during the transition into the Little Ice Age and by some models [Swingedouw et al., 2021; Arellano-Nava et al., 2022]. The risk of a SPG overturning collapse has been evaluated as 40 per cent in low- and medium-emission scenarios when selecting the CMIP6 models that best represent the observed oceanic stratification [Swingedouw et al., 2021].

What's new

In GTPR23, the AMOC was assessed as a tipping system with medium confidence, with a likely timescale of decades to centuries, and an uncertain path-dependent threshold [Loriani et al., 2023].

Since GTPR23, there have been several relevant publications. CMIP6-based projections show marked decline in the Arctic Beaufort Gyre, however the uncertainty of the gyre freshwater content trends is still large both in the models and observations [Athanase et al., 2025, Lin et al., 2023; Wang et al., 2025]. Increased freshwater export to the North Atlantic may weaken deep-water convection in key AMOC regions, but so far there is no published observational evidence of this happening. Various freshwater forcing experiments in models of varying complexity reaffirm evidence for potential AMOC collapse: In an ocean-only model, gradual freshwater forcing can trigger intermediate tipping events, leading to abrupt reorganisations of North Atlantic circulation [Lohmann et al., 2024; Lohmann & Lucarini, 2024] in multiple partially collapsed stable states. Four steady states are found using both surface freshwater forcing and changing CO_2 in CLIMBER-X [Willeit and Ganopolski, 2024]. A similar behaviour is observed in a high resolution model by Gou et al. [2024], where different convection areas reach tipping points independently. Van Westen et al. [2025] demonstrate that an AMOC collapse can still occur in a strongly eddying ocean-only model under freshwater hosing, indicating that ocean eddies do not prevent tipping. For the first time, an abrupt AMOC weakening has been simulated in Earth System Models without the need for externally imposed freshwater perturbations or an extreme emission scenario [NASA-GISS-E2-1-G in Romanou et al., 2023; MRI-ESM2-0 in Drijfhout et al., 2025]. This transition is triggered by stochastic variability in sea-ice transport and melting in the Irminger Sea. The stochastic bifurcation mechanism proposed in Romanou et al. (2023) has been explained by Boerner et al. [2025, in review] in terms of the collision between the `on' state of the circulation with the unstable circulation pattern associated with the `edge' state of the system.

Along similar lines, Gu et al [2024] find that nonlinear processes might amplify stochastic variability, leading to states with convection shutdown in the Labrador Sea. On the other hand, there have been recent studies that have identified contrasting mechanisms influencing the stability of the AMOC. Empirical modelling suggests that noise-induced tipping events are unlikely under present-day variability unless the AMOC is already close to a critical threshold [Chapman et al., 2024]. Furthermore, Baker et al. [2025] report a stabilising feedback present in CMIP6 models on a centennial time-scale, wherein sustained wind-driven upwelling in the Southern Ocean counteracts AMOC weakening—even under scenarios of extreme greenhouse gas forcing and freshwater input. However, these simulations are relatively short and may therefore correspond to a transient state. Also, the small AMOC strengths reported in several scenarios resemble the residual circulation persisting after collapse in extended simulations [Drijfhout et al., 2025; van Westen and Baatsen, 2025; van Westen et al., 2025]. The effect of the CO_2 ramping rate on the weak or collapse state of the AMOC has also been addressed [Hankel, 2024].

In terms of direct and proxy observation, Terhaar et al. [2025] suggest that the AMOC has not weakened in the last 60 years as derived from surface heat flux reconstructions serving as proxy indicator. Also, based on experiments with an idealised model, Zimmermann et al. [2025] advocate for cautious use of purely statistical early warning indicators since they may raise false alarms about approaching critical. On the other hand, a newly developed, physics-based observable early warning signal for AMOC tipping (representing the strength of the salt-advection feedback [Vanderborght et al., 2025]) suggests that the AMOC has destabilised over the past 40 years when applied to reanalysis and assimilation products [Van Westen et al., 2024], supported by deep-learning based reconstructions [Michel et al., 2025]. Furthermore, this indicator is biased positively in CMIP6 models, implying that these models may underestimate the risk of tipping [Arumì-Planas et al., 2024; van Westen and Dijkstra, 2024].

In GTPR23, like the AMOC, the SPG was assessed as a tipping system with medium confidence, however with a shorter timescale of years to decades, and a likely warming threshold range of 1.1 to 3.8°C [Loriani et al., 2023]. Since GTPR23, there have been new publications providing additional evidence for SPG as a tipping system. Proxy records from bivalve shells provide empirical evidence that the SPG crossed a tipping point during the transition into the Little Ice Age, with early warning signals appearing before the abrupt SPG weakening in the 14th century. The destabilisation was likely triggered by freshwater input from melting glaciers during the Medieval Warm Period, followed by an anomalous export of Arctic sea ice into the subpolar North Atlantic [Arellano-Nava et al., 2022]. A broader compilation of bivalve proxy records suggests that the subpolar North Atlantic experienced two periods of stability loss in recent times: one preceding the 1920s North Atlantic circulation regime shift, and the second in recent decades, indicating that the SPG region may be moving towards a tipping point [Arellano-Nava et al., 2025 in press].

Recent observations show that the SPG is undergoing strong freshening and reduced convection activity. The eastern SPG system has recently experienced its largest freshening of the past 120 years, primarily due to changes in ocean circulation [Holliday et al., 2020]. Two convective shutdowns in the Labrador Sea were observed in 2021 and 2023, with the latter being more intense. In 2023, convection shoaled to depths of less than 700 m, linked to extensive near-surface freshening driven by extreme Arctic sea-ice melt and enhanced by freshwater release from the Beaufort Gyre [Yashayaev, 2024]. This freshening also spread to the Irminger Sea, reaching depths of up to 1,500 m [Fried et al., 2024]. These events highlight the growing vulnerability of the SPG to crossing a tipping point.

Turning to model evidence, an analysis of abrupt shifts in CMIP6 models finds that 24 out of 57 models exhibit an abrupt SPG weakening, occurring within a global warming range of 0.3°C to 0.3°C, with a median critical temperature of approximately 1.5°C above pre-industrial levels [Terpstra et al., 2025]. In another study still under review, 'abrupt changes' and 'state transitions' are detected in the SPG in three models at 1.2-4.1°C and in 10 models at 1.2-5.6°C respectively (Table A2.2.1), and abrupt shifts are also detected in the AMOC in nine models between 1.1 and 3.9°C [Angevaare & Drijfhout, in review]. However, such abrupt shifts do not necessarily represent tipping points without confirming self-perpetuating dynamics. Menary et al. [2025] further classify different types of abrupt SPG changes, raising the need to define robust metrics and causal mechanisms [Falkena et al., in review] for the identification of abrupt events.

Based on this new research, the GTP community maintains its assessment of both AMOC and SPG being tipping systems with medium confidence, however acknowledging the increase in amount and agreement of evidence. For both, conceptual and low-complexity models suggest alternative stable states, further evidenced by palaeo records and process-based state-of-the-art climate models. Uncertainty persists around the magnitude of freshwater and thermal forcing that could initiate tipping, and the proximity to a potential tipping point.

Southern ocean overturning circulation

What it is

Ocean convection also occurs in the Southern Ocean (SO) around Antarctica, forming the second branch of the global ocean overturning circulation alongside the AMOC [Fox-Kemper et al., 2021; Heuzé et al., 2021]. Sea ice formation and strong offshore winds help produce dense salty water that sinks from the Antarctic shelves to the deep ocean, forming the Antarctic Bottom Water mass [Holland and Kwok., 2012; Abernathey et al., 2016]. The response of the SO overturning to global warming is less well studied than the AMOC, and is limited by the lack of Antarctic meltwater inclusion in models [Fox-Kemper et al., 2021; Heuzé et al., 2021; Purich & England 2023], but evidence has accumulated for an ongoing and continued decline [Lago & England, 2019; Liu et al., 2022; Gunn et al., 2023; Li et al, 2023; Zhou et al., 2023; Rosser et al., 2025 in review], and palaeo records suggest it has previously collapsed in response to meltwater pulses and could do so again [Skinner et al., 2010; Hayes et al., 2014; Gottschalk et al., 2016; Jaccard et al., 2016; Huang et al., 2020; Turney et al., 2020; Abram et al. 2025].

What's new

In GTPR23, Southern Ocean convection was assessed as a tipping system with medium confidence, with a likely timescale of decades and an unknown threshold [Loriani et al., 2023]. Additionally, there is the prospect of abrupt change in continental shelf circulation, leading to sudden rising ocean temperatures in contact with the Antarctic ice shelves [Li et al., 2023; Purich and England, 2023; Abram et al. 2025]. Cold ice shelf cavities in the Weddell and Ross Seas may be particularly vulnerable to warming under future climate scenarios, which could dramatically increase basal melting and contribute to sea level rise. This has been highlighted as another tipping mechanism [Hellmer et al., 2012; 2017; Siahaan et al., 2022; Naughten et al., 2023].

Over the past two years since GTPR23, a handful of studies have further investigated Southern Ocean convection and water mass change tipping systems, with much of the research effort concentrated on sea ice variability, but with some additional studies of indicators of ocean overturning change and future projections. On Southern Ocean convection and overturning, Gunn et al. [2025; in review] combines historical observations (1985-2024) and model projections of the upcoming decades (2041-2050) to assess changes in the abyssal Southern Ocean. They show that long-term freshening of the abyssal ocean has slowed and even reversed in some locations, as Dense Shelf Waters may no longer be reaching the abyssal ocean. Rosser et al., [2025; in review] demonstrate that the Southern Ocean overturning circulation collapses across nearly all CMIP6 models, even under strong mitigation scenarios.This disruption of the long-standing connection between the continental shelf and the abyss unfolds over decades and is driven by ice shelf melt and subsequent freshening. As the projected changes out to 2050 are already consistent with recent observations to 2025, there is evidence that model projections may underestimate the pace of change in the real system. This analysis indicates a potential tipping point in the ocean overturning connection between water over the shelf and water in the abyssal ocean.

Recent Antarctic sea-ice decline has raised further concerns that elements of the Antarctic ocean-ice system are changing more rapidly than first predicted. Since GTPR23 progress has been made in understanding its causes but uncertainty remains about the consequences for ocean convection. Using a reanalysis data product [Josey et al., 2024] and observations alongside models [Song et al 2024], recent work has shown that as sea ice cover is reduced, particularly in the Weddell, Bellingshausen, and Ross Seas, ocean heat loss to the atmosphere has doubled, also shifting the timing of peak heat loss. This intensification of winter heat loss leads to enhanced storm activity and also increased formation of dense surface water, but at locations far from the Antarctic shelf where dense shelf water is formed. A recent paper linking sea ice decline, heat loss, and a post-2015 surface salinity trend was misreported in the media as indicating an "SMOC reversal", but the implications for deep convection were not discussed in that study [Silvano et al., 2025]. Being remote from where Dense Shelf Water is formed, this effect is unlikely to contribute to changes in the abyssal overturning cell. However, advection and mixing of that off-shelf water mass may eventually impact the formation of dense water on the shelf, but the implications for Antarctic Bottom Water (AABW) formation remain unsubstantiated and is further complicated by decreased sea ice production, which diminishes AABW production. Nevertheless, this work highlights the potential interaction of different tipping points; namely, meltwater reduced AABW formation over the shelf [Li et al., 2023], contrasting changes in water masses off the shelf where sea ice loss has occurred [Josey et al., 2024]). In another study, using a coupled ocean-sea ice-ice shelf model forced by CMIP6 model-mean projected atmospheric conditions, Xie et al. [2025] find a decrease of more than half the rate of dense shelf water formation in the Ross Sea and a 300 metre thinning of AABW in the deep ocean by 2100. This reduction, a signature of an overturning slowdown in the region, is caused by the combined effects of meltwater-driven freshening with declining sea ice production.

A recent review of abrupt change around Antarctica finds evidence for emerging rapid, interacting and sometimes self-perpetuating changes in the Antarctic environment [Abram et al. 2025]. The study finds that Antarctic sea-ice coverage has reduced to levels far below its natural variability of recent centuries, with evidence that future changes could be more abrupt, nonlinear and potentially irreversible than Arctic sea-ice. The study also reviews evidence that the recent slowdown in the Southern Ocean overturning circulation is set to intensify this century, driven by increasing rates of ice melt around Antarctica. A slowdown of the SO overturning circulation in turn reduces the uptake of carbon by the oceans [Liu et al., 2022] and also causes further shelf water warming [Li et al., 2023; Purich and England, 2023], which are both expected to drive further ice shelf melt; an amplifying feedback that could lead to an eventual collapse in the SO overturning circulation.

Based on this new research, the GTP community maintains its assessment of the Southern Ocean overturning circulation as being a tipping system with medium confidence (high agreement, medium evidence), with evidence growing that the formation of Dense Shelf Water is declining and could reach a tipping point, but uncertainty remaining around the role of sea ice and interactions with ice shelf cavities.

Monsoons

What it is

Monsoons describe the large seasonal changes in the direction and strength of prevailing winds driven by seasonal insolation and local temperature differences between land and ocean, leading to heavy summer rainfall over land. Several subcontinental scale monsoon systems are recognised, including the Indian Summer Monsoon (ISM), the East Asian Summer Monsoon (EASM), the West African Monsoon (WAM), and the South American Monsoon (SAM). Today these are seen as being interconnected as part of one global monsoon system [Geen et al., 2020] strongly linked to the seasonal migration of the Intertropical Convergence Zone (ITCZ), where northern and southern hemisphere trade winds converge. The EASM however, extends to the subtropics, and is influenced by mid-latitude frontal systems and the jet stream as well as the Tibetan Plateau [Molnar et al., 2010; Son et al., 2019]. Rainfall projections are subject to high uncertainty in climate models, with projections of overall strengthening of the global monsoon precipitation in the future [Hsu et al., 2012]. Early tipping point studies suggested that the ISM could tip to a weak state as a result of aerosol emissions [Lenton et al., 2008; Levermann et al., 2009]. Similarly, the East Asian Summer Monsoon (EASM) was proposed to tip once an oceanic humidity threshold is crossed [Schewe et al., 2012]. However, more recent studies have cast doubt on both hypotheses [Boos and Storelvmo, 2016; Seshadri, 2017]. Palaeo records from the 'African Humid Period' also suggest that the WAM might interact with Sahel vegetation in a way that could tip this combined system to a wetter and greener state [Charney 1975]. In case of an AMOC collapse, the ITCZ and thus monsoons could strongly shift southwards, as evidenced by palaeo studies [Stager et al., 2011].

What's new

In GTPR23, the WAM was assessed as a tipping system with low confidence, and ISM and SAM assessed as unclear [Loriani et al., 2023]. Since GTPR23, there have been several new publications relevant to these tipping systems. By simulating a generic monsoon system on an aquaplanet, Katzenberger & Levermann [2025] introduce a new understanding that monsoons can be considered to undergo periodic tipping between stable 'on' and 'off' states. Changing climate conditions could thereby push the system towards a permanently altered state. Using an intermediate complexity model, Recchia and Lucarini [2023] showed the distinct response of the South and East Asian monsoon to anthropogenic forcings, emphasizing that aerosol forcing, rather than GHGs forcings, has the potential to strongly reduce the intensity of the monsoonal precipitation, with stronger impacts expected in the East Asian sector.

Furthermore, Loriani et al [2025] have included the EASM (not considered in GTPR23) in their assessment, classifying it as an uncertain tipping system based on limited understanding about potential tipping processes. Like the other monsoon systems, EASM could be subject to the effects of an AMOC collapse [Ben-Yami et al., 2024]. A recent analysis of CMIP6 models reveals a projected increase of extreme wet seasons frequencies, precipitation and interannual variability of the EASM [Katzenberger and Levermann, 2024], albeit not reporting major systematic shifts. Stronger evidence stems from proxy records indicating several abrupt and irreversible regime shifts since the Last Glacial Maximum [Lu et al, 2025], linked to abrupt shifts in the AMOC and Saharan vegetation. Finally, recent analysis of abrupt shifts in CMIP6 model results detected some abrupt shifts in the Indian Summer Monsoon (at ~0.8°C global warming) but not other monsoons [Terpstra et al., 2025] (Table A2.2.1), but they were not persistent, and do not necessarily represent tipping dynamics. Based on this research, the GTP community maintains its assessment of the West African Monsoon being a tipping system with low confidence. Similarly, for the South American and Indian Monsoon the assessment of an uncertain tipping system is maintained. The same classification of an uncertain tipping system is made for the now-added East Asian Summer monsoon.

El Niño southern oscillation ('ENSO')

What it is

The El Niño-Southern Oscillation (ENSO) is the dominant interannual mode of variability in Earth's climate [Timmermann et al., 2018]. Every three to five years, the 5-6°C difference between the warmer western tropical Pacific and cooler eastern tropical Pacific maintained by easterly trade winds becomes weakened, resulting in an 'El Niño' event (the warm phase of ENSO). Conversely, during a 'La Niña' event (the cold phase of ENSO) this temperature gradient intensifies. Both phases lead to substantial weather pattern shifts around the Earth, with substantial impacts on people and ecosystems [e.g. Holbrook et al., 2020; McPhaden et al,. 2020; Callahan & Mankin 2023]. Climate models differ, but despite overall stronger trade winds, colder eastern equatorial Pacific, and weaker ENSO events since the 1990s/2000s [Capotondi et al., 2015; Ma & Zhou, 2016; Fedorov et al., 2020; Seager et al., 2022; Wills et al., 2022; Heede and Fedorov 2023a], global warming is generally expected to result in an increase in ENSO variability, leading to more extreme El Niño and La Niña events [Cai et al., 2015; 2018; 2022; Heede and Fedorov 2023b; Wang et al., 2023]. Palaeorecords suggest that the amplitude and frequency of ENSO events has gradually increased during the Holocene [Freund et al., 2018; Grothe et al., 2020; Lawman et al., 2022] and that a 'permanent El Niño-like state' may have existed in the Pliocene 3 million years ago [Wara et al,. 2005; Fedorov et al., 2006, 2013, 2015; Tierney et al., 2019], leading to the suggestion that ENSO might feature a tipping point towards a permanent or extreme state [Lenton et al. 2008]. However, the evidence so far does not support a threshold beyond which a self-sustaining regime shift to such a state occurs [Loriani et al., 2023].

What's new

In GTPR23, ENSO was assessed as not a tipping system with medium confidence [Loriani et al., 2023]. Since GTPR23, there have been several new publications relevant to this tipping system. In particular, the 2023-24 strong El Niño event has helped to drive record-breaking global temperatures across land and sea [Jiang et al., 2025], with substantial implications for ecosystems. While a rare extreme, models indicate that such large jumps in temperature are not unexpected during strong El Niño event when combined with the current global warming trend [Terhaar et al., 2025], and may have been made more likely by the prolonged La Niña event (itself potentially linked to global warming [Wang et al., 2023]) preceding it [Raghuraman et al., 2024]. These results suggest a combination of underlying global warming, a strong El Niño, and the particular timing and pattern of this and the preceding La Niña could largely drive the observed the recent jump in global temperatures, rather than being a regime shift in global warming or a change in ENSO dynamics, which will be confirmed if temperatures revert to the long-term trend [Terhaar et al., 2025].

For the future, recent research continues to support an increase in ENSO variability and extreme El Niño event frequency, with an analysis of ENSO dynamics during past glacial changes indicating that cooler conditions led to less ENSO variability and fewer extreme El Niño events [Thirumalai & DiNezio et al., 2024; corroborating e.g. Brown et al., 2020], and therefore the inverse can be expected with future warming. Bayr et al. [2024] recently argued that ENSO could be considered a tipping system on the basis of stronger El Niño events potentially triggering other tipping systems via higher global temperatures, but this warming is temporary, and no self-sustaining state shift is observed or projected within ENSO's own dynamics, which is key to be considered a tipping system (rather than impacts on other systems). As such, the GTP community maintains its assessment of ENSO not being a tipping system with medium confidence.

Midlatitude dynamics

What it is

A key aspect of the mid-latitude atmospheric circulation is the 'jet stream', a band of strong westerly winds with largest velocities at an altitude of 7-12 km which separates cold polar air masses from temperate lower-latitude air masses. The jet features large 'meanders' (linked to planetary, or Rossby, waves) which normally move and dissipate but can become quasi-stationary, leading to high-impact climate extremes. A local example of such persistent weather features are atmospheric 'blocking' events, which are closely associated with several extremes including wintertime cold spells and summertime heatwaves [Kautz et al., 2022] and conditions favouring wildfires [Luo et al., 2025]. Global warming has likely already led to a poleward shift of the mid-latitude jet [Woolings et al., 2023] and a similar trend is expected to continue in the future [Oudar et al., 2020]. At the same time, amplified Arctic warming is leading to a reduced meridional temperature gradient between the high and low latitudes. This has been posited to slow down the mid-latitude circulation and the jet stream, increasing the latter's waviness. An enhanced waviness, in turn, would favour more persistent midlatitude weather and the connected extreme events [Kornhuber & Tamarin-Brodsky, 2021; Coumou et al., 2018]. Observations indeed evidence a slowdown of the boreal mid-latitude summer storm tracks over the last several decades likely associated with anthropogenic emissions [Chemke & Coumou 2024]. However, the strength of the poleward shift and the degree to which jet waviness and midlatitude weather persistence have increased and/or can be linked to Arctic warming has been disputed [Blackport & Screen, 2020; Riboldi et al., 2020]. Potential tipping points in jet stream dynamics have been suggested [Drijfhout et al., 2013; Steffen et al., 2018], but little evidence exists for a warming threshold beyond which such behaviour might become self-sustained.

What's new

In GTPR23, mid-latitude atmospheric dynamics was assessed as not a tipping system with low confidence [Loriani et al., 2023]. Since GTPR23, there have been new investigations relevant to this tipping system, with a focus on how a future, warmer Arctic will affect mid-latitude waviness. Key results concern future changes in the meridional temperature gradient, the role of Arctic sea-ice and the relationship between jet speed and jet waviness. Arnheim et al. [2025] analysed large ensembles of climate model simulations and concluded that climate change leads to a less wavy jet. They further found that the more recent set of simulations produced a weaker Arctic Amplification, displaying an enhanced reduction of waviness and blocking compared to an earlier model version. The effects of Arctic amplification on the jet stream and midlatitude circulation may be partially countered by Arctic sea-ice loss, which contributes to a slow-down of the wintertime North Atlantic jet stream [Jiang et al., 2025]. Finally, past arguments for a future, wavier mid-latitude circulation have mostly assumed that slower jets are more wavy and persistent, but the link between jet speed, waviness and persistence has recently been challenged by Baatelan et al. [2024] and Banderier et al., [2025], who found that weakened mid-latitudinal jet strength does not equate to increased waviness and that waviness can increase in the absence of clear persistence changes. In contrast, recent work has found evidence for increasing frequency of planetary wave resonance events in historical data [Li et al., 2025] and in future model projections [Guimarães et al., 2024], but with no indication of tipping dynamics. The latest research strengthens the evidence for the midlatitude atmospheric dynamics not being a tipping system. However, due to a low level of agreement in the literature the GTP community still assesses the midlatitude atmospheric dynamics as not being a tipping system with low confidence (medium evidence, low agreement).

Tropical clouds, circulation, & climate sensitivity

What it is

Clouds - and in particular tropical clouds - play an important role in the Earth's climate system by modulating how much incoming sunlight is reflected and how much heat from the surface is trapped [Forster et al., 2021]. In general, high thin clouds tend to let more light through but trap more heat, therefore having a net warming effect, while lower thicker clouds tend to reflect more light but let more heat through, having a net cooling effect. Global warming is affecting cloud dynamics though, with implications for the Earth's climate sensitivity depending on which type of cloud is more favoured. Cloud projections remain highly uncertain though due to poor process representation, but unexpected feedbacks remain possible [Caballero & Huber, 2013; Bellomo et al,. 2014; Bloch-Johnson et al.. 2015; Mauritsen & Stevens 2015; Myers et al. 2018]. One such feedback is the loss of subtropical stratocumulus cloud decks, which in one model featured a tipping point in CO_2 concentration beyond which abrupt loss and a global warming feedback of 8°C occurred [Schneider et al,. 2019]. Another possibility is an unexpected reorganisation in tropical circulation to a 'super-MJO' (Madden-Julian Oscillation) or superrotation state beyond some level of warming [Caballero & Carlson 2016; Seeley & Wordsworth 2021; Tziperman & Farrell, 2009; Caballero & Huber 2010]. However, cloud processes remain a key source of uncertainty in climate models, and little evidence is currently available to support these possibilities [Sherwood et al., 2020].

What's new

In GTPR23, tropical clouds and circulation was assessed as not a tipping system with medium confidence [Loriani et al., 2023]. Scientific literature published since then has not directly addressed tipping points in this system, such that the GTP community maintains its assessment of tropical clouds, circulation and climate sensitivity not being a tipping system with medium confidence.

2.2.8 Interactions between tipping systems

What it is

The tipping systems identified in the previous subsections are generally not isolated but interact across scales in space and time [Wunderling/von der Heydt et al., 2024]. Here, we define a tipping interaction as any linkage between two tipping systems that is destabilising, stabilising or where competing effects are at play. An example of a well established destabilising interaction is the linkage between GrIS and the AMOC, where meltwater from the GrIS destabilises the AMOC [see e.g. Weijer et al., 2019]. An example for a stabilising interaction is the interaction vice versa where a weakening (or tipping) AMOC leads to cooler temperatures around Greenland, which may be strong enough to slow down (or even stop) further GrIS melt [e.g. van Westen et al., 2024; Jackson et al., 2015].

What's new

Summary

We summarise the assessments of the GTP community in Figure 2.2.5. Based on these new and former assessments, the GTP community maintains the following three important conclusions on interactions and cascading transitions between tipping systems.

1. Tipping systems in the climate system are closely interacting, meaning a substantial change in one will have consequences for connected tipping systems.
2. We are quickly approaching global warming thresholds where tipping system interactions become relevant, because multiple individual thresholds are being crossed. These are at levels of 1.5-2.0°C of global warming.
3. While the pure pressure from global warming in its speed and also its magnitude dominates over the role of interactions (which need time to unfold) on tipping risks, the interactions between climate tipping systems seem to further destabilise the Earth system in addition to climate change effects on individual tipping systems.

The following three novel top-level conclusions including the newly assessed interactions are:

1. The majority of interactions between climate tipping systems are destabilising. However, new evidence shows that the interaction from AMOC weakening to Amazon rainforest may be stabilising as well as the interaction from West Antarctic Ice Sheet melt to AMOC stability. 15 interactions are assessed as destabilising, four as stabilising and one as unclear/competing effects (see **Figure 2.2.5**; not counting the interactions of very limited evidence, coloured in grey in **Figure 2.2.5**).
2. Although of unknown and/or limited strength, permafrost loss and Arctic Sea Ice decline may form a vicious cycle where less permafrost could lead to Arctic Sea Ice retreat and Arctic Sea Ice retreat may lead to enhanced inland permafrost degradation.
3. The AMOC has already been identified as an important mediator of interactions in GTPR23 but with the new evidence reported here, it can truly be stated that the AMOC is the global mediator of tipping point interactions. The AMOC alone features in 45 per cent (9 out of 20 interactions, not counting interactions of very limited evidence) of all assessed tipping point interactions (see Figure 2.2.5).

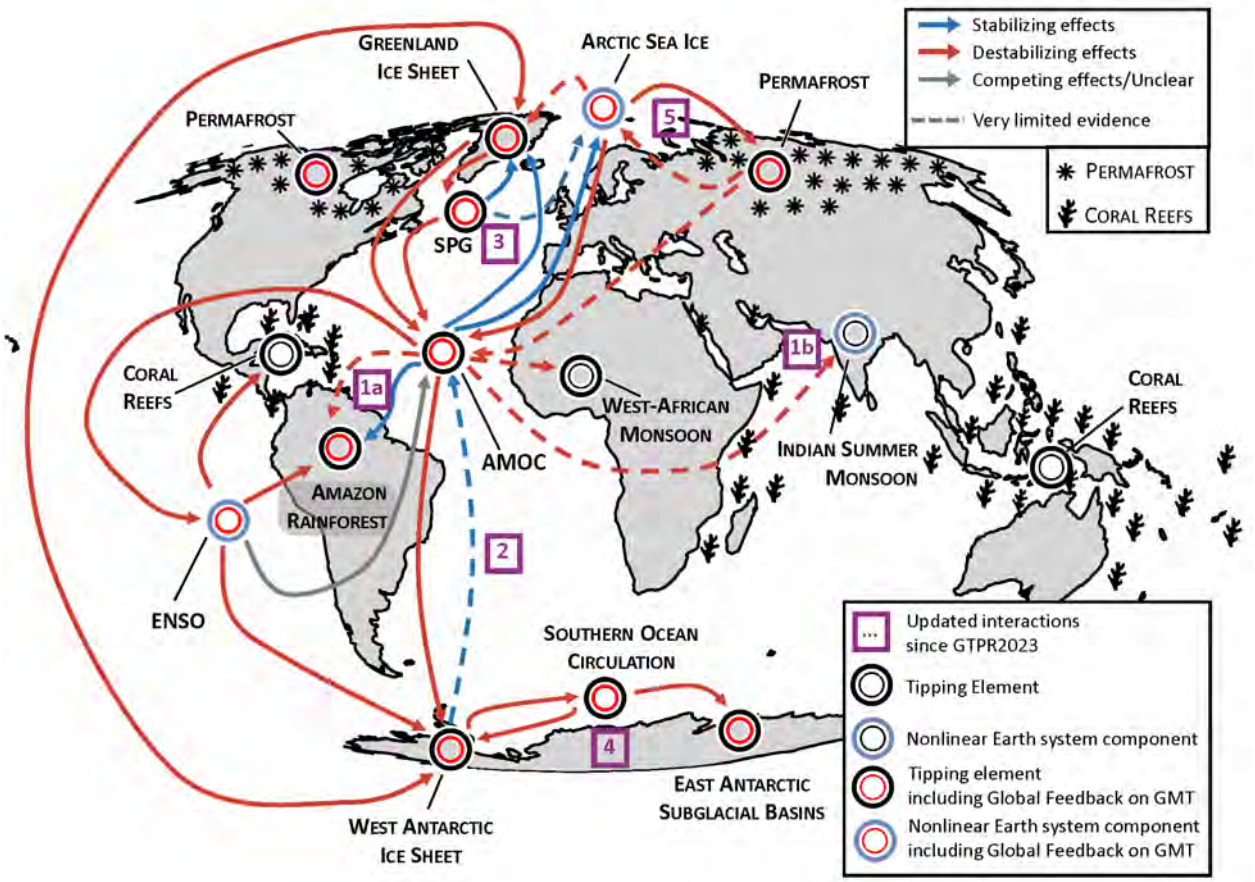


Figure 2.2.5: Update of tipping system interactions based on new evidence presented in this report. The updated interactions are denoted by purple squares and are: (1) Interactions from AMOC to global monsoon systems with the two updates (1a) AMOC→Amazon rainforest: AMOC weakening leads to increased rainfall in the southern part of the forest (blue arrow) but also to decreasing rainfall in the northern part (red dashed arrow); (1b) AMOC interaction with the Indian summer monsoon (red dashed arrow). (2) Interaction between AMOC and the West Antarctic Ice Sheet (WAIS) with limited evidence pointing towards a potential stabilising interaction from WAIS→AMOC (blue dashed arrow). (3) North Atlantic Subpolar Gyre (SPG) and its interactions with AMOC and the Greenland Ice Sheet. (4) Interaction from the Southern Ocean Circulation to the shelf regions of the Antarctic Ice Sheet and WAIS. (5) Interactions between Permafrost and Arctic Sea Ice (red arrows, now with higher evidence levels). The original figure has been updated from GTPR23 [Lenton et al., 2023] and Wunderling/von der Heydt et al. [2024].

Based on new evidence from recently published works presented here, we reassessed and for the first time evaluated the following five new interactions between climate tipping systems. Here, we focus on interactions where new evidence arose since the last Global Tipping Points Report 2023 [Lenton et al., 2023; Wunderling/von der Heydt et al., 2024].

1. Interaction from AMOC to global monsoon systems

a. AMOC → Amazon rainforest (via the South American monsoon)

The interaction between the AMOC and Amazon rainforest is complex. In the last report, it was assessed that a weakening AMOC would lead to a southward shift in the Intertropical Convergence Zone (ITCZ) that in turn could lead to increased precipitation in the southern Amazon region while intensifying drying trends in the north [e.g. Bellomo et al., 2023; Orihuela-Pinto et al., 2022]. These divergent patterns could stabilise forests in some regions while pushing others towards a degraded or savanna-like state. Indeed, most recent Earth system model and observational-data studies find that a weakening AMOC leads to an increase in rainfall in southern and eastern parts of the Amazon rainforest counteracting the global warming-related decrease in rainfall over these areas [Nian et al., 2023; Ben-Yami et al., 2024; Högner et al., 2025].

Another study confirms a vulnerability increase in northern Amazon forests due to a decrease in rainfall and increase in seasonality, based on palaeoclimatic pollen and microcharcoal data [Akabane et al., 2024]. As suspected, these studies suggest a regionally different response of the Amazon rainforest to a weakening AMOC that is now implemented in our updated tipping system interaction map (see Figure 2.2.5). In addition, seasonal precipitation changes after AMOC collapse may exert additional pressure on the rainforest [van Westen et al., 2024].

Importantly, the overall vulnerability of the Amazon rainforest is high: While the increased vulnerability in northern Amazon region combined with deforestation, wildfires and land-use change may have the capacity to trigger a systemic tipping point in the northern Amazon rainforest [Akabane et al., 2024], the effect in the southern Amazon region is different. Here, the effect of increased rainfall due to AMOC weakening is likely not of the same magnitude as drying effects from global warming [Nian et al., 2023; Högner et al., 2025] and strong deforestation, wildfires and land-use change [Albert et al., 2023; Lapola et al., 2023]. This means that global warming impacts likely decrease rainfall over the southern Amazon rainforest more than a weaker AMOC would lead to its increase.

b. AMOC interactions with the West African and Indian monsoon systems

CMIP6 models that feature a bistable AMOC show highly consistent changes in tropical monsoon systems following an AMOC collapse. The West African Monsoon and the Indian Summer Monsoon experience shorter wet seasons and longer dry seasons with mean annual precipitation decreases of 29 and 19 per cent, respectively [Ben-Yami et al., 2024]. Therefore, we classify the interaction from AMOC to both monsoon systems as destabilising with yet limited evidence (see Figure 2.2.5).

2.Interaction between AMOC and WAIS

Several recent studies report AMOC changes in response to meltwater from the Antarctic Ice Sheet and in particular from WAIS as the most vulnerable part of the Antarctic Ice Sheet. Two studies highlight the importance of both oceanic and atmospheric processes for AMOC stability [Shin et al., 2024; An et al., 2024]. On short timescales, AMOC weakening in response to meltwater input from WAIS is observed, driven by Rossby wave teleconnections and ITCZ-shift-induced precipitation changes [Shin et al., 2024; An et al., 2024], while ocean-driven strengthening may emerge on longer timescales [Shin et al., 2024]. However, under realistic meltwater input from both the Greenland and (West) Antarctic ice sheets, the additional meltwater from the Antarctic Ice Sheet can mitigate an AMOC slowdown, or even prevent its tipping [Sinet et al., 2025; Knight & Condron, 2025]. These studies use Earth system models of intermediate and full complexity (CLIMBER-X and CESM). An earlier expert elicitation assessed competing physical effects from WAIS melt to AMOC stability, including a physical mechanism for a stabilising interaction from WAIS disintegration to AMOC stabilisation [Kriegler et al., 2009]. In summary, we therefore decide to label the linkage between the West Antarctic Ice Sheet to the AMOC as stabilising (with very limited evidence for now).

3.North Atlantic subpolar gyre and its interactions

The North Atlantic subpolar gyre (SPG) has been classified a separate potential tipping system in the previous report [Loriani et al., 2023; [Loriani et al., 2023; Armstrong McKay et al., 2022]; Armstrong McKay et al., 2022], and the SPG convection has a proposed mechanism for bistability [Born and Stocker, 2014]. However, at the time of GTPR23, SPG collapse was not included in the chapter on tipping system interactions because not many studies had considered SPG connections to other tipping systems at that point in time. However, we reconsider this former assessment due to our following new lines of evidence of tipping point interactions: (1) Tipping of the SPG is associated with persistent ceasing of convection in the Labrador Sea and Irminger Sea ocean deep convection areas, with similar but smaller amplitude and more regional consequences for North Atlantic temperatures as an AMOC shutdown [Swingedouw et al., 2021]. Therefore, a shutdown of convection in the SPG cools the North Atlantic region and we expect a stabilising link from the SPG to the Greenland Ice Sheet and Arctic sea ice [Li and Born, 2019]. Importantly, changes in precipitation patterns can also contribute to the freshwater budget in the SPG region, and can therefore play a role in destabilising the SPG. (2) As the SPG convection regions significantly contribute to deepwater formation for the AMOC, a shutdown of convection in these areas could lead to an initial weakening of the AMOC [Neff et al., 2023; Rahmstorf, 1995] (i.e. destabilising link from SPG to AMOC). (3) Finally the tipping in the SPG is triggered by freshwater input that could be meltwater from a disintegrating Greenland Ice Sheet [Born & Stocker, 2014].

4.Interaction from the Southern ocean circulation to the shelf regions of the Antarctic Ice Sheet

Recent work has provided growing evidence for a potential transition from cold to warm ocean states in the Filchner-Ronne and Ross Ice Shelf cavities due to changes in the Southern Ocean Circulation. Using an ocean circulation model, Hill et al. [2024] found that temperatures in these cold ice shelf cavities could increase by 2 to 4°C, leading to significant increases in sub-shelf melt rates, building on earlier efforts suggesting that warming has been locked-in in certain regions of Antarctica [Naughten et al., 2023]. However, Hoffman et al. [2024] caution that such transitions may not occur uniformly. Their coupled Earth system model, which simulates ocean, land, sea ice, atmosphere, and ice sheet interactions, explores freshwater triggers for tipping points that could rapidly shift ice shelf cavities from cold to warm states, accelerating basal melt rates within a few decades. In addition, remote connections between melt fluxes at different ice shelves could lead to cascading effects, further destabilising ice shelves downstream. Another key driver expected for Antarctic ice shelf mass loss in coming decades are the ongoing positive trends and high variability in the Southern Annual Mode, which causes increased upwelling and subsurface warming and salinification close to ice shelves (and vice versa for negative phases), driving basal mass loss of 40 Gt/yr (around 40 per cent of the average loss) at one standard deviation of this climate mode of variability [Verfaillie et al., 2022; Osotoka et al., 2022].

5. Interactions with permafrost

a. Interactions between permafrost and Arctic Sea Ice

There is new evidence that suggests a possible destabilising linkage from declining permafrost to a decrease in Arctic Sea Ice [Nitzbon et al., 2024]. The reason is that inland permafrost degradation could increase the land-to-ocean heat transport via rivers [Wang et al., 2021] which in turn has a destabilising effect on Arctic sea ice [Park et al., 2020]. We add this interaction as an interaction with limited strength and very limited evidence (see Figure 2.2.5). Vice versa, additional evidence on top of GTPR23 [Lenton et al., 2023] shows that Arctic (winter) sea ice retreat leads to enhanced inland permafrost degradation, based on palaeoclimate [Vaks et al., 2020], and climate model studies [Lawrence et al., 2008]. Therefore, this link remains destabilising but its evidence level has increased.

b. AMOC → Permafrost

Additionally, limited new evidence suggests that an AMOC slowdown would lead to less northward heat transport, which would have a stabilising effect on land permafrost, particularly over northern Europe and Western Siberia [Park et al., 2025]. At the same time, an AMOC weakening or collapse would lead to rising sea levels across the northern Atlantic region and may weaken parts of the low-lying permafrost regions through flooding [Schwinger et al., 2023]. Vice versa, an AMOC recovery after a shutdown would increase the heat transport and destabilise high-latitude permafrost. Since an estimate of the strength of these competing effects is not assessed yet and may be limited, we do not add an additional link(s) from AMOC to Permafrost.

2.2.9 Appendix

Table A2.2.1: Global warming level (GWL) at which abrupt shifts have been detected in potential tipping systems in CMIP5/6 simulations, with previous tipping threshold estimates for comparison in part informed by CMIP5 abrupt shifts) and the number of models the shift features in [brackets].

System	Abrupt shift GWL thresholds			Tipping point GWL thresholds
	CMIP6 (1ptCO2): Terpstra et al. [2025]*	CMIP6 (SSPs): Angevaare & Drijfhout [in review]**	CMIP5: Drijfhout et al. [2015]***	A. McKay et al. [2022]****
North Atlantic subpolar gyre	0.5-2.9 [24/57]	1.2-4.1 (from abrupt change') [3]***** 1.2-5.6 ('state transitions') [10]	1.4-3.8 [5]	1.1-3.8 (based on Sgubin et al. [2017])
AMOC	-	1.1-3.9 [9]	1.4-1.9 [1]	1.4-8.0
Localised land permafrost	1.0-3.8 [8/46] (total soil moisture content) 1.2-3.3 [19/36] (soil frozen water content)	-	5.6 [1]	1.0-2.4
Amazon rainforest	- [-/7] (inconsistent small shifts 0.9-5.0)	-	2.5-6.2 [2]	2.0-6.0
Boreal forests	- [-/7] (inconsistent shifts 0.8-4.9)	-	7.2 [2]	1.4-7.2
Ind. s. monsoon	0.8 [1/57]	-	-	-
Antarctic sea ice	0.5-5.3 [11/53]	2.0-3.2 [4]	1.4-2.9 [3]	1.4-2.9
Arctic summer sea ice	1.0-4.6 [15/53]	1.3-2.3 ('abrupt changes') [7]	-	1.3-2.9
Arctic winter sea ice	3.3-5.4 [14/53]	2.5-5.1 ('state transitions') [22]	4.5-8.2 [5]	4.5-8.7
Barents sea ice	0.5-3.0	(included in ASSI)	1.5-1.7 [2]	1.5-1.7

*90 per cent interpercentile range, rounded to one decimal place

**68 per cent range; cannot be directly compared to Terpstra et al. [2025], as latter uses 1ptCO2 scenario rather than SSPs and uses different variables and abrupt shift detection methodology

***From Drijfhout et al. [2015] Table S2

****Literature-based synthesis range

*****Not directly equivalent to events of Drijfhout et al. [2015]

Chapter 2.3 Implications of overshooting 1.5°C for Earth system tipping points

Authors: Paul D. L. Ritchie, Norman J. Steinert & Nico Wunderling, Jesse F. Abrams, Hassan Alkhayuon, Constantin W. Arnscheidt, Nils Bochow, Ruth Chapman, Joseph Clarke, Bernardo Flores, Julius Garbe, Annika Högner, Chris Huntingford, Timothy M. Lenton, Johannes Lohmann, Kerstin Lux-Gottschalk, Manjana Milkoreit, Tessa Möller, Paul Pearce-Kelly, Laura Pereira, Courtney Quinn, Carl-Friedrich Schleussner, Jörg Schwinger, Simone M. Stuenzi, Didier Swingedouw, Larissa N. Van der Laan, Kirsten Zickfeld

Reviewers: Richard Betts, John Dearing, Jonathan F. Donges

Key Messages

- **Global warming has already exceeded 1°C where tipping risk has started to become non-negligible for warm-water coral reefs, Greenland and West Antarctic ice sheets.**
- **Current global warming of 1.35-1.4°C exceeds the central estimate of the thermal tipping point for warm water coral reefs of 1.2°C, therefore tipping is likely underway.**
- **Several systems (land permafrost, Greenland ice sheet, West Antarctic ice sheet and sub-polar gyre) likely have a tipping point around 1.5°C global warming, and several more (mountain glaciers, boreal forests and AMOC) around 2.0°C global warming.**
- **Therefore, overshooting 1.5°C of global warming raises the risk of triggering irreversible tipping events, with each 0.1°C adding to the risk.**
- **Limiting tipping risks requires minimising peak global warming and overshoot duration above 1.5°C, and ultimately reducing global warming below 1.5°C before 2100, and stabilising below 1.0°C on longer timescales.**
- **Tipping systems with fast and slow timescales respond differently to exceeding their tipping points:**
- **Fast systems are vulnerable to even short-lived exceedances and therefore their tipping points constrain the allowable peak warming.**
- **Slow systems can tolerate temporary exceedances of their tipping point but constrain the allowable duration of exceedance and the eventual temperature stabilisation level.**
- **Most tipping systems are expected to amplify global warming if tipped, making it more difficult to return to lower global warming levels in an exceedance period.**
- **Additional pressures, such as anthropogenic stressors, interacting tipping systems, and destabilising Earth system feedbacks, can amplify tipping risks further.**
- **Decreasing direct anthropogenic stressors on the Earth system can reduce the likelihood of climate-induced tipping for some systems (e.g. halting deforestation in the Amazon rainforest).**

2.3.1. Introduction

Humanity is on track to cause levels of global warming that rise above 1.5°C relative to pre-industrial levels (Reisinger et al., 2025; Bevacqua et al., 2025; Bustamante et al., 2023). Indeed, current legally-binding policies are taking us towards highly uncertain future global warming estimates of 2.2-3.4°C (mean: 2.7°C) later this century (Climate Action Tracker, 2024). To eventually limit warming levels at or below 1.5°C, it is now almost inevitable that there will be a period of overshoot during which the warming limit will be temporarily exceeded.

Temperature overshoot refers to pathways of global warming (averaged over a climatological period of e.g. 30 years) that first exceed a warming level (such as 1.5°C), followed by an eventual return to, or below, the warming level - as opposed to exceedance scenarios that permanently surpass a warming level. Therefore, temperature overshoots are often characterised by their peak warming, duration, and final stabilisation level (Schleussner et al., 2024; Schwinger et al., 2022). Two conceptual overshoot pathways over a specific global warming level are illustrated in Figure 1a.

During such overshoots, there is an increased risk of crossing uncertain tipping points (i.e., pathways temporarily exceed the tipping point uncertainty range in Figure 1a). While temperature overshoot pathways have many negative consequences on biogeophysical and biogeochemical systems, as well as socioeconomic and human impacts, and equity concerns, assessing whether they cross tipping points is critical, as this poses the added risk of triggering irreversible and self-reinforcing Earth system shifts.

Here, considering the response timescale of a system is important. Tipping systems can be categorised by their typical timescales in relation to the timescales of climate change: slow systems (e.g. ice sheets) respond over timescales much longer than climate change itself, while fast tipping systems (e.g., Subpolar Gyre, monsoons, or warm-water coral reefs) respond on similar or faster timescales (Lenton et al., 2024; Ritchie et al., 2021; Bochow et al., 2023; Swingedouw et al., 2021).

By overshooting (i.e. temporarily crossing and returning to or below) a certain temperature level, this can also mean that a tipping point is at least temporarily crossed. For a large and long-lasting crossing of a tipping point, there is a high risk of triggering tipping systems, even for slow tipping systems (Figure 1b). However, a temporary crossing of a tipping point will not necessarily result in triggering the tipping of some inherently slow systems, tipping may be avoided if the temperature overshoot is small and short (Figure 1c).

Ideally, such crossing of tipping points should be avoided, but this may already be too late for some tipping systems. As outlined in Chapter 2.2, the lower uncertainty ranges of some Earth system tipping points could have already been exceeded (Figure 2). Further committed warming is inevitable and almost certain to exceed 1.5°C, therefore exceeding the lower bounds of uncertainty ranges of additional tipping points. Nevertheless, limiting the magnitude and duration of temperature overshoot can still play a crucial role in avoiding the tipping of systems. Hence, fundamental questions arise on what the limits for peak warming and overshoot duration are to avoid tipping specific systems (Ritchie et al., 2021).

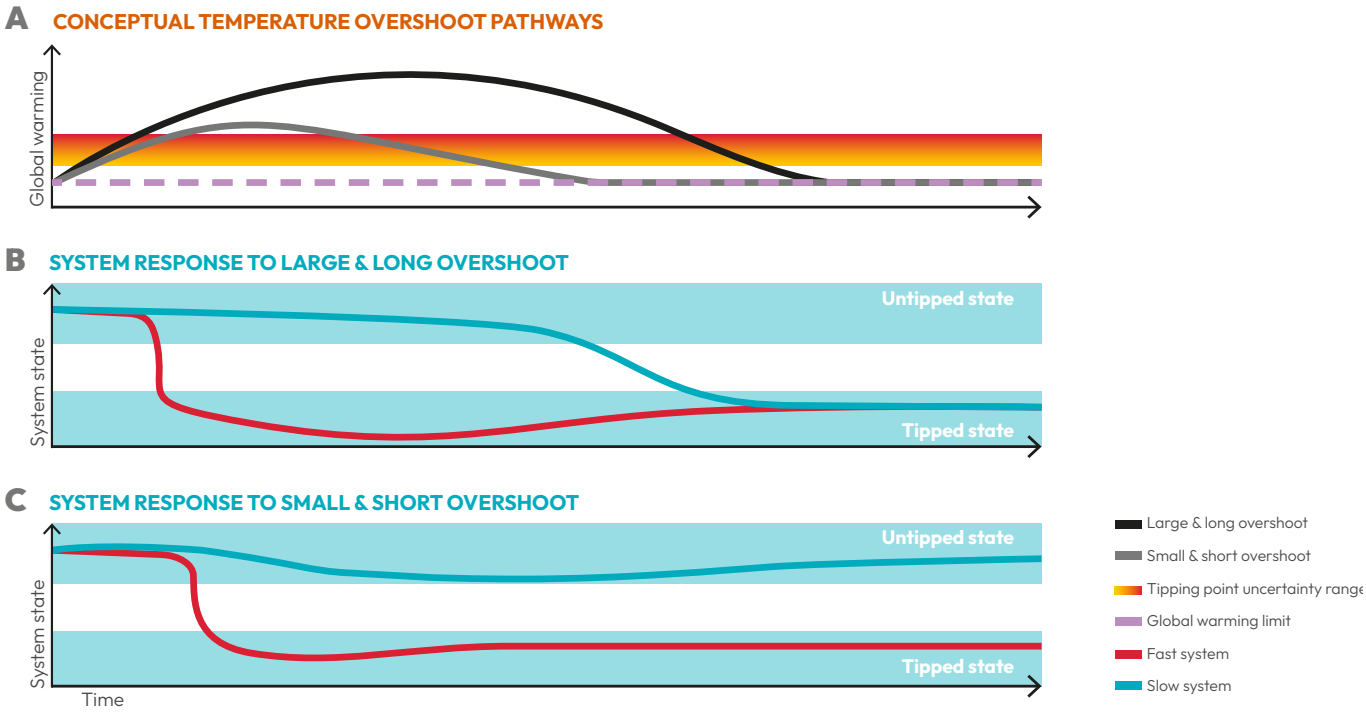


Figure 1: Response of fast and slow systems with a common tipping point to different overshoot pathways. (a) Two idealized global warming overshoot pathways that exceed a global warming limit (purple dashed line), reach some peak warming before returning and stabilising at the limit. These overshoot pathways temporarily cross an uncertain tipping point (burning ember range) that is here assumed to be the same for both a fast and a slow system. One pathway has a large peak and long overshoot duration (black) over a temperature limit (purple dashed line), the other a small peak and short overshoot duration (grey). (b) For the large and long overshoot over a temperature level, the fast system (red) tips very quickly after the tipping point is crossed, while for the slow system (blue), tipping is delayed. (c) For the small and short overshoot over a temperature level, the fast system (red) again tips, but tipping is avoided for the slow system (blue) despite also temporarily crossing its tipping point.

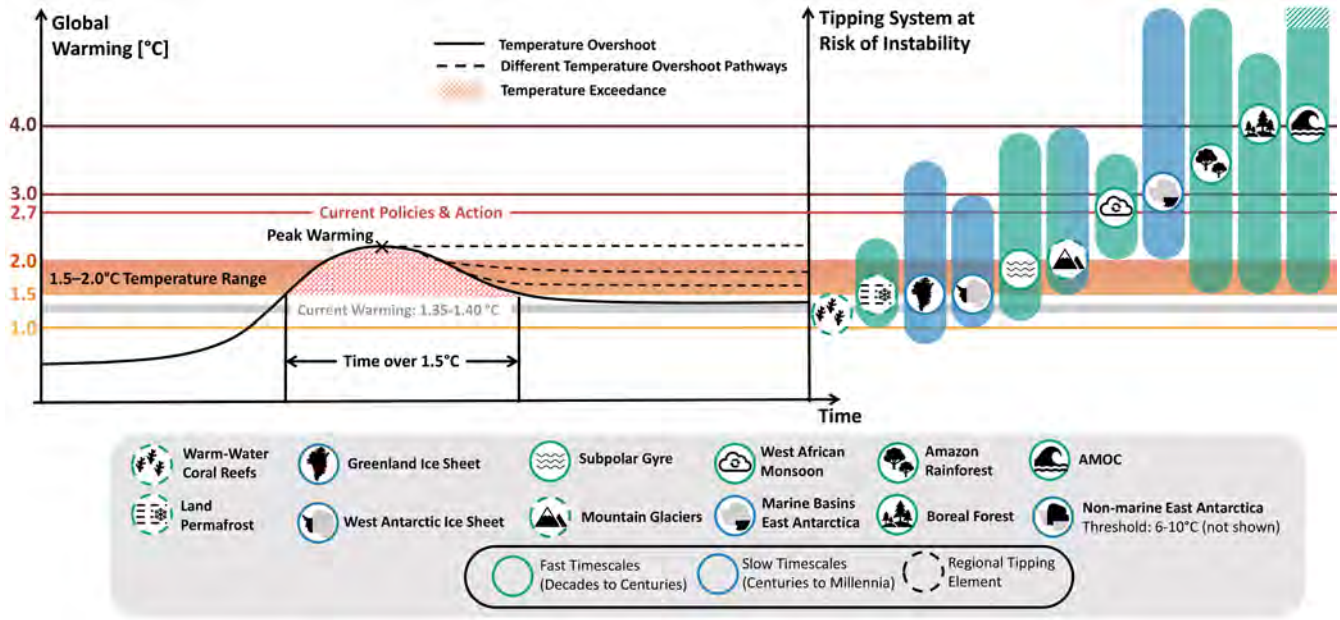


Figure 2: Overshooting 1.5°C risks crossing Earth system tipping points. Illustrative temperature overshoot pathway, exceeding and then returning to below 1.5°C (solid black line) and other stabilisation pathways (dashed black lines), dependent on uncertainties in future emissions and Earth system feedbacks. The depicted overshoot pathways at least temporarily crosses several Earth system tipping points: whether or not tipping occurs depends on the peak warming, time spent over the tipping point and the tipping system's response timescale. Icons denote tipping systems (global tipping systems are shown with a solid edge; regional tipping systems are shown with a dashed edge; local tipping systems are not shown; best-estimate tipping points based on data from Lenton et al., 2023, and in case of no updates, from Armstrong McKay et al., 2022). Uncertainties of tipping points are shown as shaded bars. Current policies & Actions lead to temperature increases of 2.2-3.4°C (mean of 2.7°C shown here; Climate Action Tracker, 2024).

2.3.2 Risk of triggering tipping systems during and after overshoot

Multiple systems of the Earth system could have their tipping point below 2°C of global warming and for some it could be below 1.5°C (Lenton et al., 2023; Armstrong-McKay et al., 2022; see Figure 2; Chapter 2.2). From a Monte Carlo analysis, even under the most optimistic emission scenarios of limiting warming to 1.5°C and stabilizing temperatures at this level, it is considered as likely as not (33-66% probability) that three tipping systems will tip (Figure 3a). One of these systems will virtually certainly (>99% probability) tip - this is the warm-water coral reefs, given the upper range of their tipping point is 1.5°C (Figure 2). Other candidates that are vulnerable to tipping include the North Atlantic Subpolar Gyre, Land Permafrost, and the Greenland and West Antarctic ice sheets. Delayed climate action and stabilising global warming at 2°C would change the probability of five systems tipping from very unlikely (<10% probability) to as likely as not (33-66% probability), and mountain glaciers, boreal forests and the AMOC are the additional tipping systems that risk being tipped. Stabilising global warming at 3°C would likely (>66% probability) cause eight tipping systems to undergo tipping.

A mathematical theory exists that relates overshoot characteristics and system timescale to determine what temperature trajectories can avoid triggering tipping (Ritchie et al., 2019) – as illustrated in Figure 1, systems with a slow response timescale are more likely to avoid tipping. This theory implies that if the time a tipping point is exceeded for is doubled then the peak amount the tipping point is exceeded by needs to be reduced by a factor of four to maintain the same level of tipping risk. Utilising this theory, we here assess the tipping risk for overshoots of the 1.5°C level (see Figure 3b).

Limiting the temperature overshoot beyond 1.5°C to a duration of 100 years could substantially reduce the number of systems that undergo tipping (compare Figure 3b to 3a). For a peak warming of 2°C, the number of systems that are as likely as not (33-66% probability) to tip drops from five to three and tipping five becomes very unlikely (<10% probability) if warming is brought back to 1.5°C (or below) within 100 years. A 100-year overshoot of 1.5°C with a peak warming of 3°C halves the number of systems likely (>66% probability) to be tipped (from eight to four) relative to staying at 3°C. However, to limit such an overshoot scenario with a large peak to 100 years would require extraordinary carbon removal rates that are unlikely to be feasible (Schleussner et al., 2024).

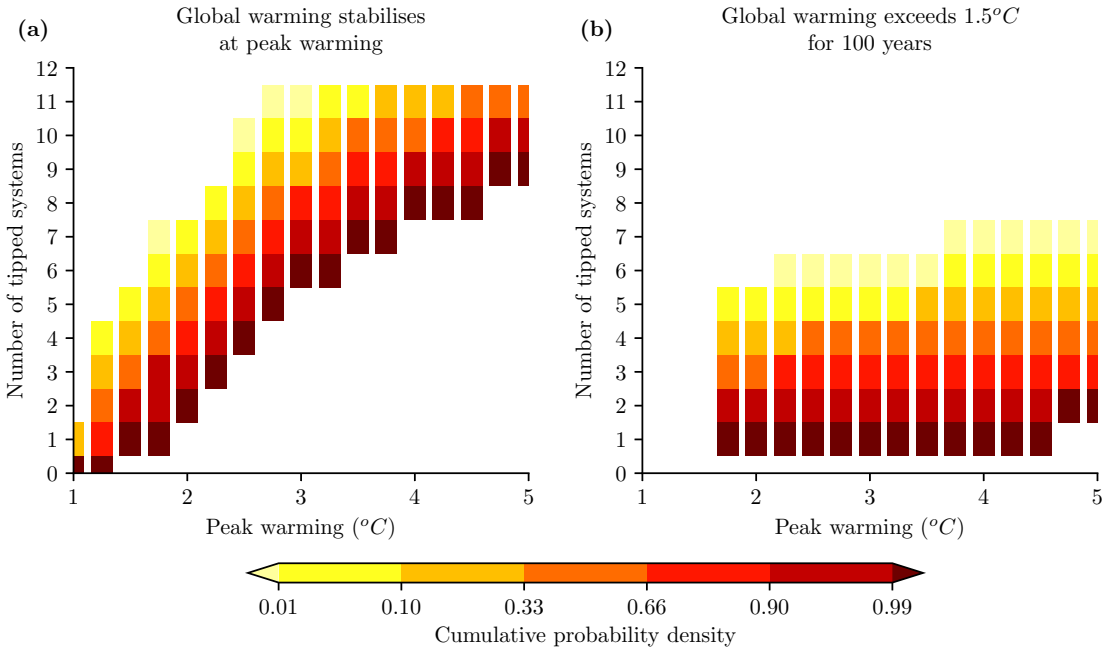


Figure 3. Tipping risk for Earth system tipping systems with and without temperature overshoot. (a) Cumulative number of tipped systems if global warming stabilises at different peak levels but does not return, and (b) cumulative number of tipped systems for different peak warming levels with overshoot beyond 1.5°C lasting for 100 years. Colour is used to represent the cumulative probability density of the number of tipped systems using the IPCC likelihood scale (IPCC-SPM, 2021): <1% Exceptionally Unlikely, <10% very unlikely, <33% unlikely, 33-66% about as likely as not, >66% likely, >90% very likely, >99% virtually certain). The same global and regional tipping systems are considered as in Figure 2. These values are determined by using the upper and lower estimates for the tipping point and tipping timescales given in Lenton et al. (2023), and if not provided, from Armstrong McKay et al. (2022).

Box: Risk assessments for tipping during overshooting temperature targets

When facing potentially severe and irreversible consequences from tipping events, we need a framework for assessing tipping risks under uncertainty. Due to limited predictability of exact tipping events (Ben-Yami et al., 2024), a probabilistic risk assessment approach (Abrams et al., 2023) becomes essential - similar to methods used in insurance and actuarial industries. This approach has recently been embraced in various reports for tipping points research (Saye et al., 2025; Laybourn et al., 2024; Trust et al., 2024) and helps quantify the likelihood of crossing tipping points under different emission scenarios (Möller et al., 2024; Wunderling et al., 2023; Deutloff et al., 2025).

Within this risk framework, we can systematically address two key types of uncertainty:

Tipping element uncertainties: Risk assessments must account for uncertainties in tipping point locations, system timescales, and interactions between tipping elements. Tipping point location uncertainty ranges vary widely across elements - from relatively narrow (1.0-1.5°C for warm-water coral reefs) to very broad (1.4-8.0°C for the AMOC). Further, tipping elements like the Amazon rainforest and ice sheets form a coupled system with interactions that are not fully understood (Dekker et al., 2018; Wunderling et al., 2021, 2024; Falkena & von der Heydt, 2024).

Scenario uncertainties: Global mean temperature (GMT) responses to emission scenarios carry considerable uncertainties due to carbon cycle feedbacks and climate sensitivity variations (IPCC AR6 WGI Chapter 4; Lee et al., 2021). Specific uncertainties in overshoot pathways include timing of peak warming relative to net-zero emissions (Corner et al., 2023), and the duration and magnitude of overshoots (Schleussner et al., 2024). These scenario uncertainties must be assessed probabilistically (Kikstra et al., 2022; Nicholls et al., 2022) and considered alongside tipping element uncertainties.

Figure 4 extends this analysis to consider different overshoot durations for different levels of tipping risk. Using the best estimates from the latest literature (Lenton et al., 2023; Armstrong McKay et al., 2022), tipping systems with fast timescales and a low tipping point (subpolar gyre and warm-water coral reefs) are the most susceptible to tipping even for short overshoot durations. In contrast, systems with slow timescales and a low tipping point (Greenland and West Antarctic ice sheets) may avoid tipping if the overshoot duration is sufficiently short and warming stabilises below their tipping point (Figure 4a). However, these ice sheets have a non-negligible probability that their tipping point is below 1.5°C. Therefore, following a precautionary principle approach (i.e. 10% or even 1% tipping risk) that seeks to limit the devastating long-term consequences of committing to ~10 metres of sea-level rise from tipping these systems, means that limiting the time over 1.5°C is not sufficient (Figure 4b, c). Instead, warming must return to below 1.0°C in the long term (Stokes et al., 2025).

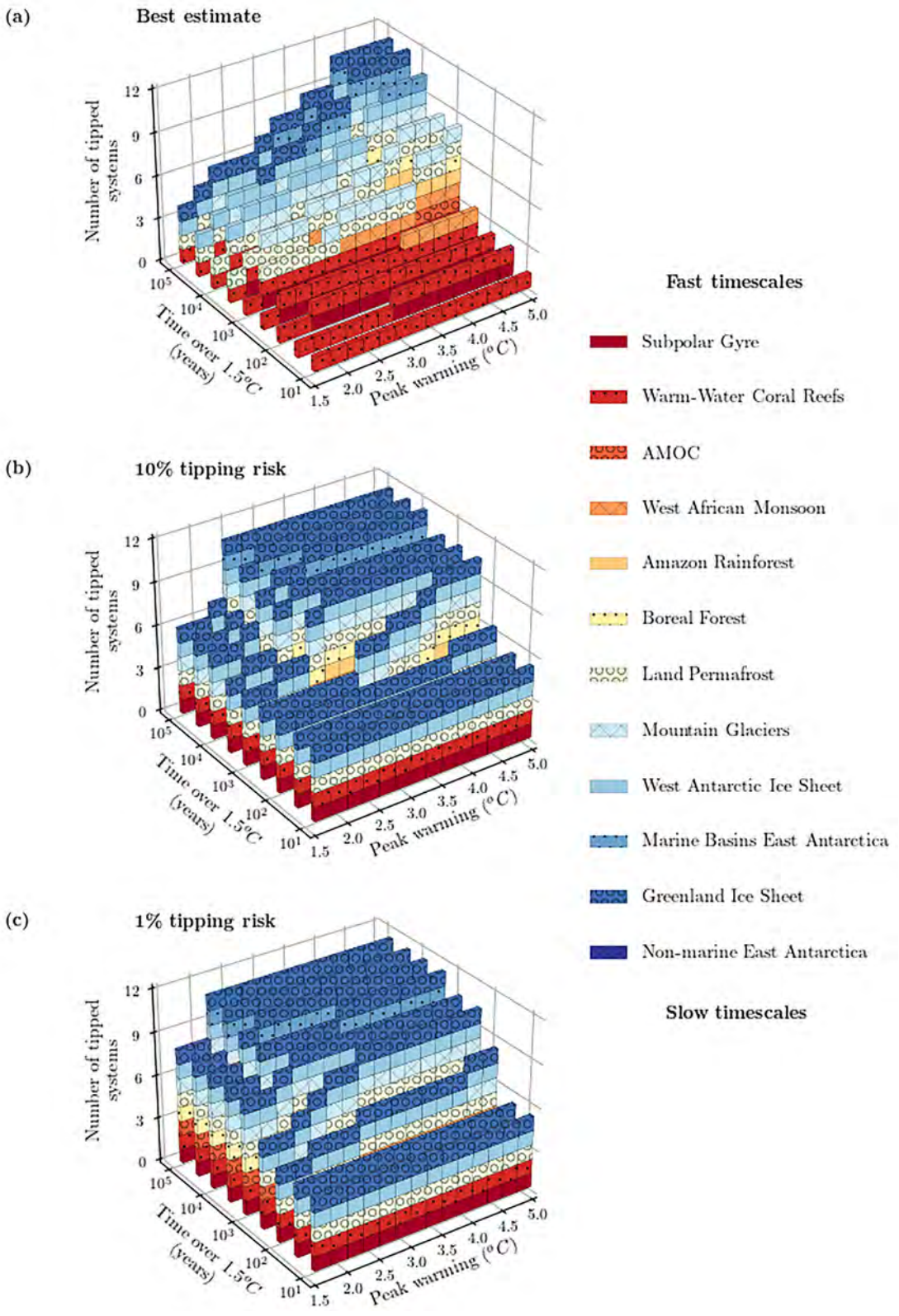


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2.3.3 Additional pressures on tipping systems

In addition to direct global warming impacts, further pressures such as direct anthropogenic interference (e.g. deforestation), tipping system interactions and Earth system feedbacks may threaten the stability of tipping systems, and the feasibility of realising/maintaining warming stabilisation levels (Willcock et al., 2023). This means that tipping points measured in units of global mean warming may effectively be lower than their reported values in the recent literature (e.g., Lenton et al., 2023; Armstrong McKay et al., 2022) where they are mainly studied in isolation, consequently reducing the scope for overshoots that do not cause tipping.

Additional anthropogenic pressures: Biosphere tipping systems suffer from additional anthropogenic influences such as deforestation in the Amazon forest systems, or overfishing and pollution in warm-water coral reefs. Combined with global warming, these additional pressures may cause these tipping systems to have their tipping point to be effectively lower than that for global warming alone (e.g. Hughes et al., 2018; Lovejoy & Nobre, 2018; Setter et al., 2022; Lenton et al., 2023, Pearce-Kelly et al., 2025). For instance the Amazon rainforest may have a tipping point between 2.0-6.0°C (Flores et al., 2024) if impacted by global warming only (see Fig. 2). However, when deforestation is accounted for as well, the tipping point of the Amazon rainforest may reduce to levels well within the Paris climate target (between 1.5-2.0°C), (see 4.1 The Amazon rainforest case study and 4.3 Warm-water coral reefs case study).

Interactions between tipping systems: Most direct interactions between tipping systems are assessed as destabilising (Wunderling et al., 2024; Lenton et al., 2023, see also section 2.2.8). Therefore, interactions between tipping systems exert additional pressure on the stability of tipping systems and become relevant at 1.5°C of global warming or higher (Wunderling et al., 2024). This is sometimes referred to as "tipping cascade risk", where increasing temperatures trigger a first system into tipping that in turn lowers the temperature tipping points for subsequent tipping systems (Wunderling et al., 2021).

Earth system feedbacks: Further, there may be Earth system feedbacks that alter the risk for triggering tipping systems. Relevant feedbacks include (but may not be limited to) the following three categories:

1. A majority of tipping systems would cause feedbacks that increase global warming levels if they tip (Armstrong McKay et al., 2022; Deutloff et al., 2025). For instance, the large ice sheets would add up to 0.2°C of additional global warming if they disintegrate and likewise 0.2°C for a dieback of the Amazon rainforest. However, there are also few but potentially strong negative feedbacks on global temperatures (e.g. 0.5°C cooling due to AMOC tipping). Therefore, the overall effect of temperature feedbacks of disintegrated tipping systems on tipping risks remains uncertain and requires improved constraints of their feedback mechanisms, direction and magnitude (Bdolach et al., 2025).
2. Second, changes in the land and ocean carbon sinks under ongoing global warming may affect global warming pathways themselves. So far, around 60% of all emissions have been taken up by land and ocean carbon sinks and only the remaining 40% contribute to atmospheric CO2-increase and global warming (Friedlingstein et al., 2025). There is now growing evidence of a long-term weakening of land carbon sinks that are also tipping systemss (e.g. in the Amazon rainforest or permafrost; Gatti et al., 2021; Ke et al., 2024). On the other hand, while also weakening on the long term, ocean carbon sinks seem to be comparatively stable across Earth System Models (Tokarska et al., 2019; Schwinger et al., 2022; Koven et al., 2023; Sanderson et al., 2024).
3. Third, there exist several feedback loops within the Earth system that could amplify global warming (Ripple et al., 2023, Lenton et al., 2023), such as cloud feedbacks (Bjordal et al., 2020; Ceppi & Nowack, 2021) or the permafrost carbon feedback (MacDougall et al., 2020; Steinert & Sanderson, 2025). They could make it harder to reduce global temperatures after an overshoot, for instance should carbon sinks get weaker.

2.3.4 Conclusion

The Global Carbon Budget (Friedlingstein et al., 2025) reports that current rates of global carbon emissions remain high and are still increasing, and therefore, at least, a temporary overshoot of 1.5°C is becoming almost inevitable (Reisinger et al., 2025; Bevacqua et al., 2025). In addition to already having potentially exceeded some tipping points, this places many further tipping systems of the climate system at risk of crossing their tipping point. This calls for a comprehensive risk assessment approach to quantify tipping likelihoods for overshoot pathways (see Box).

Additionally, achieving the required rapid reversal in warming that would prevent many tipping systems from tipping implies substantial net negative emissions. The longer CO2 emission reductions are delayed, the larger net negative emissions must be. Additionally, the larger the overshoot over a certain temperature level, the larger the need for negative emissions and the implications of those for our planet's critical biophysical systems. Current pathways that overshoot 1.5°C and return to this level by 2100 with 50% probability require up to five times the current rates of carbon dioxide removal (Smith et al., 2024). Additional feedbacks have the capacity to impede the reversal of warming, such as the potential of permafrost thawing and Amazon rainforest dieback amplifying global warming (e.g., Deutloff et al., 2025) or the weakening of land carbon sinks under climate change.

This means that five (the warm-water coral reefs, the land permafrost, the Greenland and the West Antarctic Ice Sheets and the North Atlantic subpolar gyre) systems of the Earth system may reach their tipping points below 1.5°C of global warming, and up to eight (in addition: the mountain glaciers, the boreal forests and the AMOC) below 2.0°C of global warming. The warm-water coral reefs tipping point with a central estimate of 1.2°C is likely already transgressed by current global warming levels (best estimates are between 1.34 and 1.41°C (WMO, 2025). The risk of tipping for individual tipping systems is found to increase for larger and longer overshoots over a specific temperature level such as 1.5°C. Fast tipping systems (e.g. the subpolar gyre) may be more at risk of tipping when their tipping points are crossed temporarily and therefore act as a constraint on the limits for acceptable peak global warming. The slow tipping systems respond on timescales slower than climate change and therefore set limits on overshoot duration (Ritchie et al., 2019; Ritchie et al., 2021).

However, it is critical to remark that some tipping points such as those for warm-water coral reefs and the ice sheets may have already been crossed (Stokes et al., 2025; Pearce-Kelly et al., 2025). Therefore, even a return to 1.5°C may still not be sufficient to prevent the ice sheets from tipping in the long term (Stokes et al., 2025). Instead, warming will need to be further reduced, to levels at or below 1.0°C. Therefore, urgent climate action to minimise tipping risks is required, also in light of additional anthropogenic pressures, interactions between tipping systems, Earth system feedbacks as well as uncertainties in tipping point locations and system timescales. This means that peak temperature, overshoot duration, and warming stabilisation level must be limited to sufficiently low levels to prevent Earth system components from tipping in the short and long term.

Chapter 2.4 Earth system tipping point risk assessment

Authors: Jesse F. Abrams, Andrew Hartley, Laurie Laybourn, Timothy M. Lenton, Constantin W. Arnscheidt, Dag Olav Hessen, Silvia Montagnani, Hatty Wylder-Hopkinson

Reviewers: David Armstrong McKay, Norman J. Steinert, Jonathan Rosser, Jonathan F. Donges, Luke Kemp

Key messages

Earth system tipping points have huge impacts that demand further research

- There is an urgent need for dedicated research on the impacts of crossing Earth system tipping points especially their systemic, cascading impacts through societies.
- We provide an initial analysis of these impacts relying heavily on inferences from general climate impact literature applied to anticipated tipping point changes.
- Our assessment suggests that crossing Earth system tipping points will cause profound risks across nine critical domains, including food security, energy infrastructure, economic stability and social cohesion, affecting billions globally.
- Earth system tipping points are a national security issue as food, water and heat stresses will impact populations. If climate change is unchecked then mass mortality, forced displacement and severe economic losses become likely.

All regions and billions of people face major impacts from Earth system tipping points

- Critical tipping point risks exist for small islands and East Asia from ice sheet loss, for South Asia, Southeast Asia and Central America from monsoon disruption, for West Africa from AMOC collapse and monsoon disruption and for North Asia from permafrost thaw and boreal forest tipping.
- Major tipping point risks exist for Northeast America from AMOC collapse and ice sheet loss, for Northwest Europe from AMOC collapse and suggests impacts of Amazon dieback are purely regional.
- The greatest population is ultimately at risk from monsoon disruption, followed by ice sheet loss, AMOC collapse and the loss of warm-water coral reefs.

Regional vulnerabilities to Earth system tipping points reveal extreme inequality

- Small Island Developing States face complete uninhabitability, South and Southeast Asia's 3+ billion people depend on vulnerable monsoon systems and Arctic communities face total ecosystem transformation.
- Developed regions primarily face infrastructure and economic challenges.
- The most extreme gaps in regional preparedness for tipping point risks are in Small Island Developing States, West Africa, Central America and the Amazon basin.

2.4.1. Introduction

This chapter provides an assessment of the systemic risks Earth system tipping points pose to human societies and ecosystems across all global regions, introducing a framework for risk evaluation that addresses the fundamental inadequacies of traditional approaches.

The impacts of Earth system tipping points manifest through biophysical changes in Earth system components that can translate into profound risks for human systems. Despite the gravity of these risks, significant research gaps persist in both the understanding of biophysical impacts and the translation of these impacts into systemic risks for human societies. These gaps include the scarcity of direct tipping point impact studies, weak understanding of cross-sectoral cascade mechanisms and inadequate translation of biophysical changes into policy-relevant risk assessments. Furthermore, the risks of Earth system tipping points are not addressed by existing global governance institutions, necessitating new frameworks that can address the systemic nature of these risks across multiple policy domains (JRC, 2025a; Pereira et al., 2024; Milkoreit et al., 2024; Pereira et al., 2023).

There remains limited understanding of the complex pathways through which biophysical changes translate into systemic risks at different spatial and temporal scales (Simpson et al., 2021; Lawrence et al., 2020; Ruiter et al., 2020). These cascading failures can rapidly escalate from single system disruptions to compound catastrophic scenarios where multiple Earth system components collapse simultaneously, overwhelming adaptive capacity and creating irreversible damage that exceeds the sum of individual impacts. Moreover, there is a notable scarcity of empirical data and comprehensive research on the specific impacts and pathways of Earth system tipping points, further complicating risk assessment and policy responses. However, significant advances are expected through ongoing international initiatives (such as TIPMIP (Winkelmann et al., 2025)) aimed at improving our understanding of tipping points by increasing Earth System Model representation of tipping points and making the output data freely available for further analysis.

Here, we conduct a first Earth system tipping point risk assessment, drawing on available data and approaches. While this is necessarily imperfect given the current state of knowledge, it represents a critical first step toward filling the substantial gap in tipping point risk evaluation. This approach aligns with emerging frameworks for assessing high impact-low likelihood climate risks (Wood et al., 2023), recognizing the need for new methodologies when traditional approaches prove inadequate for extreme scenarios. We synthesize available evidence to translate biophysical Earth system changes into policy-relevant risk currencies, providing a foundation for future research and decision-making while clearly identifying areas where knowledge remains limited.

Given the relative scarcity of research specifically examining the systemic risks from Earth system tipping points, this analysis draws upon two complementary approaches: (1) the limited but growing body of direct research on tipping point impacts and (2) inferences derived from the established literature on climate change impacts applied to the anticipated biophysical changes from tipping events. This approach allows us to synthesize potential consequences based on what we know about how human and natural systems respond to environmental changes of the magnitude and type expected from tipping points.

2.4.2. Assessment approach

Here we make an initial attempt to characterise and communicate the societal and ecosystem risks associated with Earth system tipping points. We synthesise scientific literature to identify the most impactful tipping points for human society and dependent ecosystems. While we aim to be as comprehensive as possible, we recognise that there is ample scope for continued improvement and co-development with scientific and user communities. Our assessment methodology builds directly on the risk framework established in Chapter 2.1, which emphasized the inadequacy of traditional impact-probability matrices for tipping point risks. Following Chapter 2.1's approach, we categorize risks using severity levels (low / moderate / major / critical) and the temperature threshold assessments from Chapter 2.2.

2.4.2.1. Risk currencies

Before examining specific systemic risks from tipping points, it is essential to frame these risks in terms of what we call "risk currencies" (Roberts et al., 2021) - the fundamental concerns that drive policy decision-making across all levels of governance. As established in Chapter 2.1, risk currencies represent the translation of Earth system impacts into risks that are intuitive for and connected to the fundamental governance concerns. In other words, risk currencies represent the core values and priorities that policymakers are mandated to protect and that societies depend upon for stability and prosperity.

Our analysis is organized around the following nine key risk currencies (Pereira et al., 2025) :

- Food security
- Energy security
- Humanitarian crisis and displacement
- National security
- Financial and economic risks
- Infrastructure and built environment
- Public health
- Biodiversity and ecosystems
- Water resources

2.4.2.2. Risk register

We use the risk currencies to construct a "risk register" that aims to summarize the potential societal impact of Earth system tipping points in a succinct, policy relevant manner. The risk register concept is introduced in Chapter 2.1.

Standard government risk registers typically use impact-probability matrices plotting potential consequences against likelihood calculations, an approach that has become deeply embedded in institutional risk management practices worldwide. However, this conventional framework is fundamentally inappropriate for tipping points for several interconnected reasons that go beyond simple uncertainty quantification (Laybourn et al., 2024). These include: the simplistic collapsing of complex interactions between hazard, vulnerability and exposure into a single "risk"; the inability to account for interactions between risks (e.g. one risk affecting the likelihood of another, or two risks occurring simultaneously and compounding); and a bias towards well-defined risk events, which might neglect slower-moving stresses.

The high uncertainty surrounding these risks makes their likelihood difficult to assess with the confidence necessary for major management decisions. This uncertainty stems not just from incomplete data, but from the fundamental nature of complex systems operating near critical thresholds (Bathiany et al., 2016, 2018). Traditional probabilistic approaches require well-characterized historical patterns and stable system behavior, neither of which applies to tipping points operating in unprecedented conditions under anthropogenic climate change (Armstrong McKay et al., 2022; Lenton et al., 2008, 2019).

This could create a systematic misinterpretation of risk where high uncertainty is routinely misconstrued as low likelihood, leading to dangerous complacency in risk management, which is particularly problematic when considering the potentially high societal impact of tipping points. The COVID-19 pandemic provides a stark illustration of this problem, where high uncertainties associated with pandemic risk led some governments to treat these scenarios as low-probability events, resulting in inadequate preparedness despite clear scientific warnings about the inevitability of pandemic emergence (Laybourn et al., 2024; UK Government, 2024). As noted by the UK COVID-19 Inquiry, both the Royal Academy of Engineers and the inquiry itself concluded that "a fixation on likelihood is inappropriate for such threats as it 'can be difficult to assess with a high degree of confidence across all risks'" and that "uncertainty and the inability to accurately judge likelihood can breed a dangerous complacency."

Additionally, traditional risk assessment frameworks fail to capture the nonlinear dynamics inherent in threshold effects and the potential for abrupt changes (Scheffer et al., 2009). These frameworks assume proportional relationships between causes and effects, whereas tipping points are characterized by disproportionate responses where small changes can trigger massive system reorganization (Lenton et al., 2008). Furthermore, unlike economic or political sudden shifts that societies can potentially recover from, climate-driven tipping dynamics, once triggered, are often irreversible over timescales relevant to human civilizations. Post-collapse recovery in these cases cannot be expected within centuries to millennia, fundamentally distinguishing these risks from other systemic threats and emphasizing their severity for long-term planning and risk management. The conventional approach also struggles with the temporal complexity of tipping points, where risks may appear low in the near term but escalate rapidly once thresholds are crossed and with the systemic nature of cascading risks that can create "domino effects" across multiple Earth system components (Klose et al., 2021; Wunderling et al., 2021).

Given these fundamental limitations, several alternative approaches could provide more appropriate frameworks for tipping point risk assessment, drawing inspiration from advances in disaster risk reduction and complex systems analysis:

- **Impact vs. Proximity to Thresholds:** This approach would plot potential impacts against how close systems are to identified tipping thresholds, using observable indicators and early warning signals (Lenton et al., 2024) rather than probabilistic forecasts. This leverages current scientific understanding of threshold dynamics while avoiding the false precision of probability estimates. Recent advances in early warning systems for tipping points, including statistical indicators of critical slowing down and machine learning approaches, provide increasingly sophisticated tools for threshold proximity assessment (Dylewsky et al., 2023; Bury et al., 2021; Bathiany et al., 2016).
- **Impact vs. Adaptive Capacity:** This framework would assess potential consequences against the capacity of affected systems (social, economic, ecological) to adapt and respond to changes (Folke et al., 2010). This shifts focus from predicting when changes will occur to evaluating societal resilience and transformation capacity, drawing on extensive literature from resilience science and adaptive management.
- **Impact vs. Exposure/Vulnerability:** This approach would map potential impacts against the exposure and vulnerability of different populations, sectors and regions, similar to frameworks used in disaster risk reduction under the Sendai Framework for Disaster Risk Reduction 2015-2030 (UNDR, 2015). This emphasizes the distributional aspects of tipping point risks and can inform targeted intervention strategies, following established methodologies from the disaster risk reduction community.

Here we lead with the temperature threshold approach (impact vs. proximity to thresholds) as introduced in Chapter 2.1 in our primary risk register, as it provides the most scientifically grounded foundation given current knowledge of tipping points. This avoids traditional likelihood-probability, and relies on the best available scientific estimates of temperature thresholds at which each tipping point is triggered. This approach focuses on proximity to known physical thresholds rather than statistical likelihood calculations, providing policy-relevant information about which tipping points may be triggered under different warming scenarios. However, we explore the adaptive capacity and vulnerability dimensions through detailed regional and sectoral analyses, which examine how the same physical changes translate into differential risks across regions and policy domains depending on exposure, vulnerability, and adaptive capacity.

2.4.2.3. Overall approach

To populate the risk register and provide a comprehensive risk assessment, we map Earth system tipping point hazards to biophysical impacts and direct regional impacts (and associated risks) and we map them through systemic interactions and risk currencies to assess systemic and cascading risks.

First we systematically analyze how passing each tipping point translates into measurable physical changes across temperature, sea level, precipitation, atmospheric circulation, ocean circulation, biogeochemical cycles, modes of variability and extreme events. A summary is provided in Table 1. This provides the scientific foundation for understanding the direct impacts of different tipping points on specific regions and for understanding how biophysical changes propagate through Earth system components to create cascading impacts.

From this we undertake a regional impact assessment using the IPCC SREX reference regions (see 2.4.2.5 below). This shows how different tipping points create uneven geographical vulnerabilities, ranging from limited effects to critical system-threatening consequences. We also undertake a systemic risk assessment mapping how these physical changes translate into risks across nine "risk currencies" (critical policy domains) identified above. The mapping between physical impact variables and risk currencies is summarised in Table 2. This translation bridges the gap between Earth system science and policy-relevant risk currencies that drive decision-making at all governance levels.

Before getting to the results we detail two important aspects.

2.4.2.4. Use of present-day exposure and vulnerabilities

In this assessment, we aim to describe the societal and ecosystem consequences in the context of present-day exposure and vulnerability indices. While ideally we would consider the social and economic context of the world at the time each tipping point occurs, this approach is not feasible for several interconnected reasons. In the context of centennial-scale climate projections, this has been achieved through the use of integrated assessment models (IAMs) that describe socio-economic development pathways (van Beek et al., 2020; Riahi et al., 2017) that are appropriate to varying levels of greenhouse gas emissions. This framework has proved useful for relating climate outcomes, derived from earth system models (ESMs), to the socio-economic decisions the world would have taken if that climate outcome were to occur. However, these assumptions break down in the context of tipping points, because most tipping point experiments with ESMs are not driven by emissions from IAMs and therefore have no socio-economic context. Additionally, most tipping point modelling is not appropriate for ascertaining a real-world time-frame for the onset, transition and new state of a tipping point mechanism.

Therefore, our approach focuses on present-day vulnerabilities while acknowledging that actual impacts will depend on future adaptive capacity, technological development and societal resilience that cannot be reliably projected decades in advance. It is important to note that both the triggering of tipping points and the manifestation of their impacts operate across widely varying timescales.

Tipping point triggering typically occurs within decades of crossing temperature thresholds, but impact onset varies dramatically - from rapid changes like coral bleaching (months to years) and regional climate shifts from SPG collapse (a decade), to slower processes like ice sheet contributions to sea level rise (centuries to millennia) and complete ecosystem transitions (decades to centuries). This temporal complexity means our assessment captures potential end-state impacts rather than the dynamic evolution of risks over time.

2.4.2.5. Regional impact assessment

Here we examine how tipping points create impacts across 26 IPCC SREX regions (Field et al., 2012) (Figure 1) with the addition of Small Island States (SIS). This draws from a systematic assessment of major Earth system tipping points (AMOC collapse, Greenland and West Antarctic ice sheet loss, permafrost thaw, monsoon disruption, coral reef die-off, Amazon dieback and boreal forest shifts) across nine risk currencies (food security, energy security, water resources, infrastructure, public health, biodiversity, humanitarian crises, financial systems and national security). We use the SREX regional classification system rather than the more recent AR5 or AR6 regional frameworks due to its coarser spatial resolution, which better matches the limited granularity of available information on tipping point impacts. The broader regional categories in SREX 2012 provide a more appropriate scale for synthesizing the sparse literature on tipping point consequences, while the finer-resolution regions in later IPCC reports would require impact data that does not yet exist for most tipping point-region combinations.

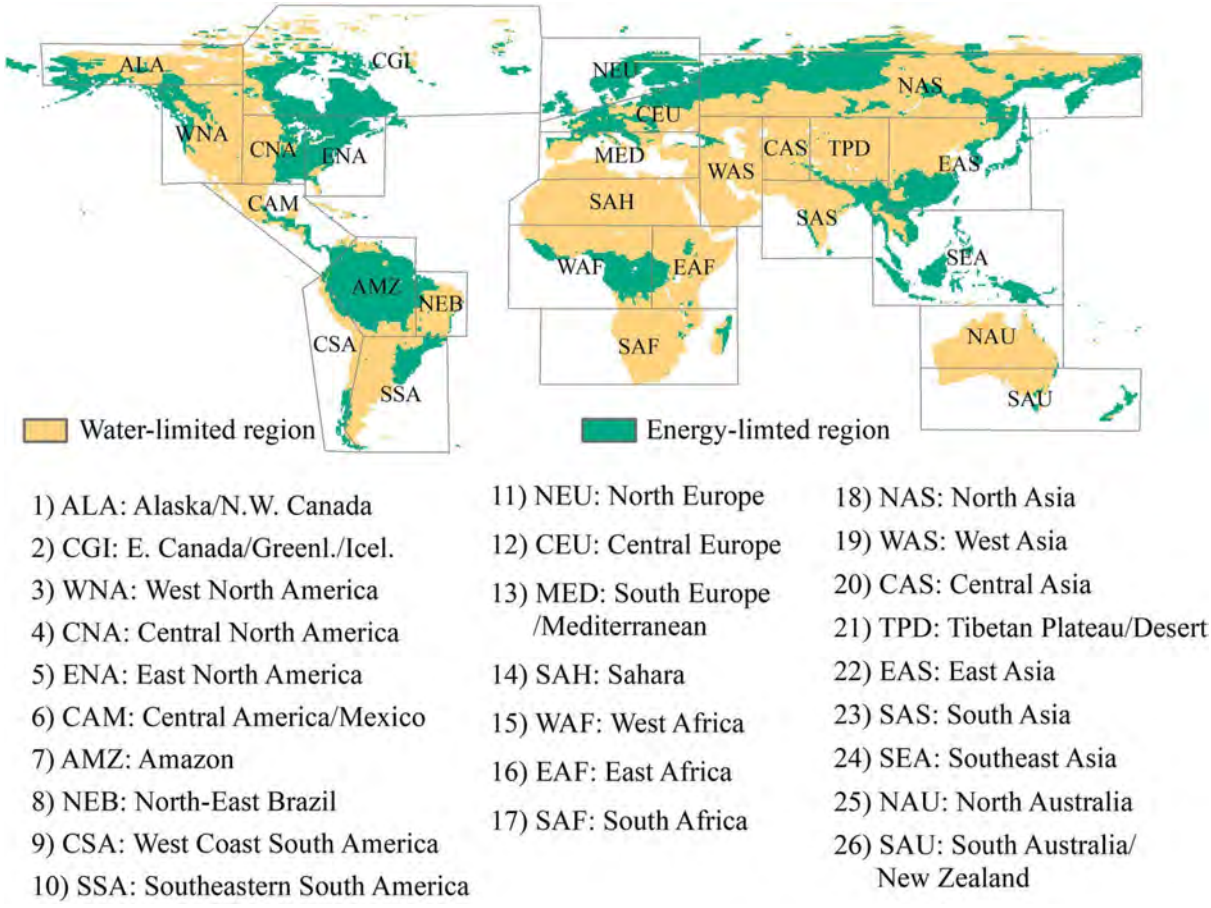


Figure 1. *The regional classification used in this chapter. We adopt the IPCC SREX reference regions with the addition of Small Island States (SIS) (Image source: (Yin et al., 2022)).*

Table 1. *Physical impacts of Earth system tipping points. Summary of how each tipping point translates into measurable physical changes across temperature, sea level, precipitation, atmospheric circulation, ocean circulation, biogeochemical cycles, modes of variability and extreme events.*

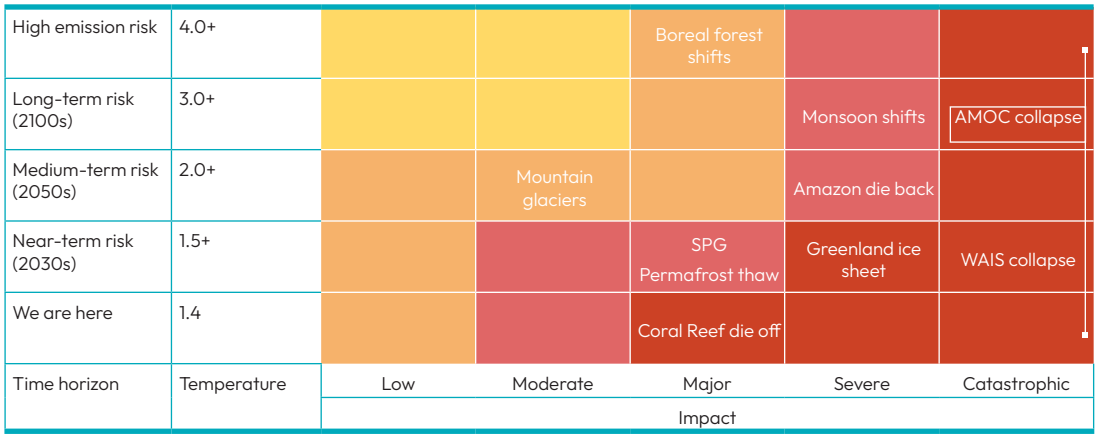
Tipping event	Temperature	Sea level	Precipitation	Atmospheric circulation	Ocean circulation	Biogeochemical cycles	Modes of variability	Extreme events
AMOC collapse	↓↓ N. Atlantic (3-8°C cooling), ↓ N. Europe, ↑ S. Hemisphere	Regional ↑ 0.2-0.3m N. Atlantic coast	↓↓ Sahel, W. Africa monsoon, ↓ Europe growing season, ↑ Amazon	Southward ITCZ shift, altered storm tracks	Fundamental reorganization, ↓ heat transport	↑ CO_2 from reduced ocean uptake, biome changes	NAO changes, ↑ ENSO variability	↓ Hurricane activity, altered European storms
SPG deep convection collapse	Regional cooling N. Atlantic surface waters, ↓ temps NW Europe/E. Canada	Minimal direct effect	↓ Britain/Ireland precipitation, altered NW European patterns	Altered jet stream positioning, modified NAO patterns, shifted storm track pathways	Collapse of deep convection Labrador/ Irminger Seas, halted winter mixing	↓ Marine productivity, altered nutrient cycles	Strong NAO variability changes, altered storm tracks eastward	↑ Winter storm intensity, altered North Atlantic weather
Greenland Ice Sheet loss	Local ↑, minimal global effect	↑ ≤7.42m global, uneven distribution	Local shift to rainfall, reduced deflection	Less jet stream deflection	↓ THC, freshwater discharge	Permafrost flooding, ↑ CO_2, CH_4	Altered NAO patterns	Storm surges, icebergs
West Antarctic Ice Sheet collapse	Local ↑, minimal global effect	↑ ≤5.08m abrupt, uneven	Local precipitation shifts	Altered polar circulation	↑ or ↓ THC, new archipelago	Permafrost flooding, ↑ CO_2, CH_4	Unknown changes	Storm surges, icebergs
Permafrost thaw	Regional ↑↑ (up to 12°C amplification)	Minimal direct effect	Altered regional hydrology	Regional circulation changes	Freshwater discharge changes	Major ↑ CO_2, CH_4 release (1,460-1,700 GtC stored)	Regional climate mode changes	Thermokarst formation, ground instability
Monsoon disruption	Regional ↑ summer temperatures	Regional coastal effects	↓↓ Seasonal precipitation (40 per cent reductions observed)	Walker circulation changes, ITCZ shifts	Indian/Pacific Ocean coupling changes	↓ Land carbon storage	ENSO coupling changes	↑ Droughts, heat waves
Coral reef die-off	Regional marine ↑	Loss of coastal protection effect	Minimal direct effect	Minimal direct effect	Local ecosystem changes	↓ Marine carbon cycling	Minimal effect	↑ Coastal storm damage
Amazon dieback	↑ Regional warming, ↓ evapotranspiration	Minimal direct effect	↓↓ Regional (25-35 per cent recycling loss), altered global patterns	Walker circulation changes	Minimal direct effect	Major ↑ CO_2 (150-200 GtC release)	ENSO feedback potential	↑↑ Fire frequency, ↑ droughts
Boreal forest shifts	↓ Winter, ↑ summer regional	Minimal direct effect	↓ Regional precipitation	Regional circulation effects	Minimal direct effect	Major ↑ CO_2 from forest loss	Regional mode changes	↑↑ Wildfire, insect outbreaks
Mountain glaciers	Local ↑, regional cooling effects from altered albedo	Minor direct contribution compared to ice sheets	Altered regional hydrology, reduced seasonal buffering	Minimal direct effect	Altered fjord/ coastal circulation patterns	Changed organic matter turnover, freshwater discharge	Regional hydrological variability changes	Glacial outburst floods, coastal erosion

Table 2. Mapping between tipping point impacts and risk currency variables.

Risk Currency	Physical Impact Pathways	Specific Variables Affected
Food security	Temperature changes, precipitation shifts, sea level rise, ecosystem collapse	Crop yields, fisheries productivity, agricultural land loss, food prices, nutrition security
Energy security	Infrastructure damage, resource availability, demand changes	Power generation capacity, transmission networks, heating/cooling demand, renewable potential, fossil fuel infrastructure
Water resources	Precipitation patterns, hydrological cycles, saltwater intrusion	Freshwater availability, water quality, aquifer contamination, reservoir levels, seasonal flows
Infrastructure & built environment	Sea level rise, permafrost thaw, extreme weather, ecosystem changes	Building foundations, transport networks, coastal defenses, urban planning, asset values
Public health	Temperature extremes, air quality, food/water security, displacement	Mortality, morbidity, mental health, healthcare capacity, disease vectors, heat stress
Biodiversity & ecosystems	Habitat loss, species migration, ecosystem state changes	Species extinction, ecosystem services, carbon storage, pollination, natural capital
Financial & economic risks	Asset damages, productivity losses, market disruption	GDP impacts, insurance costs, stranded assets, credit risks, investment uncertainty
Humanitarian crisis & displacement	Habitability loss, livelihood collapse, resource scarcity	Population displacement, migration flows, refugee crises, community breakdown
National security	Resource conflicts, border pressures, economic instability	Military deployment, border security, international tensions, failed states

2.4.3. Summary risk assessment

First we provide the overall Earth system tipping points risk register (Figure 2), then we unpack it. Here we summarise striking findings regarding the most impactful tipping points, critical timescales, direct regional impacts (Table 3) and systemic risks (Table 4). Then we provide more details structured by risk currency (2.4.4.) and by world region (2.4.5.).



Darker colour shading represents a greater degree of threat posed, which is a function of the temperature threshold and thus proximity of the trigger to the present day and of the impact.

Temperature thresholds are uncertain, which means it cannot be ruled out that tipping points are triggered sooner. This uncertainty is included only for AMOC as an illustrative example.

Figure 2. *Earth system tipping points risk register. Temperature-threshold-based risk assessment showing when different tipping points may be triggered under various warming scenarios, with impacts categorized by severity. Temperature thresholds are based on best available scientific estimates from Chapter 2.2 and the literature (including Armstrong McKay et al. 2022), incorporating potential interactions between tipping points and updated model assessments. Some thresholds may differ from individual previous assessments due to consideration of tipping point interactions, updated scientific evidence, refined estimates of system stability and potential model biases toward overstability—as a risk assessment, we err toward lower thresholds to avoid underestimating risks. The color-coding reflects both impact severity and proximity to current warming levels: tipping points with severe impacts at lower temperature thresholds deserve more immediate attention than similar-impact events occurring only at higher warming. For example, a moderate impact event like mountain glacier loss at 2°C warming (orange) is more urgent than a moderate impact event at 3°C warming (yellow), while severe events like Greenland Ice Sheet collapse at 1.5°C (light red) are higher priority than severe events like monsoon shifts at 3°C (orange).*

The assessment reveals several critical insights for global risk management:

Highest impact tipping points

- Monsoon disruption would affect the largest number of people globally, with over 5 billion people dependent on monsoon systems across South Asia, Southeast Asia, East Asia and West Africa. Monsoon weakening is very likely to cause severe food and water security impacts, with potential 40 per cent reductions in seasonal precipitation observed in some regions, critically threatening agricultural systems that support billions. Monsoon disruption would likely have major impacts on regional energy systems dependent on hydroelectric power, with massive cooling demand increases during altered seasonal patterns.
- Ice sheet loss threatens over 2 billion people in coastal areas globally, with potential for multi-meter sea level rise over centuries creating permanent displacement pressures. The combination of Greenland and West Antarctic Ice Sheet collapse could contribute up to 12+ meters of sea level rise, with severe impacts on coastal infrastructure and agriculture, particularly threatening small island developing states with complete uninhabitability. Ice sheet collapse would likely accelerate AMOC weakening through freshwater discharge, potentially triggering monsoon disruptions, while regional sea level variations could exceed global averages by 30-50 per cent in some coastal regions.
- AMOC collapse is very likely to have severe impacts on food and water security in North and Central Europe, as well as West Africa and is likely to have moderate impacts on energy security across the Northern hemisphere. AMOC collapse will likely impact monsoons globally. It will also likely lead to significant sea level rise for north Atlantic coastal regions. These impacts are likely to lead in turn to moderate to high economic insecurity. AMOC collapse would also affect several other Earth system tipping points, including very likely accelerating West Antarctic Ice Sheet collapse to moderate extent, potentially affecting Amazon dieback and could stabilise Greenland Ice Sheet collapse to a low extent. AMOC collapse would likely trigger monsoon weakening globally through southward shifts of the Intertropical Convergence Zone.
- Coral reef die-off would affect over 500 million people dependent on reef systems for food security, coastal protection and economic livelihoods. The ongoing Fourth Global Coral Bleaching Event has affected 83.8 per cent of the world's coral reef area, demonstrating that reefs have crossed critical thresholds. Coral reef loss is very likely to eliminate critical protein sources for 150+ million people while removing natural coastal protection that reduces wave energy by up to 97 per cent. It is likely to lead to economic losses, particularly in the Coral Triangle region where economic losses could exceed $75 billion from tourism and fisheries collapse alone. Coral reef die-off would likely accelerate under multiple tipping point interactions, with ocean acidification from permafrost carbon release and altered ocean circulation from AMOC collapse creating compounding stresses that prevent recovery even if global temperatures stabilize.

Critical timeframes

- Immediate risks (2025-2035) include coral reef die-off and SPG collapse under current warming trajectories, which are already showing signs of approaching critical thresholds.
- Medium-term risks (2035-2050) include Amazon dieback, monsoon instability and ice sheet loss acceleration, with multiple tipping points potentially triggered within the Paris Agreement range of 1.5-2°C global warming.
- Long-term risks (2050-2080) involve the possibility of multiple system failures and cascading effects, with the highest cascade risks identified as:
  - AMOC collapse → Monsoon weakening → Global precipitation shifts
  - Ice sheet loss → AMOC weakening → Sea level acceleration
  - Permafrost thaw → Boreal shifts → Arctic amplification

Most vulnerable regions and populations

Table 3 summarizes the combined direct impacts of different tipping points on each world region. This reveals striking patterns of geographical inequality, with some regions facing existential threats while others experience primarily economic and infrastructure challenges. Small Island Developing States, South Asia, Southeast Asia, West Africa and Arctic regions face critical system-threatening level impacts, while many developed regions in temperate zones face major impacts requiring significant adaptation but not ones that threaten societal collapse.

- Small Island Developing States face existential threats from sea level rise affecting 1+ million people, representing the first potential climate refugees at a national scale. Many coral atolls and low-lying islands could face complete inundation with even 1-2 meter sea level rise, while economic costs could reach 100 per cent+ of GDP rendering entire nations uninhabitable.
- South Asia emerges as the region with the highest absolute population exposure, with 2+ billion people critically dependent on monsoon systems vulnerable to disruption. The Ganges-Brahmaputra Delta alone, supporting 90 per cent of Bangladesh's rice production, faces severe threats from sea level rise that could displace 15 million people from even modest sea level rise scenarios.
- Southeast Asia faces critical vulnerabilities affecting 600+ million people, particularly through Coral reef die-off in the Coral Triangle region containing the highest marine biodiversity globally. The Mekong Delta, producing 50 per cent of Vietnam's rice, faces severe threats from sea level rise, while major coastal megacities including Bangkok, Ho Chi Minh City and Jakarta could be severely threatened.
- Arctic and Northern communities face massive ecosystem transformation affecting indigenous populations whose traditional ways of life depend on stable permafrost, sea ice and boreal forest systems. With 70 per cent of current infrastructure in permafrost regions potentially facing high thaw potential by 2050, entire communities may require relocation.
- West Africa has 400+ million people dependent on monsoon systems strongly connected to AMOC stability, in a region that has already experienced seven political coups in three years, suggesting potential climate-political stability linkages.

Sectoral impact assessment

- Food Security faces the most widespread impacts, with tipping points threatening agricultural systems supporting billions through altered precipitation patterns, temperature changes and extreme weather intensification. The scale ranges from localized impacts affecting millions to global food system disruption.
- Energy Security faces major challenges from changing precipitation patterns affecting hydroelectric power, sea level rise threatening coastal energy infrastructure and altered weather patterns affecting renewable energy potential.
- National Security implications include resource conflicts, climate migration pressures and economic disruption, with particular risks in already politically unstable regions like the Sahel.
- Financial and Economic Systems face challenges from the nonlinear and irreversible nature of tipping events that would challenge traditional risk assessment models and insurance frameworks, with potential for systemic financial instability.

Next we provide more details, unpacking the results in terms of risk currencies (2.4.4.) and then detailing impacts by world region (2.4.5.).

Table 3. *Tipping element direct impact matrix by IPCC SREX region. Direct impacts of each tipping point are mapped across all global regions using the IPCC SREX reference regions showing how different tipping points create uneven geographical vulnerabilities.*

Region	AMOC collapse	Ice sheet loss	SPG collapse	Permafrost	Boreal forest	Monsoons	Coral reefs	Amazon	Mountain glaciers
Small Islands (SIS)	MAJOR	CRITICAL	LOW	LOW	LOW	CRITICAL	CRITICAL	LOW	LOW
South Asia (SAS)	CRITICAL	CRITICAL	LOW	MAJOR	LOW	CRITICAL	CRITICAL	MODERATE	MAJOR
Southeast Asia (SEA)	MAJOR	CRITICAL	LOW	LOW	LOW	CRITICAL	CRITICAL	MODERATE	LOW
East Asia (EAS)	MAJOR	CRITICAL	LOW	MAJOR	MAJOR	CRITICAL	CRITICAL	MODERATE	LOW
North Asia (NAS)	MAJOR	MAJOR	LOW	CRITICAL	CRITICAL	LOW	LOW	LOW	LOW
West Africa (WAF)	CRITICAL	CRITICAL	MODERATE	LOW	LOW	CRITICAL	MAJOR	LOW	LOW
Eastern N. America (ENA)	CRITICAL	CRITICAL	MODERATE	LOW	MAJOR	LOW	MAJOR	LOW	LOW
Central America (CAM)	CRITICAL	CRITICAL	LOW	LOW	LOW	CRITICAL	CRITICAL	MODERATE	LOW
Northern Europe (NEU)	CRITICAL	MAJOR	CRITICAL	MAJOR	CRITICAL	LOW	LOW	LOW	MAJOR
Alaska/NW Canada (ALA)	MODERATE	MAJOR	LOW	CRITICAL	CRITICAL	LOW	LOW	LOW	CRITICAL
Amazon (AMZ)	MAJOR	MAJOR	LOW	LOW	LOW	CRITICAL	LOW	CRITICAL	LOW
East Africa (EAF)	MAJOR	MAJOR	LOW	LOW	LOW	CRITICAL	CRITICAL	LOW	LOW
Western N. America (WNA)	MODERATE	CRITICAL	LOW	MODERATE	MAJOR	CRITICAL	LOW	LOW	MAJOR
Tibetan Plateau (TIB)	LOW	LOW	LOW	CRITICAL	MAJOR	CRITICAL	LOW	MAJOR	CRITICAL
Central Europe (CEU)	MAJOR	MAJOR	MAJOR	LOW	MAJOR	LOW	LOW	LOW	LOW
West Asia (WAS)	MAJOR	CRITICAL	LOW	MODERATE	LOW	MAJOR	CRITICAL	LOW	MAJOR
Southern Europe (MED)	MAJOR	CRITICAL	MODERATE	LOW	LOW	LOW	LOW	LOW	LOW
Central Asia (CAS)	MODERATE	LOW	LOW	MAJOR	MAJOR	MAJOR	LOW	LOW	MAJOR
Northeast Brazil (NEB)	MAJOR	CRITICAL	LOW	LOW	LOW	CRITICAL	CRITICAL	MAJOR	LOW
North Australia (NAU)	MODERATE	MAJOR	LOW	LOW	LOW	CRITICAL	CRITICAL	MODERATE	LOW
South Australia (SAU)	LOW	MAJOR	LOW	LOW	LOW	LOW	MAJOR	LOW	LOW
Eastern Canada / Greenland (CGI)	MAJOR	CRITICAL	MAJOR	CRITICAL	CRITICAL	LOW	LOW	LOW	CRITICAL
Southeast S. America (SSA)	MAJOR	CRITICAL	LOW	LOW	LOW	MAJOR	LOW	CRITICAL	LOW
West Coast S. America (WSA)	MODERATE	MAJOR	LOW	MODERATE	LOW	MAJOR	MODERATE	CRITICAL	CRITICAL
Southern Africa (SAF)	MODERATE	MAJOR	LOW	LOW	LOW	MAJOR	MAJOR	LOW	LOW
Central N. America (CNA)	MODERATE	LOW	LOW	MODERATE	MODERATE	MAJOR	LOW	LOW	LOW

Legend:

- CRITICAL = System-threatening impacts
- MAJOR = Significant adaptation required
- MODERATE = Manageable impacts requiring some adaptation
- LOW = Limited impacts

Table 4. *Potential systemic risk impacts of passing different climate tipping points. Physical changes translate into risks across nine critical policy domains.*

Tipping event	Food security	Energy security	Water resources	Infrastructure & built environment	Public health	Biodiversity & ecosystems	Financial & economic risks	Humanitarian crisis & displacement	National security
AMOC collapse	↓↓ Agricultural productivity N. Europe (32 per cent to 7 per cent arable land), monsoon disruption affecting 2B+ people	↑ Heating demand Europe, ↓ hydroelectric from precipitation changes	↓↓ Precipitation patterns (-0.5 to -2 mm/d), hydrological disruption	Massive adaptation costs (€500B+ Europe), storm track changes	Cold stress, food insecurity health impacts	Major ecosystem shifts, forest stress	€500B+ protection costs, agricultural losses	10M+ displacement Europe	Resource conflicts, Sahel political instability
Subpolar gyre deep convection collapse	Atlantic fisheries collapse (cod, herring), European food security	Altered renewable energy potential	Limited direct water impacts	Increased storm risks coastal infrastructure	Food insecurity from fisheries loss	Marine ecosystem fundamental shifts	Fisheries economic collapse	Coastal fishing community displacement	Resource conflicts over marine resources
Greenland Ice Sheet collapse	Saltwater intrusion coastal agriculture	Coastal energy infrastructure threatened	Massive freshwater discharge, saltwater contamination	Multi-meter SLR (up to 7.42m), coastal infrastructure loss	Displacement health impacts, contaminated water supply	Coastal ecosystem complete loss	Trillions in coastal asset losses	Millions displaced from coastal cities	Arctic geopolitical tensions, border pressures
West Antarctic Ice Sheet collapse	Coastal agricultural land loss	Coastal power plants at risk	Freshwater supply contamination	Multi-meter SLR (up to 5.08m), infrastructure submersion	Health system strain from displacement	Marine ecosystem disruption	Insurance market collapse coastal regions	Island nations uninhabitable	International refugee crises
Permafrost thaw	↓ Agricultural zones, soil constraints in thaw regions	Critical pipeline/ infrastructure damage, Trans-Alaska Pipeline threatened	Hydrological changes, thermokarst lake formation	70 per cent permafrost infrastructure at risk by 2050	Carbon feedback acceleration health impacts	Massive boreal ecosystem shifts, wetland formation	Infrastructure replacement costs trillions	Arctic indigenous community displacement	Arctic sovereignty challenges
Coral reef die-off	↓↓ Reef fisheries (150M+ people Coral Triangle), protein source loss	Coastal energy infrastructure vulnerability	Loss of coastal protection from storm surge	↓ Natural coastal protection, ↑ storm damage	Food insecurity, storm-related injuries and deaths	>99 per cent coral biodiversity loss under 2.5°C	$75B+ tourism/ fisheries losses Coral Triangle alone	Small island nation complete displacement	Resource conflicts over marine territories
Amazon dieback	Regional precipitation loss affecting agriculture	↓ Hydroelectric potential, biomass energy disruption	25-35 per cent precipitation recycling loss, river navigation disruption	Fire risks to infrastructure, transportation disruption	Fire smoke health impacts, heat stress	50-70 per cent conversion to savanna, massive biodiversity loss	$957B-3,589B economic damages over 30 years	Indigenous peoples displacement, millions affected	Regional political instability, Brazil-neighbors tensions
Boreal forest shifts	Forest-agriculture transitions, wildfire risks to crops	Biomass energy disruption, wildfire risks to power transmission	Watershed changes, fire impacts on water quality	↑↑ Wildfire risks to infrastructure, forest industry collapse	Wildfire smoke health emergencies	Largest global ecosystem transformation	Forest industry economic collapse	Rural community abandonment	Resource conflicts over forest transitions

Table 4. Continued

Tipping event	Food security	Energy security	Water resources	Infrastructure & built environment	Public health	Biodiversity & ecosystems	Financial & economic risks	Humanitarian crisis & displacement	National security
South Asian monsoon disruption	Critical threat to 2B+ people, rice production collapse	Massive cooling demand impacts, hydroelectric disruption	Primary water source for billions disrupted	Urban infrastructure strain from monsoon variability	Heat stress, water-related disease	All major ecosystems dependent on monsoon	Economic disruption for 1/4 world population	Mass internal displacement, international migration	Regional conflicts over water resources
West African monsoon collapse	400M+ people agriculture dependent on monsoon	Hydroelectric generation severely affected	Primary water source hundreds of millions	Sahel infrastructure adaptation needs	Heat stress, food/ water insecurity	Sahel ecosystem shifts forest-grassland	Agricultural economy collapse	Mass displacement from Sahel	Political instability (7 coups in 3 years)
East Asian monsoon disruption	1.5B+ people agricultural productivity threatened	Energy system impacts from monsoon changes	Water resources for massive populations	Infrastructure planning disruption	Heat/humidity health impacts	Regional ecosystem disruption	Major economic disruption East Asia	Internal displacement pressures	Regional tensions over water/food
Mountain glaciers	Regional impacts on glacier-fed agriculture	Altered hydroelectric potential, seasonal variability	Critical impacts on glacier-dependent regions	Glacial outburst flood risks, coastal changes	Limited direct impacts	Major ecosystem transformations in fjords/mountains	Tourism losses, infrastructure adaptation costs	Indigenous community displacement, cultural losses	Arctic sovereignty challenges, border access changes

2.4.4. Systemic threats in terms of risk currencies

To understand how Earth system tipping points translate into tangible policy and governance challenges, we must examine their impacts through the lens of what societies fundamentally depend upon for stability and prosperity. The following analysis organizes tipping point consequences across nine critical *risk currencies* that represent the core values and priorities policymakers are mandated to protect: food security, energy security, humanitarian crisis and displacement, national security, financial and economic risks, infrastructure and built environment, public health, biodiversity and ecosystems and water resources. This aims to bridge the gap between Earth system science and policy-relevant impacts, demonstrating how tipping points in the Earth system cascade through interconnected human systems to create systemic risks.

Food security

Earth system tipping points pose severe threats to global food production through multiple pathways. Food systems are highly vulnerable to tipping point impacts as they are affected by multiple dimensions (Wheeler and von Braun, 2013), with sensitivity to precipitation and temperature (Lenton et al., 2023). Simultaneous harvest failures across major crop-producing regions are a threat to global food security, driven by concurrent weather extremes from strongly meandering jet streams (Anderson et al., 2019, 2024; Gupta et al., 2023; Kornhuber et al., 2023; Hasegawa et al., 2022; Mehrabi and Ramankutty, 2019; Tigchelaar et al., 2018; Zscheischler et al., 2018).

Tipping points also threaten food security through indirect pathways, including altered pest and disease dynamics as changing temperature and precipitation patterns expand the geographic range and seasonal activity of crop pests and pathogens (Deutsch et al., 2018).

AMOC collapse demonstrates the scale of potential agricultural disruption, with research showing it would cause widespread cessation of arable farming in Northern Europe. In Britain, suitable farmland would drop by as much as 32 per cent, decreasing agricultural output by £346 million annually (Ritchie et al., 2020). Regional cooling in Northern Europe could cause widespread agricultural system collapse, while altered precipitation patterns would affect agricultural systems supporting billions across affected monsoon regions. The West African, Indian Summer and East Asian monsoons would be disrupted with shorter wet and longer dry seasons and less overall rainfall, affecting food production for populations dependent on these systems (Ben-Yami et al., 2024; Ben-Yami et al., 2023).

Amazon dieback would severely disrupt food systems through crop failures and declining fish stocks, with rising food prices and reduced nutrition access particularly affecting the 30 million regional residents. Indigenous and traditional communities face acute risks as their food security depends on intact forest-river ecosystem interactions (Begazo-Curie and Vranken, 2025; Leal Filho et al., 2025; Monteverde et al., 2024; Banerjee et al., 2022; Tregidgo et al., 2020). Coral reef collapse would eliminate reef fisheries supporting 150+ million people in the Coral Triangle region alone, with complete loss of this primary protein source for many small island populations creating severe food security crises.

Research on "non-tipping" climate impacts suggests that the abrupt and severe changes characteristic of tipping events would amplify food security risks through crop yield volatility, supply chain disruption and price shocks beyond what gradual climate change would produce (Tchonkouang et al., 2024; Mirzabaev et al., 2023; Ortiz-Bobea et al., 2021; Davis et al., 2020). The often irreversible nature of tipping point changes means agricultural systems cannot rely on temporary adaptation but must undergo fundamental transformation to cope with permanently altered growing conditions.

Energy security

Energy systems face critical vulnerabilities from climate change through infrastructure damage, supply disruption and demand volatility (Yalew et al., 2020; van Vliet et al., 2016). Earth system tipping points could amplify these existing vulnerabilities, potentially making infrastructure damage, supply disruption and demand volatility permanent and irreversible. Sea level rise from ice sheet collapse threatens coastal nuclear plants, refineries and LNG terminals, while permafrost thaw puts 70 per cent of current infrastructure in permafrost regions at high risk by 2050, including critical assets like the Trans-Alaska Pipeline (JRC, 2025b; Manos et al., 2025; Langer et al., 2023). Permafrost and boreal forest changes create extreme wildfire risks to power transmission networks documented across Alaska, Canada and Siberia (Virkkala et al., 2025; Kim et al., 2024; Scholten et al., 2024; Buma et al., 2022).

Supply security faces major disruption through altered precipitation patterns affecting hydroelectric generation. AMOC collapse could severely reduce hydroelectric potential across Europe and West Africa through precipitation changes (Jackson et al., 2015), while monsoon disruptions threaten systems supporting billions across South and Southeast Asia (Ben-Yami et al., 2023; Zhao et al., 2023; Chemison et al., 2022; Sandeep et al., 2020; Amrith, 2016; Loo et al., 2015; Intergovernmental Panel on Climate Change, 2014). Amazon dieback could reduce regional hydroelectric potential by 25-35 per cent through precipitation recycling loss (Lenton et al., 2023). Mountain glacier retreat would fundamentally alter regional hydrology, with glaciers contributing up to half of downstream discharge while buffering seasonal variability, affecting hydroelectric generation potential for the nearly 1.5 billion people living in glacier-influenced regions globally.

Demand patterns face unprecedented volatility from temperature regime changes. AMOC collapse would require massive increases in heating energy demand across Northern Europe while altering renewable energy potential through changed offshore wind patterns (Ritchie et al., 2020). The irreversible nature of tipping point changes means energy systems cannot rely on temporary adaptation but must undergo fundamental transformation, with cascading failures becoming more likely as multiple tipping points interact across energy value chains.

Humanitarian crisis and displacement

Tipping point impacts create cascading humanitarian emergencies through ecosystem collapse, resource scarcity and livability challenges. Extreme events including droughts in the Amazon region are disruptive to the food and transport systems of Indigenous peoples and communities who depend on local resources, with lower river water levels affecting transportation, food security and health, potentially influencing migration from rural areas (Lenton et al., 2023). As traditional knowledge systems, ecosystems and forest-based livelihoods deteriorate, entire communities may lose their ability to sustain themselves, creating self-reinforcing cycles of socio-ecological vulnerability (Pinho et al., 2015).

Mountain glacier retreat creates profound cultural losses for Indigenous communities whose identities and traditional knowledge systems are inseparable from glacial landscapes. For Tlingit communities in southeast Alaska, rapid deglaciation disrupts relationships with glaciers spanning millennia, depriving future generations of cultural touchstones and traditional practices while forcing adaptation of harvest and land management systems (Ord, 2024). Small Island Developing States face complete loss of territory that would trigger unprecedented questions of statehood and require total population relocation, creating new categories of climate refugees.

AMOC collapse would create displacement pressures affecting millions across Europe and West Africa. West Africa monsoon disruption threatens 400+ million people dependent on monsoon precipitation patterns, with the potential for unprecedented humanitarian displacement in a region that has already experienced multiple military coups since 2020, suggesting limited capacity to manage climate-driven migration (Ben-Yami et al., 2024; Kipo-Sunyehzi & Lambon, 2025; Larémont, 2021; Mulitza et al., 2008; Neupane & Cook, 2013; Peterson, 2024; Surazu, 2024; Taruvinga, 2023). The southward shift of the Intertropical Convergence Zone would trigger acute humanitarian emergencies as shortened wet seasons and reduced rainfall render pastoralist and farming livelihoods impossible across vast areas of the Sahel, forcing millions to abandon their homes and traditional territories (Defrance et al., 2017, 2020; Mulitza et al., 2008). Rural migration during extended dry periods, combined with displacement from irregular intense flooding that destroys settlements, would create cascading humanitarian crises as drought and flood refugees overwhelm urban areas and neighboring regions already struggling with 8 million internally displaced persons and a 172 per cent increase in humanitarian need since 2016 (International Rescue Committee., 2023).

Research on climate-induced displacement provides a foundation for understanding how the scale and irreversibility of tipping point impacts would generate unprecedented migration pressures. While existing displacement studies focus on gradual climate impacts (Duijndam et al., 2025; Almulhim et al., 2024; Hoffmann et al., 2024; Askland et al., 2022), tipping point research warns that crossing these thresholds could trigger 'catastrophic impacts on human societies' including mass displacement suggesting that the irreversible nature of tipping point changes would generate migration pressures that exceed current projections based on linear climate impacts.

National security

Earth system instability threatens national security through resource conflicts, border pressures from climate migration and economic disruption (Laybourn et al., 2024). Climate variability is directly linked to economic impacts and political stability, with the AMOC strongly connected to precipitation over the Sahel, a region that has experienced at least five successful military coups since 2020 (Kipo-Sunyehzi and Lambon, 2025; Ben-Yami et al., 2024; Peterson, 2024; Surazu, 2024; Taruvinga, 2023; Larémont, 2021; Neupane and Cook, 2013; Mulitza et al., 2008).

Earth system tipping points create complex cascades between conflict and cooperation that challenge traditional national security frameworks. Research specifically examining tipping point-security linkages identifies how climate tipping events can trigger cascading dynamics where initial cooperation attempts may collapse into conflict spirals, or conversely, where crisis-driven cooperation can emerge from conflict situations (Scheffran et al., 2025). These dynamics are amplified by negative social tipping processes that Earth system destabilization can trigger, including social anomie, political radicalization and polarization, mass displacement, resource conflicts and financial destabilization that can reinforce ecological breakdown through reduced adaptive capacity (Spaiser et al., 2024). The interconnected nature of Earth system tipping points means that cascading failures - such as AMOC collapse simultaneously triggering monsoon disruption and Amazon dieback - could overwhelm existing security frameworks designed for singular threats, creating self-reinforcing cycles where climate-induced social instability reduces society's capacity to address climate risks while generating unpredictable shifts between cooperation and conflict that exceed current diplomatic and military planning scenarios.

Amazon degradation increases risks of violent conflict through riots and protests over rising food prices and resource shortages, tensions between displaced populations and host communities and potential for authoritarian shifts driven by social radicalization and climate-induced unrest (Scheffran et al., 2025; Spaiser et al., 2024). Mountain glacier retreat in Alaska creates international governance challenges as icefields straddle borders and deglaciation may create more points of access across the US-Canada border, raising national security and defense considerations.

Insights taken from the literature on climate-conflict linkages (Mach et al., 2019; Burke et al., 2015; Hsiang et al., 2011) suggests that tipping point impacts would exacerbate existing vulnerabilities and create new sources of instability. The cascading impacts could include political destabilization as established political systems face legitimacy challenges from climate-induced hardships, potentially leading to social unrest and violence as people turn against political elites unable to provide effective responses to multiplying crises.

Financial and economic risks

Melting of the Antarctic Ice Sheet could impose severe costs on Small Island Developing States and increase the worldwide social cost of carbon emissions (Dietz and Koninx, 2022). Ecosystem tipping points pose risks to economic stability through reduced food and energy security, damage to assets such as real estate and infrastructure and health risks that impair household productivity (Bloom et al., 2024; Burlig and Preonas, 2024; Pereira et al., 2024; Yang et al., 2023; Dietz and Koninx, 2022; Hjort et al., 2022; Hallegatte and Walsh, 2021; Lapola et al., 2018; Hsiang, 2010). However, most existing economic assessments of climate tipping points have taken a narrow approach, focusing primarily on relating GDP to mean annual temperature effects while neglecting the broader systemic impacts (Keen, 2020). For instance, early studies suggested that AMOC collapse might actually be economically beneficial due to regional cooling effects, leading to counterintuitive conclusions that such events could reduce the social cost of carbon (Dietz et al., 2021; Anthoff et al., 2016). These studies use standard damage functions that rely on simple temperature-damage relationships which are inadequate for normal climate change and completely fail for tipping points. A recent study of AMOC weakening demonstrates this problem clearly - incorporating just one additional impact pathway - the reduction in ocean carbon uptake that leads to higher atmospheric CO_2 and accelerated global warming - reveals economic damages of several trillion US dollars that completely offset the supposed benefits (Schaumann and Alastrué de Asenjo, 2025). This AMOC carbon feedback alone could flip the economic consequences of AMOC weakening from a net benefit to a net cost to society, highlighting how current damage functions systematically underestimate tipping point impacts by ignoring critical Earth system feedbacks.

Furthermore, financial markets may trigger "Minsky moments" (Kaldorf and Rottner, 2024; Miller and Dikau, 2022; Behlul, 2011) - sudden collapses in asset values - as investors anticipate future tipping point risks, even before physical thresholds are crossed, creating cascades that move outside the climate system into financial systems. The insurance sector particularly faces withdrawal from climate-vulnerable regions, creating uninsurable "climate deserts" (Boomhower et al., 2024; Kousky et al., 2024; Storey et al., 2024) where economic losses from extreme events already amount to 1 per cent of GDP in the euro area and are expected to rise without action (Alogoskoufis et al., 2021). The systemic nature of climate change for financial stability suggests the need for macroprudential responses including systemic risk buffers and exposure concentration limits, though modeling complexity and uncertainty present significant challenges. Uncertain climate policies may induce destabilizing swings in green asset prices, while unexpected transitions could leave high-carbon firms with stranded assets, translating into credit risk for funding institutions.

Infrastructure and built environment

Infrastructure systems face threats from Earth system tipping points through physical damage, design standard obsolescence and cascading system failures (Bhattacharya et al., 2025; Fekete and Nehren, 2024; de Abreu et al., 2022; Palin et al., 2021; Hawchar et al., 2020). Sea level rise from ice sheet collapse would create unprecedented challenges (Kopp et al., 2014, 2017; Hinkel et al., 2014), with losses and protection costs potentially as high as hundreds of billions of Euros for Europe alone (Vousdoukas et al., 2020) and 70 per cent of permafrost infrastructure at risk by 2050, requiring massive adaptation investments or community relocation (Hjort et al., 2022).

AMOC collapse would fundamentally alter storm tracks and precipitation patterns, making existing infrastructure inadequate, while boreal forest shifts create extreme wildfire risks to transportation networks and power transmission systems documented across northern regions (Bellomo and Mehling, 2024; Fekete and Nehren, 2024; Bellomo et al., 2023; Walker et al., 2019; Jackson et al., 2015). The unprecedented scale of tipping point changes could overwhelm existing adaptation measures and require fundamental rethinking of design standards, as these irreversible shifts render existing infrastructure planning assumptions obsolete, forcing complete system redesigns rather than incremental adaptations (Buhl and Markolf, 2023; IPCC, 2022; Zhang et al., 2020). Indeed, current climate change is already outpacing adaptation measures as seen with recent extreme events, with ongoing impacts outpacing global mitigation efforts and adaptation progress slowing when it should be accelerating (UNEP, 2024; Newman and Noy, 2023; Magnan et al., 2022; Currie-Alder et al., 2021).

Public health

Public health systems face compounding emergencies from climate change through direct health impacts, healthcare system disruption and cascading crises that exceed system capacity (Romanello et al., 2024; van Daalen et al., 2024; Ebi, Capon, et al., 2021; Ebi, Vanos, et al., 2021; Kovats and Hajat, 2008), while tipping points could exacerbate these same vulnerabilities beyond current adaptive capacity. Permafrost thaw can accelerate global warming through carbon release (Turetsky et al., 2020; Olefeldt et al., 2016; Schuur et al., 2015) while potentially releasing ancient viruses and pathogens previously trapped in frozen soils, creating amplified health risks and novel disease emergence concerns (Mackelprang et al., 2025; Wu et al., 2022; Revich et al., 2012).

Boreal forest shifts generate extensive wildfire smoke (Phillips et al., 2022; Whitman et al., 2019) creating respiratory emergencies across populations (Aguilera et al., 2021; Reid et al., 2016), while food security collapses threaten nutrition for billions, with monsoon disruption affecting 2+ billion people in South Asia (Asutosh et al., 2025; Fiaz et al., 2025; Fanzo et al., 2024; Turner and Annamalai, 2012) and coral reef die-off eliminating protein sources for 150+ million in the Coral Triangle (Crona et al., 2015; Cruz-Trinidad et al., 2014; WWF, 2009). Mental health impacts emerge from displacement pressures (Torres and Casey, 2017; McMichael et al., 2012), with potential displacement of 13 million people in the US from sea level rise alone (Hauer et al., 2016), while healthcare infrastructure faces direct physical threats precisely when demand surges from cascading health emergencies that would exceed system capacity (NRDC, 2024).

Biodiversity and ecosystems

Earth system tipping points pose severe threats to global biodiversity through habitat destruction, ecosystem collapse and species extinction cascades, leading to abrupt and possibly irreversible shifts between alternative ecosystem states (Pecl et al., 2017; Urban, 2015). Evidence exists for tipping points in ecosystems including forest dieback, dryland desertification, lake eutrophication, coral reef die-off and fishery collapse, with several biomes such as the Amazon rainforest losing resilience and approaching key tipping thresholds. Recent analysis reveals a biodiversity paradox: increased biodiversity lowers collapse thresholds while enhancing restoration potential (Dakos et al., 2019). Stable ecosystems underpin all economic activity through providing natural resources, regulating climate and providing resilience against disasters, yet human pressures are increasing ecosystem tipping point risks (Marsden et al., 2024; Dasgupta, 2021; Folke et al., 2021; Dakos et al., 2019). Research suggests that tipping point events would create compounding ecological emergencies exceeding ecosystem adaptation capacity, potentially triggering irreversible losses of species and functions essential for planetary stability.

AMOC collapse represents a particularly severe example of how circulation changes trigger cascading biological impacts. AMOC collapse would reduce North Atlantic marine productivity by up to 30 per cent over the 21st century while decreasing fisheries species abundance by up to 17 per cent locally, fundamentally altering marine food web structure (Boot et al., 2025). The collapse creates phenological mismatches where ecosystem timing shifts faster than species adaptation capacity, particularly affecting the North Atlantic bloom timing and its dependent food webs. Temperature-driven biogeographical shifts cascade through multiple trophic levels with amplifying effects, while reduced ecosystem carbon sequestration capacity creates positive feedbacks that accelerate atmospheric CO_2 accumulation (Boot et al., 2024). Terrestrial systems face complex disruptions as altered precipitation patterns and temperature regimes drive vegetation state changes and species range contractions. Dynamic vegetation models demonstrate significant relationships between AMOC strength and ecosystem composition, suggesting widespread transitions under collapse scenarios. These changes enhance the ongoing biodiversity crisis by creating additional stresses on vulnerable species already facing habitat loss and climate change, with documented effects including amphibian population declines and contracted geographic ranges for plants and animals (Ureta et al., 2022; Velasco et al., 2021).

Terrestrial systems face disruption as altered precipitation patterns affect productivity zones, with shifts in the Intertropical Convergence Zone relocating prime productivity in equatorial rainforests. Amazon forest loss would eliminate critical habitat for over 25 per cent of terrestrial species while disrupting moisture recycling essential for regional ecosystem stability.

The Fourth Global Coral Bleaching Event reveals the severity of ecosystem simplification, where reefs that survive have a different community structure with much less diversity in coral species. The 'reef to rubble' phenomenon causes coral colonies to fragment and transition to rubble, representing ecosystem transformation to new states that are difficult to recover from (Kai L Kopecky et al., 2023; Kenyon, Doropoulos, et al., 2023). This simplification adversely impacts thousands of species that rely on complex three-dimensional reef architecture, fundamentally altering ecosystem services provided to over half a billion people globally.

Water resources

Tipping points threaten global water security through altered precipitation patterns, hydrological cycle disruption and freshwater system collapse, with water security encompassing scarcity, quality, hazards, access and governance challenges. AMOC collapse would trigger southward shifts of tropical precipitation zones and disrupt monsoon systems (DiNezio et al., 2025; Steinert et al., 2025; Ben-Yami et al., 2024; Ben-Yami et al., 2023; Good et al., 2022; Kug et al., 2022), with palaeoclimate evidence showing that past AMOC weakening led to abrupt Asian and African monsoon collapse (Mohtadi et al., 2014, 2016). This would create complex regional impacts, with substantial Sahel rainfall reductions affecting primary water sources for hundreds of millions in West Africa (Defrance et al., 2017, 2020), while South Asian monsoon weakening affects primary water sources for billions of people (Dagdeviren et al., 2021),

Forest cover loss affects hydrologic systems of major freshwater-producing regions, with critical thresholds identified after which hydrologic regimes shift rapidly (Domínguez-Tuda and Gutiérrez-Jurado, 2024; Yang et al., 2021). Amazon dieback would disrupt critical moisture recycling processes, with an estimated 30 per cent of Amazon rainfall originating from forest evapotranspiration, affecting water availability across South America through disrupted atmospheric moisture transport (Beveridge et al., 2024).

Mountain glacier retreat fundamentally alters regional hydrology, with glaciers contributing up to half of downstream discharge while buffering seasonal variability through enhanced melt during warm, dry years. Rapid deglaciation initially increases discharge until around 2080, followed by decreased total discharge as glacier volume diminishes, affecting both freshwater security and hydroelectric generation potential for the nearly 1.5 billion people living in glacier-influenced regions globally. Greater variability in timing and volume of freshwater delivery affects dominant circulation patterns in nearshore waters, influencing transport and delivery of materials and nutrients to offshore ecosystems.

Human interference through climate forcing, water withdrawal and land-use change has disturbed hydrological cycles, with examples including aquatic system collapse. Recent research suggests tipping point events would create unprecedented hydrological disruption (van Thienen et al., 2025) affecting agriculture, energy, urban supplies and ecosystems, with cascading effects on food security, public health and economic stability globally.

2.4.5. Regional impact assessment

This section examines how Earth system tipping points manifest as concrete risks across different world regions, translating global-scale biophysical changes into localized consequences that vary dramatically based on geographical location, exposure patterns and socioeconomic context. We analyze impacts across 27 regions using the IPCC SREX classification system, which provides an appropriate spatial scale for synthesizing the currently limited literature on tipping point consequences. For each region, we assess exposure to major tipping points including AMOC collapse, ice sheet loss, permafrost thaw, monsoon disruption, coral reef die-off, Amazon dieback and boreal forest shifts, examining how these translate into direct impacts across the nine risk currencies established in our framework. This regional analysis reveals the highly uneven distribution of tipping point risks globally and identifies which populations face the most severe consequences from Earth system instability.

2.4.5.1 Europe

Major tipping point exposures

Europe faces dramatic impacts from AMOC collapse, sea level rise affecting extensive coastlines, permafrost thaw in northern regions, boreal forest shifts and Arctic sea ice loss effects. The region's high latitude position makes it particularly vulnerable to circulation changes and ice sheet effects.

Subpolar gyre

Collapse of deep convection in the subpolar gyre (Labrador and Irminger Seas) represents a critical early stage in broader North Atlantic circulation breakdown, with the key distinction that deep convection can collapse much faster than the full AMOC system winds down (Sgubin et al., 2017). While AMOC collapse by definition includes the loss of deep convection, subpolar gyre collapse deserves specific focus because it can occur decades sooner than complete AMOC shutdown, creating immediate regional impacts. The rapid cooling of large surface ocean areas from halted deep convection directly impacts atmospheric circulation, strengthening winter storms and altering weather patterns across the North Atlantic region (Swingedouw et al., 2021; Sgubin et al., 2017). This creates a stepping-stone scenario where subpolar gyre collapse serves as both an early warning signal and a driver of accelerated AMOC weakening, making it a critical threshold for monitoring and risk assessment.

NEU (northern Europe) could face major impacts from subpolar gyre collapse through altered ocean temperatures and circulation patterns affecting regional climate. Changes in ocean heat transport could modify coastal temperatures and precipitation patterns, potentially affecting agriculture and energy systems. Marine ecosystems supporting major fisheries, including cod, herring and other commercially important species, could face fundamental shifts in distribution and productivity. Recent modelling studies project that the North Atlantic bloom—the phytoplankton foundation of the regional food web—faces potential collapse this century due to weakened deep winter convection, with surface chlorophyll levels halving and bloom timing shifting by over 30 days, fundamentally disrupting food web dynamics that support these commercially important fisheries (Kelly et al., 2025). The collapse could also affect storm tracks and intensity across the North Atlantic (Shaw et al., 2016; Woollings et al., 2012), potentially increasing extreme weather risks to infrastructure and coastal communities. Changes in subpolar gyre strength are linked to North Atlantic Oscillation variability, which controls the latitudinal position of storm tracks and wind strength in the North Atlantic region, with subpolar gyre variations potentially affecting the northward-shifted storm track and North Atlantic Current strength (Bhagtani et al., 2024, 2025; Koul et al., 2020; Cannaby and Hüsrevo-lu, 2009; Sarafanov, 2009). CEU (central Europe) may experience moderate impacts through teleconnections affecting Atlantic weather patterns that influence continental European climate. Changes in storm frequency and intensity originating from altered North Atlantic conditions could affect agriculture and water resources. MED (Mediterranean) would likely see limited direct impacts from subpolar gyre changes, though some effects on Atlantic-origin weather patterns reaching Iberia and western Mediterranean regions may occur.

AMOC collapse

AMOC collapse could cause cooling and drying (Bellomo and Mehling, 2024; Caesar et al., 2018; Jackson et al., 2015) that may fundamentally transform agricultural systems and energy demands across Europe. These impacts result from fundamental asymmetries in ocean heat transport where heat loss occurs over smaller northern areas compared to southern heat distribution, making Northern Hemisphere regions particularly vulnerable as net receivers of Atlantic heat transport (S. Drijfhout, 2015; S. S. Drijfhout, 2015). Sea-ice expansion plays a critical amplifying role, capping atmospheric heat release while reflecting solar radiation back to space, creating self-reinforcing cooling effects that are larger in colder baseline climates. These changes can produce measurable drops in global mean temperatures despite originating from regional circulation shifts, with cooling patterns evolving over decades as winter sea ice expands southward (van Westen and Baatsen, 2025; van Westen et al., 2024).

Northern Europe (NEU) would likely experience the most severe impacts, with 3-8°C cooling and dramatic shifts in precipitation patterns shown in modelling studies that could cause widespread cessation of arable farming in northern Europe. Northwest European winters would become substantially harsher, characterized by stronger winds, more frequent snow events and intensified cold extremes leading to more frequent stormy conditions (Meccia et al., 2024, 2025; van Westen and Baatsen, 2025; Howard et al., 2024; Woollings et al., 2012). Summer weather patterns may shift toward sunnier, less cloudy conditions driven by more frequent blocking high-pressure systems east of the British Isles, associated with cool northerly winds (Bellomo et al., 2023; Haarsma et al., 2015). Storm tracks would intensify and extend eastward, particularly over northern regions of western and central Europe, leading to higher and more frequent storm surges that enhance coastal flooding risks (Howard et al., 2024; Yang et al., 2020; Lehmann et al., 2014; Woollings et al., 2012).

Marine ecosystems from the northeast Atlantic would face fundamental restructuring as reduced deep convection decreases nutrient entrainment, leading to phytoplankton productivity declines of up to 30 per cent over the 21st century. Critical fisheries species could decline locally by up to 17 per cent, fundamentally altering food web structure and economic dependencies (Boot et al., 2025). The timing of the North Atlantic bloom may shift substantially, creating phenological mismatches where species higher in food webs cannot adapt quickly enough to changing seasonal patterns, potentially causing ecosystem function collapse.

In Britain, rainfall during the growing season could be reduced by 123mm (approximately 20 per cent) and land suitable for arable farming could drop from 32 per cent to 7 per cent, reducing agricultural output by £346 million annually (Ritchie et al., 2020). This represents a critical food security threat affecting millions across the region. Shortened growing seasons may cause crop failures across Scandinavia, while reduced precipitation (-0.5 to -2 mm/d) and altered hydrological cycles could stress water resources (Bellomo and Mehling, 2024; Bellomo et al., 2023; Ritchie et al., 2020; Lynch-Stieglitz, 2017) . Storm track changes would likely make existing infrastructure and built environment inadequate, potentially requiring massive increases in heating energy demand and affecting renewable energy security potential. Sea transport will be hampered by increased risk of frozen sea during winter (van Westen and Baatsen, 2025).

Central Europe (CEU) could face 2-4°C cooling, particularly in Atlantic-influenced western areas, experiencing similar but less severe storm intensification patterns, potentially leading to reduced agricultural productivity and altered crop zones affecting major agricultural regions like the North German Plain, creating significant food security challenges (Bellomo and Mehling, 2024; Bellomo et al., 2023; Jackson et al., 2015). Forest ecosystem stress and altered species distributions may occur alongside infrastructure and built environment adaptation needs for altered climate patterns, while biodiversity and ecosystems face unprecedented stress from rapid climate transitions.

Southern Europe and the Mediterranean (MED) could experience moderate cooling (1-2°C) in Atlantic-influenced areas (Bellomo and Mehling, 2024; Jackson et al., 2015). Altered precipitation patterns potentially affecting Mediterranean agriculture and reduced precipitation in western Mediterranean regions that may stress ecosystems and water resources, while the eastern Mediterranean would likely see minimal direct impacts from AMOC changes.

Sea level rise from ice sheet collapse

Ice sheet collapse would accelerate sea level rise rates substantially in coming decades, with an additional 0.7m by 2100 in IPCC AR6's high-impact storyline, while the full multi-meter rise (up to 7.4m from Greenland, 5.1m from West Antarctica) would unfold over centuries (Siahaan et al., 2022; Stokes et al., 2022; Payne et al., 2021; Golledge, 2020; Dutton et al., 2015; Bamber et al., 2009; Dowdeswell, 2006; Alley et al., 2005). Critically, AMOC collapse would compound these impacts by raising sea levels by up to 1m along some European coastlines through altered ocean circulation patterns (van Westen et al., 2024; Chafik et al., 2019; Chen et al., 2019; Bouttes et al., 2014; Körper et al., 2009; Levermann et al., 2005), creating compound flooding risks that exceed global mean projections. Regional variations in sea level change due to gravitational and rotational effects mean some areas face disproportionately higher impacts, with the combination of accelerated ice sheet contributions and circulation changes creating unprecedented coastal vulnerability in the near term. NEU could face critical threats to low-lying agricultural areas in the Netherlands and Denmark, with major port Rotterdam and coastal cities like Amsterdam and Copenhagen potentially requiring massive coastal protection investments or partial abandonment of low-lying areas. Research on coastal impacts suggests protection costs could exceed hundreds of billion of Euros for Europe (Hinkel et al., 2014, with potential displacement of 10+ million people from low-lying areas.

CEU may experience major impacts on North German plain agricultural areas and infrastructure, with Hamburg and other North Sea ports potentially threatened by multi-meter sea level rise (Siahaan et al., 2022; Stokes et al., 2022; Payne et al., 2021; Golledge, 2020; Dutton et al., 2015; Bamber et al., 2009; Dowdeswell, 2006; Alley et al., 2005). The Wadden Sea and coastal ecosystems could be fundamentally altered. MED would likely face critical threats to major coastal cities including Venice and Alexandria, with the Po Valley and Nile Delta agricultural areas potentially severely affected by saltwater intrusion. Research indicates these low-lying areas could face permanent inundation or increased flooding, potentially displacing millions and disrupting regional economies (Hsiao et al., 2021; Silveira et al., 2021; Mohd et al., 2018; Rueda et al., 2017; Vitousek, Patrick L Barnard, et al., 2017; Vitousek, Patrick L. Barnard, et al., 2017).

Glacier collapse

Retreating glaciers, such as those in Svalbard, could impact NEU, exposing previously ice-covered land, altering freshwater and coastal water regimes while amplifying local warming through feedbacks like ice-albedo and melt-elevation effects (Marshall, 2021). Retreating glaciers in Arctic fjords, such as Billefjorden in Svalbard, have led to increased areas of shallows, decreased salinity and elevated temperatures in inner basins (van der Kamp et al., 2025). These changes are partly due to the influx of Atlantic waters from the shelf, transforming the fjord environment towards conditions characteristic of boreal ecosystems (Drewnik et al., 2016). The retreat of glaciers further drives differentiation of benthic communities and other ecological shifts over small spatial scales, indicating that ice loss triggers complex, localized environmental changes (van der Kamp et al., 2025). Consequently, there is an increase in organic matter turnover, significantly impacting local marine life .

Beyond the major ice sheets, smaller Arctic glaciers are experiencing extreme losses that may signal early tipping points, often linked to sea ice decline. Notably, Svalbard glaciers lost ~60 billion tons of ice in 2024, exceeding the annual ice loss from the entire Greenland Ice Sheet (Schuler et al., 2025). Such rapid glacier retreat further transforms local ecosystems and poses challenges for regional communities reliant on glacial meltwater.

Permafrost thaw

Permafrost thaw in northern Scandinavia causes ground instability, though impacts in Northern Europe are more limited than in North Asia and North America due to fewer settlements, lower ground ice content and better infrastructure maintenance (Hjort et al., 2022). NEU would likely experience the most significant impacts simply because that's where the permafrost is located - primarily in northern Scandinavia. Infrastructure damage in northern Norway, Sweden and Finland from ground instability could require massive adaptation investments or community relocation (Ramage et al., 2021). Traditional livelihoods of Indigenous populations and reindeer herders face disruption from changing landscape stability. Permafrost thaw causes changing landscapes and ecosystem shifts, including wetland formation, altered tundra vegetation and disrupted habitats for migratory birds, caribou and other Arctic wildlife (Berteaux et al., 2017; Jones et al., 2015; Keuper et al., 2012; Post et al., 2009), while infrastructure including buildings, roads and energy networks (such as pipelines) in permafrost regions face similar threats from ground instability. CEU and MED would have no direct permafrost impacts, experiencing only global carbon feedback effects.

Boreal forest shifts

NEU may experience critical impacts with major albedo changes documented and wildfire smoke health impacts (El Garroussi et al., 2024). Forest-agriculture transitions in Fennoscandia could occur with wildfire risks (Kelly et al., 2024; Rolstad et al., 2017), while watershed changes and fire impacts on water quality may affect forest capacity for forest growth, carbon uptake and sequestration as well as infrastructure. Critical wildfire risks to infrastructure and forest industry disruption could occur, with Fennoscandian boreal forest ecosystem shifts and northward treeline movement potentially affecting energy infrastructure and biomass energy.

CEU could face major impacts through smoke drift from northern fires affecting air quality and economic disruption from reduced timber and biomass energy supplies, while forest-agriculture transitions in northern regions may create new land use pressures.

2.4.5.2 Africa

Major tipping point exposures

Africa faces severe impacts from AMOC collapse and West African monsoon disruption altering precipitation patterns, sea level rise affecting extensive coastlines, Coral reef die-off and ecosystem changes from global warming feedbacks. The continent's high dependence on rain-fed agriculture makes it particularly vulnerable to precipitation changes.

Changes in North Atlantic circulation (SPG and AMOC collapse) and monsoon disruption

AMOC collapse would likely trigger a southward shift of the Intertropical Convergence Zone and weaken the West African monsoon system, potentially dramatically reducing precipitation across parts of the Sahel and West Africa (Defrance et al., 2017, 2020; Held et al., 2005). Collapse of deep convection in the subpolar gyre can also lead to significant weakening of the West African monsoon in several models (Swingedouw et al., 2021), creating an additional pathway through which North Atlantic circulation changes can affect the region beyond full AMOC collapse.

West Africa (WAF) could face the most severe impacts, with AMOC collapse potentially causing substantial Sahel rainfall reductions (Steinert et al., 2025; Defrance et al., 2017, 2020). The southward shift in tropical precipitation zones would create severe agriculture, ecosystem and livelihood disruptions affecting 400+ million people dependent on West African monsoon patterns (Sylla et al., 2018; Sultan and Gaetani, 2016). The West African monsoon would be disrupted with shorter wet and longer dry seasons and less overall rainfall, following the same global pattern affecting other Northern Hemisphere monsoon systems (Ben-Yami et al., 2024; Ben-Yami et al., 2023). The AMOC is strongly connected to precipitation over the Sahel, a region that has experienced at least five successful military coups since 2020, suggesting potential climate-political stability linkages (Ben-Yami et al., 2024; Kipo-Sunyehzi & Lambon, 2025; Larémont, 2021; Mulitza et al., 2008; Neupane & Cook, 2013; Peterson, 2024; Surazu, 2024; Taruvinga, 2023).

Extended dry periods would stress savanna ecosystems and agricultural systems, while irregular intense rainfall events would generate erosion and flooding that damages both natural habitats and human settlements. Primary water sources for hundreds of millions may be disrupted (Omotoso and Omotayo, 2024; Omotoso et al., 2023; Diallo et al., 2016), while Sahel ecosystem shifts between forest and grassland states could occur as precipitation patterns change fundamentally. Hydroelectric generation may be severely affected by precipitation variability, while dust storm frequency would likely increase, affecting air quality across the region.

East Africa (EAF) may face altered Indian Ocean circulation patterns related to AMOC collapse that could disrupt monsoon reliability and affect agricultural productivity across Ethiopia, Kenya and Tanzania. Highland agriculture for 200+ million people depends on monsoon rains (Muema et al., 2023; Thornton and Herrero, 2015; Thornton et al., 2010, 2014; Jones and Thornton, 2009; P K Thornton et al., 2009; Philip K. Thornton et al., 2009) that could be significantly disrupted and major river systems dependent on monsoon precipitation may face disruption (Nooni et al., 2025; Palmer et al., 2023; Richardson et al., 2022; Ficchì et al., 2021). Highland forest and grassland ecosystems could be severely affected and hydroelectric generation severely impacted. Southern Africa (SAF) would likely experience limited direct AMOC impacts, primarily through marginally elevated Southern Hemisphere warming and altered global circulation patterns that may affect regional agriculture and water resources through monsoon teleconnections.

Sea level rise from ice sheet collapse

Ice sheet collapse would accelerate sea level rise rates substantially beyond current projections with the potential for multi-meter rise over centuries (Siahaan et al., 2022; Stokes et al., 2022; Payne et al., 2021; Golledge, 2020; Dutton et al., 2015; Bamber et al., 2009; Dowdeswell, 2006; Alley et al., 2005) that could disproportionately affect low-lying coastal areas (Brown et al., 2018; Nicholls and Cazenave, 2010; Harvey and Nicholls, 2008), with additional impacts from increased storm surge and coastal erosion (Lenton et al., 2023). WAF may face critical threats with cities like Lagos, Accra and Dakar potentially severely threatened. Coastal agricultural areas and river deltas could be flooded, while the Niger Delta oil infrastructure may be severely threatened. The World Bank estimates that erosion, flooding and pollution already cause $3.8 billion in damages annually in just four West African countries (Benin, Côte d'Ivoire, Senegal and Togo), suggesting massive economic vulnerability to larger sea level rise (Croitoru et al., 2019).

EAF could face major impacts on coastal agricultural areas, with ports like Dar es Salaam and Mombasa potentially threatened, disrupting transport infrastructure. Saltwater intrusion into coastal aquifers may affect water resources, while coastal and marine ecosystems could be altered. SAF may experience coastal agricultural area impacts, with cities like Cape Town and Durban potentially threatened by sea level rise, creating significant infrastructure and economic challenges.

Coral reef die-off

The Fourth Global Coral Bleaching Event, declared in April 2024, has affected 83.8 per cent of the world's coral reef area as of May 2025, with mass bleaching documented in at least 83 countries and territories - the most widespread bleaching event ever recorded (NOAA Coral Reef Watch, 2024, 2025; World Economic Forum, 2025; Goreau and Hayes, 2024; Reimer et al., 2024). This demonstrates that coral reefs have crossed the estimated 1.2°C tipping point threshold and are now in an overshoot state requiring urgent policy action to reduce stressor levels below critical thresholds (Pearce-Kelly et al., 2025).

Mass coral mortality events repeated more than twice per decade give insufficient time for recovery of impacted populations and ecological function (Hughes, Anderson, et al., 2018; Hughes, Kerry, et al., 2018), with repeated bleaching preventing recovery through failure of reproduction, dispersal, recruitment and growth. The potential for significant thermal refugia is increasingly doubtful (Pearce-Kelly et al., 2025; Dixon et al., 2022; Setter et al., 2022), as very few reef areas are predicted to remain below tipping thresholds of all key stressors. Reefs that survive will have different community structure with much less diversity in coral species (Hughes, Kerry, et al., 2018), as the 'reef to rubble' phenomenon causes coral colonies to fragment and transition to rubble (Kai L Kopecky et al., 2023; Kai L. Kopecky et al., 2023; Kenyon, Doropoulos, et al., 2023), representing ecosystem transformation to new states that are difficult to recover from. Recent observations during the latest global bleaching event show greater sensitivity in taxa previously thought resilient (Byrne et al., 2025).

WAF, EAF and SAF would all face critical impacts from coral reef collapse, with coastal communities across these regions affected by the loss of reef fisheries that provide essential protein sources for millions (Obura et al., 2022; Hicks et al., 2019). Reef-dependent coastal fisheries would be eliminated, creating severe food security crises, while the loss of natural coastal protection from reef systems would increase storm damage risks to major cities and critical infrastructure including ports and transport networks. WAF's coral systems may collapse with significant biodiversity loss, while EAF and SAF would experience similar patterns of fishery collapse affecting coastal food security (Obura et al., 2022; Cinner et al., 2012). However, coral resilience varies significantly across African waters. While Atlantic and Indian Ocean coral systems face severe vulnerability under current warming trajectories, Red Sea corals have demonstrated surprising resilience to thermal stress, potentially serving as important refugia (Eladawy et al., 2022; Osman et al., 2018; Fine et al., 2013; van Hooidonk et al., 2013). This contrast between vulnerable and resilient coral populations highlights the critical importance of protecting climate-adapted reefs for future ecosystem recovery efforts across the region.

2.4.5.3 Asia

Major tipping point exposures

Asia faces impacts from monsoon disruption, sea level rise threatening densely populated coasts, permafrost thaw in northern regions, Coral reef die-off in tropical waters, boreal forest shifts and shifting precipitation patterns from global circulation changes.

AMOC collapse and monsoon disruption

AMOC collapse could disrupt global circulation patterns, creating a broad reorganization where the Southern Hemisphere becomes wetter while the Northern Hemisphere becomes drier, potentially affecting both the South Asian and East Asian monsoon systems through altered atmospheric circulation and ocean temperatures (Lenton et al., 2023). These changes reflect fundamental shifts in tropical precipitation zones, with the West African, Indian Summer and East Asian monsoons experiencing shorter wet seasons, longer dry periods and reduced overall rainfall (Ben-Yami et al., 2024; Ben-Yami et al., 2023). Paleoclimate evidence from the Okinawa Trough demonstrates that ITCZ migration significantly modulates East Asian monsoon systems, with southward ITCZ shifts correlating with weakened winter monsoon patterns, providing geological precedent for how AMOC-driven ITCZ changes can affect regional monsoon variability (Zheng et al., 2014).

Pacific circulation undergoes substantial modification as warming south and cooling north of the Equator alters El Niño-Southern Oscillation behavior. ENSO patterns shift eastward with warming signals becoming more geographically confined, while ENSO periods become more regular and predictable, fundamentally changing global weather variability patterns (Williamson et al., 2017)

South Asia (SAS) may face major impacts with South Asian monsoon weakening, potentially affecting regional temperatures and agriculture for 2+ billion people dependent on monsoon systems (Ben-Yami et al., 2024; Rehman et al., 2024; Chandio et al., 2023; Zhao et al., 2023; Wassenburg et al., 2021; Sandeep et al., 2020; Christensen et al., 2019; Amrith, 2016; Mohtadi et al., 2016; Turner and Annamalai, 2012; Lal et al., 2011). Primary water sources for billions of people may be disrupted (Dagdeviren et al., 2021; Amrith, 2016), while urban areas could be severely affected by monsoon variability. All major ecosystems depend on monsoon precipitation patterns and disruption would affect regional ecosystem productivity. Hydroelectric generation and cooling demand are potentially critically impacted, while altered circulation patterns linked to AMOC weakening would stress both terrestrial and marine systems across the region through temperature and precipitation regime changes.

East Asia (EAS) could see limited direct AMOC impacts, though some Pacific teleconnection effects may occur affecting monsoon patterns and agricultural productivity for 1.5+ billion people. Southeast Asia (SEA) may experience major impacts with altered monsoon circulation, potentially affecting regional temperatures and monsoon changes that could affect rice production and other agriculture, threatening food security for 600+ million people (Zhang et al., 2022; Loo et al., 2015; Buckley et al., 2014; Redfern et al., 2012; Wassmann et al., 2009). North Asia (NAS), West Asia (WAS), Central Asia (CAS) and the Tibetan Plateau (TIB) would likely experience limited direct impacts from AMOC collapse, primarily through teleconnections and altered global circulation patterns.

Sea level rise from ice sheet collapse

Long-term multi-meter sea level rise (Siahaan et al., 2022; Stokes et al., 2022; Payne et al., 2021; Golledge, 2020; Dutton et al., 2015; Bamber et al., 2009; Dowdeswell, 2006; Alley et al., 2005) could have severe impacts on Asian coastlines due to high population density in low-lying areas and extensive delta regions vulnerable to inundation (Nicholls and Kebede, 2012; Nicholls and Cazenave, 2010; Harvey and Nicholls, 2008; Nicholls and Tol, 2006). EAS may face critical threats with research indicating 78 million Chinese live in low-elevation cities vulnerable to sea level rise, while major cities, including Shanghai and other megacities could be severely threatened (WEF, 2025; Ao et al., 2024). The Yangtze Delta and coastal ecosystems may be lost, with coastal energy infrastructure potentially severely threatened.

SAS could experience critical impacts with research indicating that even a 0.5-meter rise would result in loss of 11 per cent of Bangladesh's land area, potentially displacing up to 15 million people and fouling drinking water due to salinity intrusion (Islam et al., 2025; WEF, 2025; Becker et al., 2020; Hossain et al., 2020; Shammi et al., 2019; Bose, 2013). The Ganges-Brahmaputra Delta, where 90 per cent of Bangladesh's rice production occurs, may be severely affected. Major cities, including Mumbai and Dhaka, could be severely threatened, while the Sundarbans and other delta ecosystems may be lost. SEA may face critical threats with the Mekong Delta (50 per cent of Vietnam's rice production) potentially severely affected and major cities, including Bangkok, Ho Chi Minh City and Jakarta could be threatened.

Coral reef die-off

SEA and the Coral Triangle region may face devastating impacts, as this area contains the highest marine biodiversity globally and supports over half a billion people for their livelihoods and over a quarter of marine species. Complete coral collapse could eliminate critical coastal protection and fisheries supporting 150+ million people in the region, with economic losses potentially exceeding $75 billion from tourism and fisheries collapse (Hughes et al., 2017). The simplification of reef structures will have adverse impacts on the thousands of species that rely on the complex three-dimensional structure of reefs, fundamentally altering the ecosystem services reefs currently provide.

EAS could face major impacts in southern regions with reef-dependent fisheries potentially lost in the South China Sea and loss of coastal protection for southern coastal cities. SAS may experience critical impacts with massive coastal populations dependent on reef fisheries for protein and loss of coastal protection that could increase storm surge risk for densely populated coasts. WAS could face critical impacts as Red Sea and Persian Gulf coral systems are among the most biodiverse globally, with reef-dependent fisheries potentially lost and major food security impacts for Gulf states.

Boreal forest shifts

NAS could face critical impacts with albedo changes documented and with stronger warming in the boreal region in Russia than in the global mean (Schaphoff et al., 2016) and extensive wildfire smoke. Massive forest-agriculture potential may exist but wildfire risks and soil constraints could limit development (Vallotton and Unc, 2024; Eckdahl et al., 2023; Altdorff et al., 2021; Walker et al., 2019). Critical major watershed changes across Siberia may occur, with extensive wildfire risks to Siberian infrastructure and transportation networks. Massive Siberian boreal ecosystem transformation, affecting the world's largest terrestrial carbon storehouse, could have disproportionate global climate impacts (Fu et al., 2023; Bradshaw and Warkentin, 2015; Gauthier et al., 2015).

EAS may experience impacts with high-altitude or northeastern boreal forest changes and regional warming, while forest-agriculture transitions and watershed changes could occur in forested regions. SAS, SEA and WAS would likely experience limited direct impacts from boreal changes, primarily through global carbon feedback effects.

Permafrost thaw

NAS would likely experience the most critical impacts, with warming amplification documented (Schaphoff et al., 2016). Major hydrological changes across Siberia may include thermokarst lake formation and drainage, while extensive infrastructure damage across Siberian development could affect cities, roads and railways. Oil and gas pipeline infrastructure may be severely threatened, with extraction facilities potentially damaged.

CAS and TIB could face major impacts from high-altitude permafrost thaw, which is projected to degrade by up to 86 per cent across the Tibetan Plateau during 2020–2100, reducing surface water runoff and intensifying subsurface storage - thus exacerbating water shortages, particularly during drought seasons (T. Wang et al., 2023). Permafrost's role in regulating soil moisture and groundwater–surface water dynamics is critical to the hydrology of Asia's major river headwaters, affecting water availability for billions downstream (Gao et al., 2021). Additionally, thaw-driven changes in groundwater transit times alter dissolved organic carbon processing in headwater regions, impacting biogeochemistry and water quality (Sun et al., 2021). In the Yangtze source region, changes in freeze–thaw cycles are shifting seasonal runoff and sediment patterns, posing risks to water quality and river-dependent systems (Li et al., 2023). Mountain agriculture and pastoral activities are particularly vulnerable to these changes in soil stability and water availability. Permafrost thaw also poses broader environmental hazards: as the frozen ground loses stability, legacy industrial contaminants—including heavy metals and hydrocarbons—at thousands of Arctic sites may be released into ecosystems (Langer et al., 2023). SAS, SEA and WAS are likely to experience more limited direct impacts from permafrost thaw, though indirect consequences through hydrological changes and global feedbacks remain important.

Amazon dieback

Recent climate network analysis reveals significant teleconnections between Amazon rainforest changes and Asian climate systems, with the Amazon exhibiting strong negative correlations with Tibetan Plateau snow cover through a robust atmospheric pathway that propagates changes in approximately 15 days (Liu et al., 2023). The Amazon's role extends beyond regional food systems through atmospheric teleconnections that synchronize climate extremes globally, with precipitation-related indicators showing negative correlations (-0.54 to -0.20) between Amazon changes and the Tibetan Plateau, potentially affecting water resources for billions dependent on Asian river systems fed by Tibetan glaciers and snow. Amazon dieback creates cascading hydrological impacts through disrupted atmospheric moisture transport, with the identified teleconnection pathway suggesting that Amazon forest loss could affect snow cover and water storage in the "Third Pole," impacting water security for populations across South and East Asia dependent on glacier-fed river systems, while temperature-related indicators show correlations as high as 0.92 between the Amazon and Tibetan Plateau regions (Liu et al., 2023).

Mountain glaciers

Mountain glacier tipping dynamics will lead to glacial lake outburst flood (GLOF) hazards across South Asia (SAS), the Tibetan Plateau (TIB), and Central Asia (CAS), where accelerating ice loss destabilizes thousands of moraine-dammed lake systems. SAS contains over 15,000 glacial lakes with more than 2,000 classified as potentially dangerous due to rapid glacier retreat rates of 10-60 meters per year (Veh et al., 2020; Bajracharya and Mool, 2009), while TIB's 47,000+ glacial lakes represent the largest global concentration of GLOF risks, with GLOF frequency exhibiting a significant increasing trend since 1980 and intensified activity in southeastern Tibet (T. Zhang et al., 2023). CAS mountain ranges contain numerous unstable glacial lakes posing immediate threats to downstream communities (Petrov et al., 2017). Historical catastrophes including SAS's 2013 Kedarnath floods, the 2016 Gongbatongsha GLOF in TIB that destroyed hydropower infrastructure 40 km downstream, and CAS's 2002 Dasht lake outburst demonstrate how glacier system collapse can trigger civilizational-scale impacts (D. Zhang et al., 2023; Allen et al., 2016). Crossing glacier tipping thresholds creates irreversible GLOF risk increases as new lakes form faster than natural drainage systems can establish stable outlets, with approximately large swathes of land at risk from potential GLOFs across these regions, threatening water security for billions of people downstream and infrastructure investments worth hundreds of billions of dollars (T. Zhang et al., 2023; Immerzeel et al., 2020).

2.4.5.4 North America

Major tipping point exposures

North America faces cooling from AMOC collapse, permafrost thaw in northern regions, changing precipitation patterns affecting agriculture, sea level rise impacts on extensive coastlines, boreal forest ecosystem shifts and monsoon disruption.

AMOC collapse

AMOC collapse could cool the North Atlantic region while disrupting storm tracks and altering precipitation patterns across North America through changes in atmospheric circulation patterns (Bellomo and Mehling, 2024; Jackson et al., 2023; Woollings et al., 2012). The sea-ice amplification mechanisms and storm track intensification patterns described for Europe would similarly affect Eastern North America.

Eastern North America (ENA) may experience regional cooling (1-3°C) along the Atlantic coast with increased temperature variability that could affect agriculture and energy systems. Following the same storm intensification patterns seen in Europe, Eastern North America would experience altered storm tracks and increased coastal vulnerability. Accelerated coastal flooding may threaten Boston, New York, Philadelphia, Washington DC and Miami with 20-30cm additional sea level rise beyond the global mean documented along the eastern seaboard (Goddard et al., 2015; Ezer et al., 2013). The disrupted jet stream would create more frequent blocking patterns similar to those affecting Britain, leading to prolonged cold snaps and altered precipitation timing.

Marine ecosystems from Florida to Maine would face fundamental restructuring as a weakening of the AMOC alters water temperatures and nutrient distribution. Modelling studies suggest that AMOC disruption may collapse North Atlantic plankton stocks by more than 50 per cent, substantially lowering export productivity (Schmittner, 2005). The strongest decreases in marine biomass are found in the North Atlantic Ocean with decreases as large as 30 per cent over the 21st century, while species important for fisheries would decrease locally up to 17 per cent, affecting both ecosystem functioning and the services these ecosystems provide (Boot et al., 2025). These compound effects would overwhelm existing coastal defense infrastructure designed for historical storm patterns, while offshore wind patterns potentially changing and reduced cooling demand but increased heating demand.

Western North America (WNA) would likely experience minimal direct temperature impacts, with slight cooling in the Pacific Northwest, though indirect impacts through altered Pacific climate patterns may occur. Central North America (CNA) could face limited direct temperature impacts, with some cooling in the Great Lakes region, while altered precipitation patterns may affect Midwest agriculture and Great Lakes water levels could be potentially affected by regional climate changes. Modelling studies suggest that AMOC weakening and the associated southward displacement of the Intertropical Convergence Zone (ITCZ) may weaken the North American Monsoon system (Ma et al., 2024; Chemison et al., 2022; Parsons et al., 2014). Reduced monsoon rainfall would affect northern Mexico and the U.S. Southwest directly, while also altering teleconnections into the Great Plains. Such shifts could exacerbate drought risk in the Midwestern grain belt, compounding agricultural disruptions already expected from altered storm tracks and increased climate variability.

Alaska/N.W. Canada (ALA) may experience reduced Arctic warming due to decreased northward heat transport, with Arctic Ocean circulation changes that could affect sea ice formation and alter freshwater balance.

Subpolar gyre

Collapse of convection in the North Atlantic subpolar gyre would fundamentally alter regional oceanography with cascading effects on food security, economic stability and infrastructure resilience. The system is vulnerable to interactions with AMOC weakening, creating compound circulation failures. ENA could face major food security impacts through collapse of Atlantic fisheries and altered agricultural conditions from changed coastal climate. Critical infrastructure along the Atlantic seaboard may face increased extreme weather risks from altered storm patterns. CGI may experience severe economic impacts from fisheries collapse in the Grand Banks and other critical areas supporting regional economies. National security implications include resource conflicts over disrupted marine resources and potential displacement from affected coastal communities.

Permafrost thaw

ALA would likely experience amplified Arctic warming enhanced by global permafrost-carbon feedback and regional Arctic amplification (Ward Jones et al., 2022), with extensive infrastructure damage including buildings, roads and pipelines damaged by ground instability (Hjort et al., 2022), with documented loss of life (Gibson et al., 2021; Miner et al., 2021). Climate-driven expansion of northern agriculture must consider permafrost interactions and cultivation risks (Ward Jones et al., 2022). Traditional food systems face disruption as climate-driven changes affect the ability to sustain natural diets and store food, impacting the livelihood and health of Arctic communities, with ice cellars experiencing thermal instability under warming conditions (Maslakov et al., 2022). Ecosystem changes - such as shifts in wetland formation and species habitat shifts - could be possible (Jin et al., 2021; Chin et al., 2016). Emergent biogeochemical risks include the release of biological, chemical and radioactive materials sequestered in permafrost for tens to hundreds of thousands of years, potentially disrupting ecosystem function and endangering human health (Miner et al., 2021). Mercury releases from thawing permafrost could reach levels comparable to current global anthropogenic emissions by 2200, with fish mercury concentrations potentially exceeding EPA guidelines by 2050 under high emissions scenarios (Schaefer et al., 2020).

Eastern Canada/Greenland/Iceland (CGI) could face major impacts with regional warming amplification from carbon feedback and buildings and infrastructure in permafrost zones potentially severely damaged. Arctic coastal erosion is projected to increase dramatically, with erosion rates doubling to tripling by 2100, accelerating coastal retreat through the combined effects of permafrost thaw, sea-level rise and increased wave action (Nielsen et al., 2022). This coastal permafrost thaw contributes additional complications as coastal erosion releases 6.9-17.2 TgC annually by century's end, with the link between coastal permafrost thaw, sea-level rise and coastal erosion creating accelerating feedback loops (Creel et al., 2024; Z. Wang et al., 2023; Nielsen et al., 2022). WNA, CNA and ENA would likely experience limited direct impacts from permafrost thaw, primarily through global warming amplification from Arctic permafrost-carbon feedback effects.

Sea level rise from ice sheet collapse

Long-term multi-meter sea level rise from ice sheet collapse (Siahaan et al., 2022; Stokes et al., 2022; Payne et al., 2021; Golledge, 2020; Dutton et al., 2015; Bamber et al., 2009; Dowdeswell, 2006; Alley et al., 2005) could affect all coastal regions, with regional variations in impacts due to land subsidence, ocean currents and local factors (Lenton et al., 2023). ENA may face critical threats with major US coastal cities including Miami, New Orleans and New York potentially facing severe flooding from multi-meter sea level rise. Research indicates that in the United States, where almost 40 per cent of people live in coastal communities, 4.2 million people could face displacement from 3 feet of sea level rise, while up to 13.1 million could face displacement from 6 feet of permanent inundation by 2100 (Hauer et al., 2016). The Chesapeake Bay, Delaware Bay and Everglades could be lost, while coastal nuclear plants, refineries and LNG terminals may be at risk.

WNA could face critical threats with major coastal cities (Vancouver, Seattle, San Francisco, Los Angeles) potentially severely threatened. Coastal agricultural valleys (Central Valley, Fraser Valley) may be severely impacted by saltwater intrusion, while coastal wetland and estuary loss could occur and coastal nuclear plants and refineries may be at risk. CNA would likely experience limited direct impacts from sea level rise due to its inland location. ALA may face major impacts with coastal infrastructure threatened by sea level rise, while Arctic marine ecosystems could be fundamentally altered.

Boreal forest shifts

ALA may experience critical impacts from boreal forest shifts, with albedo changes potentially causing regional warming amplification and wildfire smoke health impacts. Major watershed changes and wildfire impacts on water quality and supply could occur, while extreme wildfire risk to infrastructure is already documented, including spruce beetle infrastructure damage (~0.5 million hectares affected since 2016). Massive ecosystem shifts from boreal to mixed forest/grassland may affect species habitat, with critical wildfire risks to power transmission and oil pipeline infrastructure creating energy disruption.

CGI could face major impacts with albedo changes and wildfire smoke impacts on air quality. Forest-agriculture transitions may occur with new agricultural potential but wildfire risks, while watershed changes from forest transitions and fire impacts on water systems could affect infrastructure. Critical boreal forest ecosystem shifts and northward treeline expansion may occur, with major wildfire risks to energy infrastructure and changes in biomass energy potential. WNA may experience major impacts with enhanced wildfire activity documented and smoke health impacts, while severe wildfire risks to infrastructure are already documented and critical mountain forest ecosystem shifts and species migrations could occur. CNA and ENA would likely experience limited direct boreal forest impacts, though ENA may face major impacts with southern boreal forest changes and enhanced fire activity affecting forest-agriculture transitions in northern regions.

Ice sheet and glacier collapse

Beyond global sea level contribution, Greenland Ice Sheet collapse would create massive freshwater discharge fundamentally altering North Atlantic circulation. CGI could face critical impacts with disrupted regional climate systems and collapse of Atlantic fisheries from altered oceanography. ENA may experience major long-term threats to coastal cities and critical infrastructure from long-term multi-meter sea level rise, while immediate impacts could include disrupted AMOC affecting regional agriculture and energy systems. WNA and CNA would face primarily global sea level impacts on coastal infrastructure.

Ice sheet and glacier loss exposes new land, alters regional water regimes and amplifies local warming, with cascading effects on ecosystems and human settlements. Retreating glaciers, such as those in CGI, expose previously ice-covered land, altering freshwater and coastal water regimes while amplifying local warming through feedbacks like ice-albedo and melt-elevation effects (Marshall, 2021). Calving events from Greenland's marine-terminating glaciers release large icebergs into fjords and coastal waters, forming "armadas" that disrupt marine circulation (Moon et al., 2015), coastal habitats and local fisheries, while also representing a major component of ice mass loss. At the same time, the removal of ice mass causes isostatic rebound (Paxman et al., 2022), reshaping land surfaces and modifying terrestrial and freshwater systems, which has cascading effects on local communities and ecosystems.

WNA mountain glacier retreat creates GLOF and landslide risks as rapid warming pushes mountain ice systems beyond stability thresholds (Coe et al., 2017). Alaska's accelerating glacier retreat has created potentially dangerous glacial lakes, with the 2015 Taan Fjord event demonstrating how glacier destabilization can trigger tsunamis (Higman et al., 2018). Washington's Cascade Range glacier retreat creates new lake formations that could threaten Seattle's water supply infrastructure (Riedel et al., 2015), while California's Sierra Nevada exhibits similar patterns affecting water security for millions (Beltran-Peña et al., 2025). Mining infrastructure, hydroelectric facilities, and tourism operations face increasing vulnerability as glacier systems cross critical stability thresholds.

2.4.5.5 Central and South America

Major tipping point exposures

The region faces severe impacts from Amazon rainforest dieback, changing precipitation patterns from global circulation disruptions, sea level rise affecting extensive coastlines, Coral reef die-off, AMOC effects and monsoon changes. The Amazon region's role in global climate regulation makes its collapse particularly significant.

Amazon rainforest dieback

Amazon dieback relates to the disruption of close coupling between the land ecosystem and atmosphere, with the rainforest normally maintaining precipitation levels through rainfall recycling (Lenton et al., 2023). In the Amazon, around 30 per cent of the precipitating water has been evaporated within the region beforehand.

Amazon (AMZ) could face the most critical impacts with economic damages potentially between $957bn and $3,589bn over 30 years, mainly from changes in ecosystem services provision, compared to Gross Brazilian Amazon Product of approximately $150bn per year (Lapola et al., 2018). Amazon dieback would directly affect 30 million people living in the region, with Indigenous and traditional communities facing the most severe consequences as their livelihoods, cultural traditions and territorial integrity depend entirely on forest ecological stability. Since 2000, severe flood events now occur every four years instead of once every two decades, while prolonged droughts disrupt regional hydrological cycles and negatively impact food and water security (Jose A. Marengo et al., 2024; Jose Antonio Marengo et al., 2024; Souza et al., 2024).

Structural inequalities including poverty, ethnic marginalization, historical land dispossession and unequal access to adaptation resources compound these vulnerabilities. As traditional knowledge systems, ecosystems and forest-based livelihoods deteriorate, entire communities may lose their ability to sustain themselves, creating self-reinforcing cycles of socio-ecological vulnerability that drive forced displacement and migration (Quishpe et al., 2025; Pinho et al., 2015).

Regional warming from reduced evapotranspiration and increased fires may occur, while loss of precipitation recycling (25-35 per cent of rainfall) could alter hydrology (Sanchez-Martinez et al., 2025; Baker and Spracklen, 2022; Rocha et al., 2018; Zemp et al., 2017). Amazon deforestation creates contrasting seasonal precipitation effects: increased precipitation during wet seasons (+0.96 mm per month per percentage point forest loss) due to enhanced mesoscale circulation, but decreased precipitation during dry seasons due to reduced evapotranspiration, with effects weakening beyond 60 km from deforested regions (Qin et al., 2025). Deforestation also causes local temperature increases of 1-3°C, with effects extending to surrounding areas up to 60 km away (Butt et al., 2023). Wildfire risks may reduce river navigability, cause transportation disruption and potentially lead to biodiversity loss. Millions of Indigenous peoples and traditional communities could face collapse of forest-dependent livelihoods, while reduced hydroelectric potential and biomass energy disruption may occur alongside wildfire risks to infrastructure.

Southeast South America (SSA) faces the most severe downstream impacts as the La Plata basin receives approximately 24 per cent of its precipitation from Amazon moisture recycling (Beveridge et al., 2024), with cascading moisture recycling contributing 17-18 per cent to total precipitation over the La Plata basin (Z. Wang et al., 2023). Complete Amazon deforestation could reduce La Plata basin precipitation by 0.5 mm per day and decrease regional moisture transport by 22 per cent (Ruv Lemes et al., 2023). Amazon forest loss disrupts atmospheric moisture transport that provides the majority of precipitation to agricultural systems across Argentina, southern Brazil, Paraguay and Uruguay, creating catastrophic food security implications that extend far beyond the forest boundaries. With 40 per cent of the Amazon deforested, local annual precipitation would be reduced by 5–10 per cent in the Amazon basin, but cutting atmospheric moisture transport due to deforestation in climate-critical regions may induce a self-amplified drying process which would influence moisture arriving at the La Plata basin (Marengo et al., 2018).

Complete savannization combined with global warming would increase dry season length by 69 per cent and cause mean annual rainfall reduction of 44 per cent when averaged over the Amazon basin (Bottino et al., 2024). This near-complete dependence on Amazon moisture recycling makes SSA exceptionally vulnerable to agricultural collapse, water resource depletion and hydroelectric disruption.

West Coast South America (WSA) could face major impacts with altered precipitation patterns reaching Andean regions, as regions that depend on moisture recycled from the Amazon include the western flanks of the Andes Mountains (up to ~50 per cent of precipitation from Amazon moisture recycling) (Beveridge et al., 2024). The Amazon generates around half of its own rainfall by recycling moisture up to 6 times as air masses move from the Atlantic Ocean in the east across the basin to the west, with aerial rivers forming "flying rivers" that contribute to precipitation patterns within and beyond basin boundaries, particularly important for the tropical Andes and Western Amazon (Beveridge et al., 2024). Changed water availability from precipitation shifts may affect highland water resources that support millions across Peru, Ecuador and Colombia, with potential impacts on infrastructure and energy sectors.

Northeast Brazil (NEB) may experience impacts from Amazon precipitation changes, though the region faces multiple drought vulnerabilities. The semiarid lands of Northeast Brazil represent one of the most densely populated regions of the country, with rainfall variability together with land degradation creating vulnerability in rural areas, as most agriculture in this region is rainfed and deficient rainfall leads to severe drought impacts (Marengo et al., 2022) . The Central-Northeast region is among those most affected by multiple and widespread droughts, with drought characteristics varying significantly across Brazil (Gesualdo et al., 2024) . Amazon dieback may compound existing vulnerabilities in drought-prone regions already experiencing water scarcity, potentially affecting water infrastructure and hydroelectric potential, though the specific magnitude of Amazon moisture dependence for NEB requires further research.

Central America/Mexico (CAM) may face impacts through disrupted aerial rivers, as Amazon moisture transport affects precipitation patterns northward from the Amazon basin through atmospheric circulation pathways (Arraut et al., 2012).

AMOC collapse

AMOC collapse could alter global circulation patterns, affecting precipitation patterns across South America through changes in Atlantic circulation and atmospheric patterns (DiNezio et al., 2025; Steinert et al., 2025). The South American monsoon may intensify, particularly over southern Amazon regions (Ben-Yami et al., 2024; Ben-Yami et al., 2023). Central America/Mexico (CAM) may face major impacts with a southward shift of tropical rain belt potentially increasing heat stress and 10-30 per cent rainfall reduction during the growing season (Cerato et al., 2025) that could affect coffee, sugar and banana production (Varma and Bebber, 2019; Baez-Gonzalez et al., 2018; Ovalle-Rivera et al., 2015). Reduced wet season precipitation may affect water security for 50+ million people, while hurricane track changes could affect infrastructure planning and tropical forest stress from reduced precipitation may occur alongside mangrove systems affected by circulation changes.

AMZ could experience complex impacts with some forest areas potentially benefiting from increased precipitation while others may be stressed by flooding. Enhanced precipitation could benefit some agriculture but create flooding risks, while increased water availability may occur with altered seasonal patterns and flooding risks to infrastructure from enhanced precipitation (Gesualdo et al., 2024). NEB may face major impacts with altered precipitation patterns affecting drought-prone regions and increased drought risk in already water-stressed areas (Akabane et al., 2024; Nian et al., 2023), while water infrastructure could face stress and drought impacts on urban systems may occur.

SSA could see enhanced South American monsoon affecting heat patterns, with increased water availability in La Plata basin accompanied by flooding risks from enhanced precipitation (Chug et al., 2022; Parsons et al., 2014). However, La Plata basin precipitation is significantly influenced by Amazon moisture recycling through cascading moisture transport, with approximately 24-29 per cent of La Plata basin precipitation during the wet season originating from Amazon evapotranspiration (Zemp et al., 2014). This moisture recycling system involves evapotranspiration from Amazon forests that is transported southward and can be recycled multiple times along its trajectory before reaching the La Plata region (Chug et al., 2022). Enhanced vegetation growth may occur in some areas with altered flood plain ecosystems, while increased hydroelectric potential could exist alongside altered cooling/heating demands.

The South American monsoon would show opposite behavior to other monsoon systems, with rainfall increasing over the southern Amazon region in contrast to the drying experienced elsewhere (Ben Yami et al., 2024). This enhanced precipitation could benefit some agriculture but create flooding risks in areas not adapted to increased rainfall (Nian et al., 2023).

Shifts in the Intertropical Convergence Zone would shift the locations of prime productivity in the equatorial rainforests, as AMOC weakening affects tropical Atlantic sea-surface temperature patterns that influence the latitudinal position of the ITCZ and thus moisture inflow to South America (Boot et al., 2024; Ciemer et al., 2021). The altered precipitation patterns would affect both forest ecosystem composition and water availability, with complex implications for the millions of people dependent on Amazonian water and forest resources, as the region serves as a critical moisture source for continental precipitation through the Andes-Amazon-Atlantic pathway (DiNezio et al., 2025; Beveridge et al., 2024).

Sea level rise from ice sheet collapse

Long-term multi-meter sea level rise (Siahaan et al., 2022; Stokes et al., 2022; Payne et al., 2021; Golledge, 2020; Dutton et al., 2015; Bamber et al., 2009; Dowdeswell, 2006; Alley et al., 2005) could inundate coastal areas, with additional impacts from increased storm surge and saltwater intrusion into coastal aquifers and agricultural areas (Lenton et al., 2023). In CAM major cities (Veracruz, Cancun) and ports potentially may be severely threatened, while coastal agricultural plains could be flooded (Su et al., 2025; Schernewski et al., 2023; Tarolli et al., 2023; Bosserelle et al., 2022; Griggs and Reguero, 2021) and mangrove systems lost (Hülsen et al., 2025; Gilman et al., 2008). Major impact on coastal energy infrastructure may occur. A concrete example of energy infrastructure vulnerable to sea level rise in Central America is the Belize Coastal Road, which is a vital transportation link for energy distribution and is highly susceptible to inundation from even modest sea-level rise and associated storm surges, potentially disrupting power delivery to remote areas of the country (Nagy et al., 2019).

AMZ could experience major impacts on Amazon delta agricultural areas, with saltwater intrusion into the Amazon and Manaus deltas and the delta infrastructure potentially threatened. The critical Amazon delta ecosystem could be fundamentally altered, with major delta energy infrastructure at risk. NEB may face critical threats with major coastal cities (Recife, Salvador, Fortaleza) potentially severely threatened, while coastal agricultural areas could be flooded and coastal Atlantic forest remnants and mangroves lost.

WSA and SSA could face critical threats with major cities including Lima, Rio de Janeiro, Buenos Aires and Montevideo potentially facing flooding and saltwater intrusion (Su et al., 2025; Schernewski et al., 2023; Tarolli et al., 2023; Bosserelle et al., 2022; Griggs and Reguero, 2021) . Research indicates that 3 million people across Latin America and the Caribbean will be exposed to flooding from 0.43 meters of relative sea-level rise by 2100 under the RCP4.5 scenario, while over 4 million people will be exposed under the RCP8.5 scenario with 0.84 meters of sea level rise (Hauer et al., 2016; Reguero et al., 2015). Built capital valued at 334 billion USD is currently situated at elevations below the 100-year extreme sea level, with projections showing affected built capital could increase to 1,500–2,000 billion USD under future sea level rise scenarios (Reguero et al., 2015). Coastal agricultural areas may face saltwater intrusion affecting food production (Su et al., 2025; Tarolli et al., 2023).

Coral reef die-off

CAM could face critical impacts with the Caribbean (CAR) experiencing the most severe regional bleaching in history during 2023-2024, with Jamaica recording the highest sea surface temperature anomalies globally among reef systems (Goreau and Hayes, 2024). More than 90 per cent of hard corals bleached in some locations, with widespread mortality following. Heat stress in coastal communities from loss of reef fisheries income and loss of reef-dependent coastal fisheries affects food security for millions. Caribbean reefs generate approximately $8-10 billion annually through fisheries, tourism and shoreline protection, supporting over 15 per cent of GDP in several island nations (Pearce-Kelly et al., 2025). Critical loss of coastal protection from the Mesoamerican Reef system may increase hurricane damage, as healthy reefs significantly reduce wave energy (Guannel et al., 2016), providing essential coastal protection in this cyclone-exposed region. This second-largest barrier reef system globally potentially faces collapse with devastating impacts on the thousands of species that rely on complex three-dimensional reef architecture.

NEB may experience major impacts with coastal communities potentially affected by loss of reef fisheries and reef-dependent coastal fisheries lost, affecting protein sources. Major reduced coastal protection from reef systems could occur, with critical Brazilian reef systems collapse and endemic species loss as the only South Atlantic reef system. WSA and SSA have limited coral reef presence and so face minor impacts.

Mountain glacier

Tropical Andean glacier tipping creates acute GLOF risks as rapid ice mass loss destabilizes hundreds of moraine-dammed lakes (Somos-Valenzuela et al., 2016). Peru's Cordillera Blanca exemplifies how crossing glacier retreat thresholds triggers cascading lake instability (Emmer et al., 2020; Vilímek et al., 2005). Historical GLOF events such as the 1941 Huaraz disaster demonstrate how glacier system collapse can trigger society-scale impacts (Carey, 2005). Current glacier retreat rates of 30-50 meters annually are creating new unstable lakes while expanding existing ones beyond critical volume thresholds (Rabatel et al., 2013). The Quelccaya Ice Cap and other tropical glaciers face complete disappearance within decades, fundamentally altering regional hydrology and GLOF risk patterns (Thompson et al., 2013). Economic damages from major GLOF events can exceed GDP for affected regions, while upstream glacier tipping threatens water security for Lima's 10+ million residents (Bury et al., 2011).

2.4.5.6 Australasia

Major tipping point exposures

Australasia faces coral reef die-off around extensive coastlines, sea level rise impacts, changing precipitation patterns from altered global circulation, ecosystem shifts from multiple global changes and monsoon disruption effects.

Coral reef die-off

North Australia (NAU) could face critical impacts with the Great Barrier Reef experiencing catastrophic bleaching, with the Coral Sea region recording its warmest January-March temperatures in 400 years (Henley et al., 2024). The 'reef to rubble' phenomenon - where coral colonies fragment and transition to rubble (Kai L Kopecky et al., 2023; Kenyon, Doropoulos, et al., 2023; Kenyon, Harris, et al., 2023) - represents ecosystem transformation to new states that are difficult to recover from, with mass bleaching on the GBR becoming a biennial event (Byrne et al., 2025). Marine research indicates cascading effects on coastal protection and marine biodiversity may occur, with major Australian biodiversity loss as a World Heritage site could be lost. Critical reef tourism and fisheries represent major economic sectors at risk, with tourism revenue worth $6 billion annually and a major loss of coastal protection along Queensland coast.

South Australia/New Zealand (SAU) may face major impacts with coastal agricultural areas affected and coastal infrastructure threatened by long-term sea level rise, while coastal ecosystems could be altered, creating significant environmental and economic challenges.

Monsoon disruption and AMOC collapse

Changing global circulation patterns would alter precipitation patterns across Australia and New Zealand, potentially exacerbating existing aridity trends in interior Australia. For example, AMOC collapse would lead to wetter summers in northern Australia due to southward shifts in the Intertropical Convergence Zone and enhanced Indo-Australian monsoon systems, while simultaneously causing drier conditions year-round in New Zealand and southern Australia through altered storm tracks and weakened Southern Hemisphere westerlies (Du et al., 2025; Saini et al., 2025). Specifically, northern Papua New Guinea and Indonesia would receive less rainfall, while the Maritime Continent between 5°S and 6°N and southern Australian regions would display drier conditions throughout the year, with New Zealand experiencing reduced precipitation that could challenge agricultural productivity and hydropower generation (Saini et al., 2025).

NAU could face critical impacts with tropical agriculture critically dependent on monsoon precipitation and northern water resources critically dependent on monsoon (Du et al., 2025; Higgins et al., 2022), while urban areas could be severely affected by monsoon changes and tropical ecosystems critically dependent on monsoon patterns. Paleoclimate evidence indicates that Australian monsoon systems are sensitive to large-scale climate perturbations. For example, modelling of the 8.2 ka abrupt cooling event - caused by a weakening of the AMOC - suggests that northern Australia experienced shifts in precipitation due to a strengthened Indo-Australian summer monsoon and a southward shift of the Intertropical Convergence Zone (Du et al., 2025). Such responses indicate that both temperature and hydroclimate in northern Australia are strongly coupled to changes in global circulation patterns, highlighting the vulnerability of tropical agriculture, water resources and ecosystems to monsoon variability under both past and future climate perturbations. Increased rainfall in northern Australia could enhance agricultural productivity in regions that are currently underutilized due to water scarcity. However, the unpredictability of such changes poses challenges for long-term planning (Mai et al., 2025; Heidemann et al., 2023). Changes in precipitation patterns could strain existing infrastructure, especially in areas not designed to handle increased rainfall and can affect local ecosystems, potentially leading to shifts in biodiversity and the health of natural habitats (Heidemann et al., 2022; Marx et al., 2021).

Sea level rise from ice sheet collapse

NAU and South Australia/New Zealand (SAU) may face major impacts with coastal agricultural areas affected and coastal infrastructure threatened by long-term sea level rise, while coastal ecosystems could be altered, creating significant environmental and economic challenges.

2.4.5.7 Small Island Developing States

Major tipping point exposures

Small Island Developing States (SIS) face existential threats from sea level rise from ice sheet collapse, Coral reef die-off eliminating critical coastal protection and fisheries and global warming effects amplified by Arctic feedbacks. These nations represent the most vulnerable populations globally to climate tipping points, with many facing complete uninhabitability (Cooper et al., 2025; Vousdoukas et al., 2023; Leal Filho et al., 2021).

Sea level rise from ice sheet collapse

Long-term multi-meter sea level rise from Greenland and West Antarctic Ice Sheet collapse poses existential threats to low-lying island nations (Lenton et al., 2023). Many coral atolls and low-lying islands could face complete inundation, with even 1-2 meter rise (reached in the late 21st Century in IPCC AR6's high-impact storyline) making numerous island nations uninhabitable. Research indicates that most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding (Storlazzi et al., 2018).

Some islands may become uninhabitable well before complete submersion due to saltwater intrusion into freshwater supplies (Gingerich et al., 2017; Terry and Falkland, 2010), with "overwash events generally result in salty ocean water seeping into the ground and contaminating the freshwater aquifer" (Storlazzi et al., 2018; Gingerich et al., 2017). Soil salinization from saltwater intrusion reduces the productivity of working lands and can prevent crops from growing, affecting agriculture on these vulnerable islands (Su et al., 2025; Shokri et al., 2024).

Critical threats include complete loss of agricultural land for many atolls, complete freshwater contamination from saltwater intrusion and complete infrastructure loss for many islands. Economic research indicates costs as a share of GDP could reach 100 per cent+ for many island nations, rendering them uninhabitable (Dietz and Koninx, 2022). Complete loss of territory would trigger unprecedented questions of statehood and require total population relocation, creating new categories of climate refugees. The economic impacts would be devastating, with complete loss of tourism infrastructure and fishing industries, while creating massive displacement requiring international resettlement programs.

Coral reef die-off

Small Island Developing States face critical impacts as entire populations of many islands are completely dependent on reef ecosystems for survival. Reef fisheries represent the primary protein source for many small island populations, while reefs provide essential coastal protection from storm surge and wave action.

Complete coral collapse could eliminate critical coastal protection, representing an existential threat to low-lying islands that depend on reefs as natural breakwaters. The loss of reef-based fisheries would create severe food security crises, while the collapse of reef tourism would eliminate major economic foundations for many island nations. Cultural and biodiversity losses would be devastating, as coral reefs represent fundamental elements of island cultures and contain unique marine biodiversity found nowhere else on Earth. Current overshoot conditions mean that unless global temperatures return below 1.2°C with minimal overshoot (IPCC, 2018), coral reefs on any meaningful scale will be effectively lost, creating unprecedented challenges for island nation survival.

AMOC collapse and monsoon disruption

SIS are vulnerable to global circulation shifts triggered by AMOC collapse and monsoon disruption, despite not lying directly in the core regions of these tipping elements (Bellomo and Mehling, 2024). AMOC weakening would shift the ITCZ southward, altering tropical rainfall across the Pacific and Indian Oceans (DiNezio et al., 2025; Steinert et al., 2025). For many SIS in the Pacific and Indian Ocean basins, this could drive more erratic rainfall regimes, prolonged droughts, and intensified storm seasons. These changes would directly threaten freshwater availability, subsistence agriculture, and fisheries, which are already stressed by sea-level rise and saltwater intrusion. Monsoon disruption could further destabilize rainfall patterns that sustain ocean–atmosphere interactions critical for cyclone activity and regional climate regulation (Ben-Yami et al., 2024; Sandeep et al., 2020). For Caribbean SIS, changes linked to AMOC weakening may reduce hurricane frequency but increase storm intensity, amplifying risks to coastal infrastructure and tourism economies (Thirumalai et al., 2024; Bhatia et al., 2018; Cai et al., 2014). In the Pacific, altered ENSO behavior under AMOC collapse could increase the frequency of extreme drought–flood cycles, placing additional pressure on freshwater and food systems.

2.4.6. Conclusion

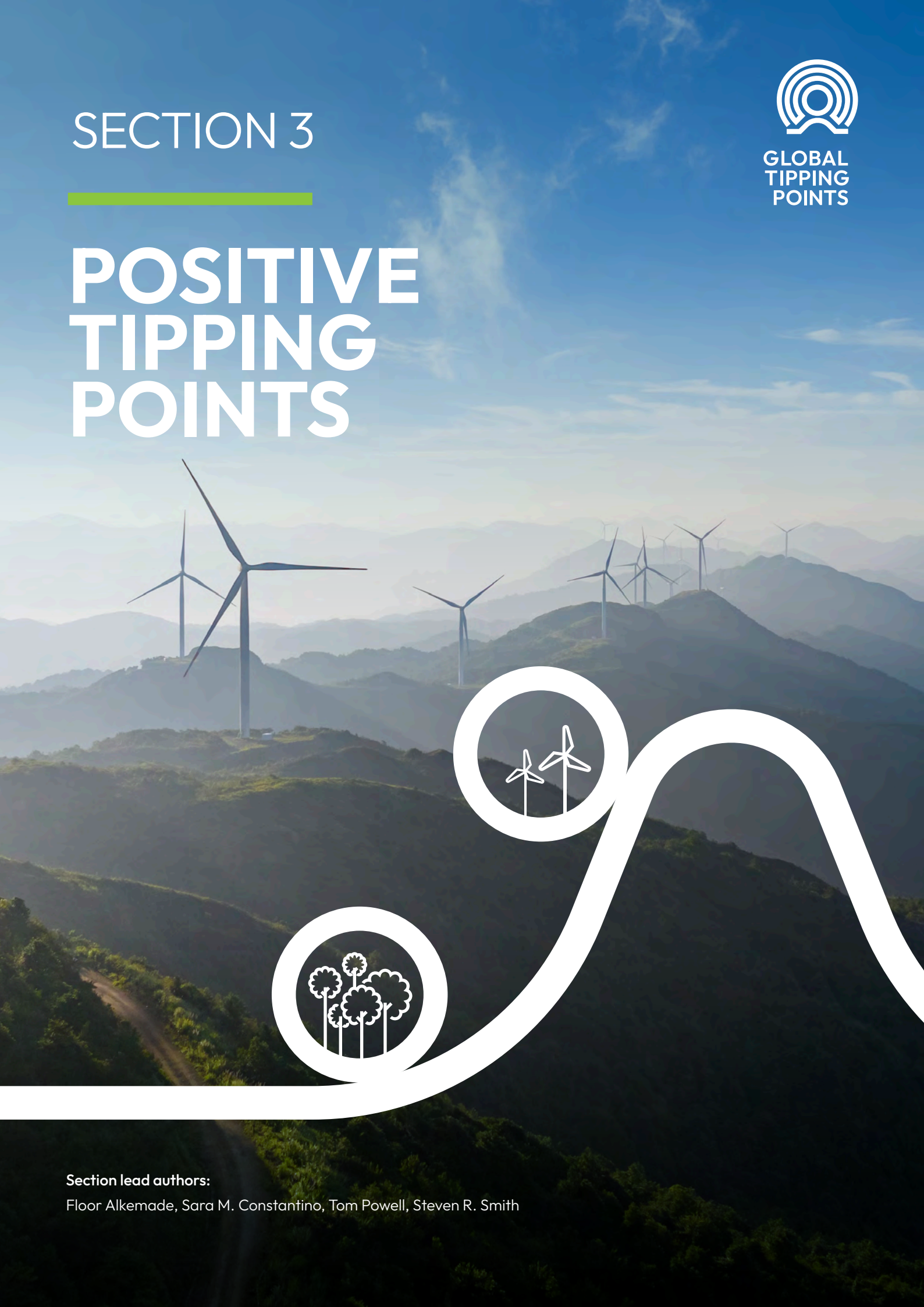
Our assessment finds that crossing Earth system tipping points poses profound systemic risks across nine critical domains - including food security, energy infrastructure, and economic stability - threatening billions of people worldwide. Tipping points constitute a pressing national and global security concern, as cascading stresses on food, water, and health systems could drive mass mortality, large-scale displacement, and severe economic losses if climate change remains unchecked. Yet the evidence base remains limited, underscoring the urgent need for dedicated research into the societal consequences of tipping point cascades.

The risks are unevenly distributed across regions. Small Island Developing States face existential threats from sea-level rise and eventual uninhabitability; South and Southeast Asia's more than three billion people depend on highly vulnerable monsoon systems; and Arctic communities face wholesale ecosystem transformation. In contrast, developed regions are more likely to encounter challenges through infrastructure disruption and economic shocks. Critical risks include ice-sheet loss for small islands and East Asia, monsoon disruption for South and Southeast Asia and Central America, AMOC collapse and rainfall shifts for West Africa, permafrost thaw and boreal forest loss in North Asia, AMOC collapse for Northeast America and Northwest Europe, and Amazon rainforest dieback across South America.

These findings highlight stark inequalities in exposure and preparedness. The most acute vulnerabilities lie in small island states, West Africa, Central America, and the Amazon basin - regions with the least capacity to adapt yet facing some of the gravest risks. Without urgent action to limit warming and strengthen resilience, Earth system tipping points could overwhelm societies and economies worldwide. Meeting this challenge requires not only rapid emissions cuts but also major investment in research and preparedness to understand and manage cascading impacts. Effectively managing these risks is essential to safeguard global stability, security, and human well-being in the decades ahead.

SECTION 3

POSITIVE TIPPING POINTS



Section lead authors:
Floor Alkemade, Sara M. Constantino, Tom Powell, Steven R. Smith

3.1 Identifying Positive Tipping Points

Authors: Steven R. Smith, Sara M. Constantino, Timothy M. Lenton, Ilona Otto, Nadia Ameli, Tom Powell, Floor Alkemade, Sebastian Villasante, Fenna Blomsma, Hatty Wylder-Hopkinson.

Reviewers: Iain Black, Owen Gaffney, Peter Lefort, Viktoria Spaiser, Caroline Zimm.

Key messages

- **Positive tipping points occur when reinforcing feedbacks in a system overwhelm balancing feedbacks, triggering self-propelling change towards a more sustainable state (see Figure 3.1.1).**
- **Policymakers can accelerate decarbonisation by prioritising technologies and behaviours that have the potential to positively tip.**
- **Easily imitable behaviours in which social influence plays a strong role (e.g. active travel) and highly modular, mass producible technologies (e.g. solar panels) have the greatest potential to be positively tipped.**
- **Deliberate actions can enable positive tipping by neutralising balancing feedback, promoting reinforcing feedback and helping make a desired change the most affordable, accessible and/or attractive option.**
- **Positive tipping points have already been crossed in the adoption of solar PV and wind power globally, in the adoption of electric vehicles, battery storage and heat pumps in leading markets and there is potential for them in various applications of green hydrogen, green ammonia and alternative proteins.**
- **Early opportunity signals can reveal a loss of resilience of an incumbent system and a window of opportunity for positive tipping, but better indicators are needed to understand tipping potential and proximities to tipping points.**
- **System interactions can create opportunities for positive tipping cascades whereby tipping in one sector (e.g., battery technology) can increase the likelihood of tipping in another (e.g., renewable energy).**

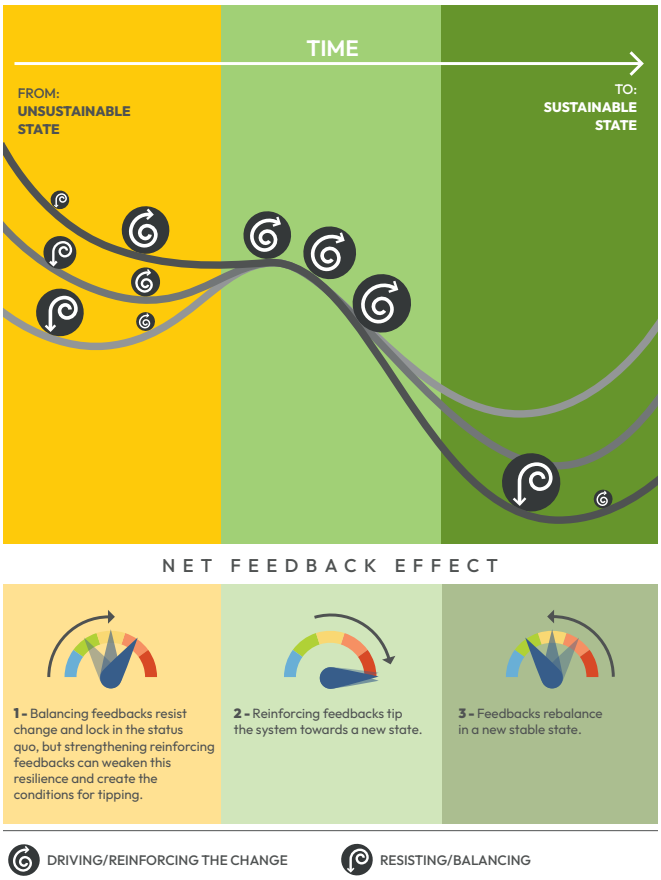


Figure 3.1.1. The ball-in-valley visual metaphor of positive tipping dynamics (Lenton et al., 2025. Reproduced with permission.

This report has made clear that vital parts of the Earth system may already have reached tipping points, others are closer than previously thought and they are interconnected. Humanity is now entering a danger zone of civilisational risk that goes beyond local damage or regional conflicts, which could impact global society's core functioning and future. We need to respond with unprecedented urgency to eliminate the drivers of Earth system tipping points (ESTPs) - primarily fossil fuel burning and nature degradation/loss - and scale up carbon removal (primarily through nature restoration), to limit overshoot of 1.5oC. This transformation needs to happen more than five times faster than current trends for a reasonable chance of limiting warming to well below 2°C (Lenton et al., 2025). Acceleration of this kind requires positive tipping points.

A tipping point is the point beyond which self-propelling change occurs in a system, giving rise to a qualitative change to an alternative stable state. In this report, 'positive' tipping points (PTPs) refer to tipping points in human systems that have the potential to eliminate or radically reduce the drivers of ESTPs or the high and increasing costs of climate change impacts and adaptation. The alternative, desired stable state may provide a host of other benefits in terms of nature and biodiversity, human health, energy security, democracy and economic productivity within planetary boundaries.

We acknowledge that positive is a value judgement based on the collective goal of achieving a sustainable and socially just future for all. Our approach, definition and use of the term are explained in the previous Global Tipping Points Report (GTPR) (Lenton et al., 2023). We also acknowledge that not all options are equally climate or nature positive. The most sustainable option is probably to avoid using a product or service in the first place. The next best option is to shift to less harmful products or services or improve their environmental performance. For example, although some countries may have already crossed a tipping point and significantly reduced the environmental impact of car travel by replacing petrol or diesel-powered cars with electric cars, an even better option would be to avoid car travel altogether, for example in favour of active travel (e.g., walking or cycling) or public transportation powered by renewable energy (OECD, 2025).

Central to the positive tipping points approach is the imperative for transformative change to be equitable or socially just, mindful that those least responsible for creating the threat of Earth system tipping points face the greatest peril. Consideration of who is being asked to change and where and how that change will be felt, are fundamental questions for all decision-makers. The positive tipping point action agenda needs to ensure diverse perspectives and representation, with a particular emphasis on the inclusion of marginalised voices, to ensure equitable and sustainable outcomes (Pereira et al., 2025).

A positive tipping point can manifest as a rapid phase-in of a desired, sustainable innovation (idea, social practice, or technology), or as a rapid transition away from an undesired, unsustainable incumbent (Allen and Malekpour, 2023) and the two can be interdependent (Turnheim and Geels, 2012).

While current responses are grossly insufficient, there are markets and sectors currently undergoing rapid transition. Solar power is growing exponentially, doubling its installed capacity every three years (although this global growth is highly skewed towards China, which accounted for 65% of additional capacity in 2024 (IRENA, 2025)). Electric vehicle (EV) sales increased 25% globally in 2024, even more in emerging markets (particularly for two and three-wheelers (Bloomberg Electric Vehicle Outlook 2025)), as lithium-ion battery prices continue to plummet. These rapid transitions are starting to reinforce each other (Nijsse et al., 2024). A second life for used EV batteries as energy storage and vehicle-to-grid (V2G) technology, are both helping renewable electricity to solve its supply/demand balancing problem and thereby lower its cost. Ever-cheaper renewable energy elevates the economic and environmental case for electric vehicles as well as for other renewable energy users, such as the production of green hydrogen, which in turn improves the viability of green steel, as well as green ammonia for fertilisers, shipping fuel and energy storage.

Furthermore, history provides countless examples - from the invention of the electricity grid to the abolition of slavery - in which change happened slowly at first, then all at once —due to the existence of positive feedbacks causing an initially gradual change to gain momentum and become self-reinforcing after a threshold was reached (Lenton et al., 2025).

There have been significant developments since the first GTPR was published in 2023. This update largely focuses on these, many of which are technological in nature. This does not imply that shifts in social behaviours, norms, beliefs or political economies are less unimportant. It reflects the fact that much of the research, policy design and capital in this area has been invested in technologies. We do discuss some behavioural options for reducing material and energy demand in overconsuming countries, but our treatment is not comprehensive. Our intended readers are primarily senior, decision-making 'insiders', but we do not ignore the role of 'outsiders' - activists, organisers and entrepreneurs - who make low-carbon technologies and behaviours politically and economically viable over years and sometimes decades of struggle. As the great systems thinker Dona Meadows herself argued, the most powerful transformation of all would be a shift to a new worldview and policy paradigm that measured progress and prosperity primarily in terms of wellbeing - human and ecosystem health - rather than wealth and the GDP. There are faint signs of hope in this regard, even in policy circles, but unfortunately not enough to warrant further discussion here.

The first significant development is that researchers have devised a framework for identifying positive tipping points and actions to trigger them (Lenton et al., 2025). This is summarised in the rest of this chapter and chapter 3.2. In this chapter, we identify the features that make a system likely to tip and apply this to identify systems with high PTP potential. In chapter 3.2, we discuss the enabling conditions, actions and actors that are key to accelerating tipping for systems along different phases of the tipping points process.

Second, there have been significant accelerations in key sectors. The overall progress is summarised in chapter 3.3, in which we provide update reports for 11 key sector transitions. Then, in chapter 3.4, we delve deeper into tipping dynamics related to renewable power and electrification of the energy system. Finally, in chapter 3.5, we investigate tipping dynamics in the food system, land-use and nature regeneration.

3.1.1 Identifying positive tipping potential

The concept of a positive tipping point is illustrated in Figure 3.1.1. Initially, well before the tipping point, balancing feedbacks within the system maintain the initial state/status quo (the ball is firmly in the lefthand valley). The stronger these balancing feedbacks are, the more resilient the current, unsustainable system to resist change (Schilling et al 2018). At the tipping point, reinforcing feedbacks within a system overcome the balancing feedbacks and can become strong enough to support self-propelling change. Change accelerates, then eventually slows as a new, qualitatively different state is reached (the ball settles into the righthand valley). Different balancing feedbacks arise that 'lock in' or stabilise the new system state. These might include new infrastructure, such as electric vehicle (EV) charging stations), new social norms, or new institutions such as EV lobbying groups and federations that consolidate and advance the interests of the EV industry and owners.

To identify whether a system has the potential for a positive tipping point it is important to understand something about its feedbacks, including the relative strength of balancing versus reinforcing feedbacks and how they influence adoption (Lenton et al., 2025; Mascia and Mills, 2018). The most fundamental reinforcing feedback is that the more people who adopt something new, the more people they can influence to also adopt it. This is called social contagion. It could simply involve people imitating one another, but often adopters learn about what they are adopting from each other. Another key reinforcing feedback is increasing returns, which occur if adoption increases the benefits (or lowers the costs) for subsequent adopters. This can happen, for example, because learning by doing improves the performance of a technology and makes it more attractive (e.g., the range of an electric car), or economies-of-scale make it more affordable, or the rollout of complementary technologies make it more accessible (technological reinforcement).

For example, the transition from internal combustion engine vehicles (ICEVs) to electric vehicles (EVs) is characterised by learning by doing, economies of scale and technological reinforcement. The more EVs and batteries that are manufactured, the better and the cheaper they get, making EVs a more affordable and attractive option. As more drivers switch to EVs there is a greater political and commercial incentive to invest in charging stations, which makes it more convenient to make the switch. There are also social influences and changing norms that can reinforce adoption, such as seeing neighbours driving EVs.

Changes in human societies occur within social networks. To understand how and why people choose new technological solutions and adopt new norms and behaviors, we need to know how and when these solutions spread within social networks, as well as how this spread is facilitated or blocked by different social structures and actors. Modelling and empirical studies that found that tipping in social networks is possible with a range of 10-43% adoption in the population, most commonly around 25% (Everall, 2025, Centola et al., 2018). This level is influenced by factors in the population such as trust, social proximity and the structure of social networks. Beyond the tipping point, the fraction of those adopting new norms or behaviors rapidly increases (Centola 2021).

However, before positive tipping can occur, these reinforcing feedbacks must overcome the balancing feedbacks and other factors that can strongly resist change. These range from well-funded misinformation and political lobbying campaigns funded by the fossil fuel industry and libertarian think tanks, to fossil fuel subsidies and other policies, to cost and inconvenience barriers for consumers (Tindall et al., 2022; Oreskes and Conway, 2010; Dunlap and McCright, 2015). These 'forces of climate delay' offer a narrative that some segments of the population find persuasive (Lamb et al., 2020; Cherry et al., 2024; Nisbett et al., 2024; McKie, 2021). The history of the tobacco industry's attempts to subvert public health/anti-smoking campaigns from the 1950s is instructive for the climate movement's current battle against those seeking to delay climate action (Malone, 2022).

The potential for PTPs is evident in recent case studies in personal transportation and the power sector (Sharpe and Lenton, 2021; Geels and Ayoub, 2023; Hoekstra and Alkemade, 2025). For example, the Norwegian car market passed a tipping point for the uptake of electric vehicles (EVs) around 2012 (Lenton, 2025), triggering an accelerating decline in sectoral emissions. Similarly, the uptake of solar photovoltaic power worldwide is estimated to have recently passed a tipping point and is set to become the dominant source of power by 2050 (Nijsse et al., 2023).

Policy and other interventions can create the enabling or threshold conditions for tipping to occur by weakening balancing feedbacks and/or strengthening reinforcing feedbacks. These enabling conditions may include making the desired innovation (idea, behaviour, technology) the most attractive, affordable and accessible option (Meldrum et al., 2023). For example, the transition from ICEVs to BEVs in Norway included several enabling conditions for positive tipping, including financial subsidies for purchasing BEVs, preferential treatment of BEVs (e.g., access to the carpool lane (Elbil, 2024)) and global improvements in the quality and affordability of batteries.

To inform effective strategies to promote PTPs it is critical to identify where and when PTPs are possible. This requires (1) defining the system of interest, (2) assessing its tipping potential and, if there is tipping potential, (3) assessing its current state (e.g. level of adoption).

Once this is understood, it is important to identify how to trigger PTPs. This involves identifying (4) key system leverage points and enabling conditions and (5) the sequence of actions needed to trigger the PTP. These steps are described in the flow diagram in Figure 3.1.2.

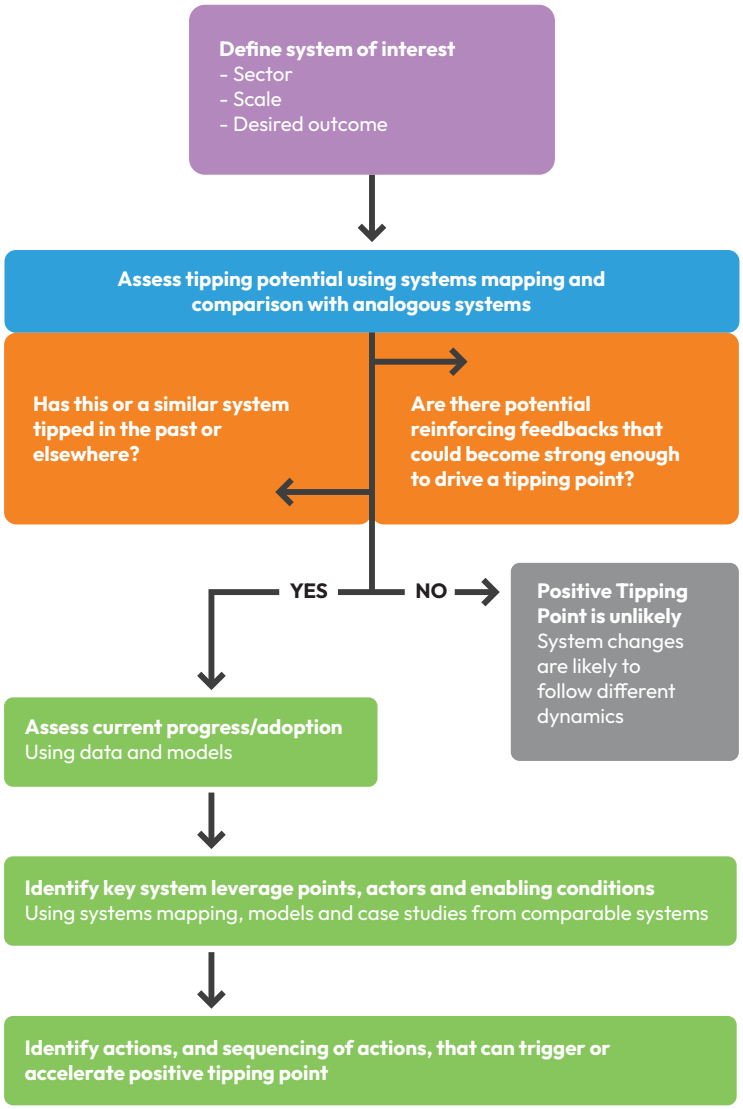


Figure 3.1.2. Simplified framework for identifying systems with potential for PTPs and for acting on those systems to bring about a transition to an alternative state (adapted from Lenton et al., 2025).

3.1.2 Defining the system of interest: actors and conflicting goals

The first step in understanding whether a system is likely to tip is to define the system of interest. This might be a specific sector, or it might be limited to a specific geographic area. For example, we might consider the global energy system or the UK car market as the system of interest.

Many different actors (e.g., policymakers, business leaders, community organisers) and actions can play a role in creating the conditions for positive tipping dynamics. For example, in the UK transport sector, policymakers at the national scale have brought in zero emission vehicle mandates for new cars by 2035; city level authorities have introduced low emission zones (LEZs) or clean air zones (CEZs) to tackle air pollution; community organisations have campaigned for pedestrianised streets and bicycle lanes; and businesses are investing in new research and manufacturing facilities for EVs, batteries and renewable power generation (Lenton et al., 2025).

However, different actors often have different goals—for example, rapid decarbonisation or social equality and wellbeing—and different visions for how to achieve those goals (e.g. market based approaches vs. regulation), or oppose them. They may also prioritise near-term changes over longer-term and harder to achieve changes. In the example of the UK transport sector, the ultimate goal might be to reduce car use altogether and to increase walking and biking, while the near-term goal may be to replace ICEVs with EVs (Behrendt, 2018).

Successful tipping dynamics depend, in part, on the irreversibility or resilience of the new desirable system. Hence, it is important to ensure public acceptance of tipping interventions to ensure they can withstand backlash (Pereira et al, 2024; EEA, 2024). Transitions, even as they meet important goals such as decarbonisation of transport, often create new winners and losers. Sometimes these groups are easy to identify upfront and those that become relatively worse off can be supported in the transition (e.g., reskilling workers in the oil and gas industry (Pollin, 2023), or compensating farmers for land-use changes (Kuhmonen, 2022)) to reduce resistance to change.

3.1.3 Assessing tipping potential

Once the system has been defined, one can assess its potential for a positive tipping point by examining similar systems, in the past or in other parts of the world, as well as mapping characteristics of the system (e.g. potential for reinforcing feedbacks). For example, the UK car market today is at a similar point in terms of EV market share to the Norwegian car market circa 2015. Norway has since undergone a rapid and near-complete transition to EVs. However, there are notable differences, including that Norway has no car manufacturers and generates almost all of its electricity using clean hydropower.

We introduced above some of the key reinforcing and balancing feedbacks that determine a system's tipping potential. Below we provide a more comprehensive list. The highest positive tipping potential occurs in systems where the relative strength of reinforcing feedbacks is high and balancing feedbacks can be weakened or neutralised.

First, reinforcing feedbacks include social contagion, increasing returns to adoption, investment pathways, positive political and policy feedbacks and discourses of positive climate action.

Social contagion describes a situation where adopters imitate and learn from one another (Rogers, 1962; Zeppini et al., 2014; Lenton et al., 2022). The adoption of a new technology, social norm, or behaviour makes it more likely that others will adopt it due to the power of imitation, conformity and social learning, the most studied example being the clustered adoption of neighbourhood rooftop solar PVs (Granovetter, 1978; Centola et al., 2018 Serra-Coch et al, 2023; Graziano & Gillingham 2014;).

Increasing returns to adoption describes systems where adoption increases the benefits (or lowers the costs) to subsequent adopters through increased accessibility of the innovation, or because of economies of scale or learning by doing that decrease prices. With **economies of scale** production rates increase faster than production costs, which lowers unit costs, which then increases demand, increasing the rate of production and so on. The more of something you produce, the cheaper it gets. Similarly, **economies of networks** occur when the value of a product or service increases the more people use it, for example a social media platform or an electric vehicle recharging network. **Technology reinforcement**: the more an innovation is used, the more additional technologies and practices emerge to complement it and make it even more valued/useful (Lenton et al., 2022) are a specific form of network externalities. **Learning by doing**: workers and firms continually learn from experience, improve processes and make efficiencies. This reduces costs by a fixed percentage for every doubling of production (according to Wright's Law), the more times you make something the better you get at making it (Yelle, 1979; Wright, 1936). Learning rates and cost reduction speeds are higher for modular technologies that are easier to mass produce (e.g., solar PVs, batteries and electric vehicles) and lower for technologies with higher degrees of design complexity and customisation (e.g., nuclear power plants, carbon capture and storage, or building retrofits) (Wilson et al., 2020; Malhotra and Schmidt, 2020).

Investment pathways - patterns of capital allocation that enable sustained financial flows into emerging low-carbon technologies and sectors - can help overcome financial lock-ins, reduce perceived risks and build market confidence, particularly in underinvested regions or markets. Early and well-aligned investments create positive feedback loops that reinforce other enabling conditions and accelerate transitions (Ameli et al 2025).

Positive political and policy feedbacks: the growth of stable, healthier, higher paying jobs in renewable energy, electrification, batteries, heat pumps and sustainable agriculture and the health benefits of cleaner air and waterways positively reinforces public and corporate support for more radical action (Lockwood et al., 2015). Related, positive policy feedback occurs when the falling costs of clean technologies or previous investments enable stronger public investment and policies for technology deployment and infrastructure (Jordan and Moore, 2020).

Discourses of climate action: Positive, hopeful stories of transformation, both real and imaginary, reinforce the belief that change at the required speed and scale is possible. Positive experiences and accounts of experimental places, projects and policies that prefigure the sustainable future we wish to create (e.g., Transition Towns) are highly motivational and can become self-propelling: "If it can happen 'there', why not 'here'" (Potential Energy Coalition, 2023; Rapid Transition Alliance, 2021; Raekstad and Gradin, 2020).

Balancing feedbacks and other factors that resist systemic change include lock-in, political and policy resistance and negative climate discourses.

Lock-in can take the form of institutional, infrastructural, technological, or psychosocial inertias in which habits, social norms, customs and beliefs are resistant to change. These inertias are reinforced by institutional structures, such as investment pathways that direct financial resources into existing systems and infrastructures, creating long-term commitments that constrain the adoption of alternative trajectories, or education and human resources structures such as curricula and professional standards that are designed for incumbent technologies (William and Bonvillian 2013).

Political resistance: climate change deniers and climate action delayers motivated by self-interest, libertarian ideology or a strategic interest in stoking populist, divisive narratives can build political coalitions to oppose change. These narratives are often centred on grounds of economic cost and loss of personal freedom/government interference (Coan et al., 2021; Lamb et al., 2020).

Policy resistance: policies that obstruct or resist clean innovation and change, such as the continuation of fossil fuel subsidies advocated by powerful incumbent lobbyists from the fossil fuel industry and weakening of policies due to concerns over financial costs and backlash from affected industries, groups or the general public (Jordan and Moore, 2020).

Discourses of denial/delay: the percolation and diffusion of mis/disinformation and counter-narratives to climate action are most effective where right-leaning (divisive, populist) political parties and media networks are influential (Earle, 2021; Lamb et al., 2020; Dunlap and McCright, 2015; Oreskes and Conway, 2014).

3.1.3 Assessing Progress in Systems with PTP Potential

Systems with high PTP potential can be at different parts of the tipping trajectory, which is often characterised by an S-curve of technology diffusion: slow at first, then rapidly rising, before flattening out again as market saturation or majority is reached. The shape of the S-curve is influenced by feedback loops. As reinforcing feedbacks take hold, the rate of adoption accelerates. The adoption rate slows again as balancing feedbacks establish a new system stability.

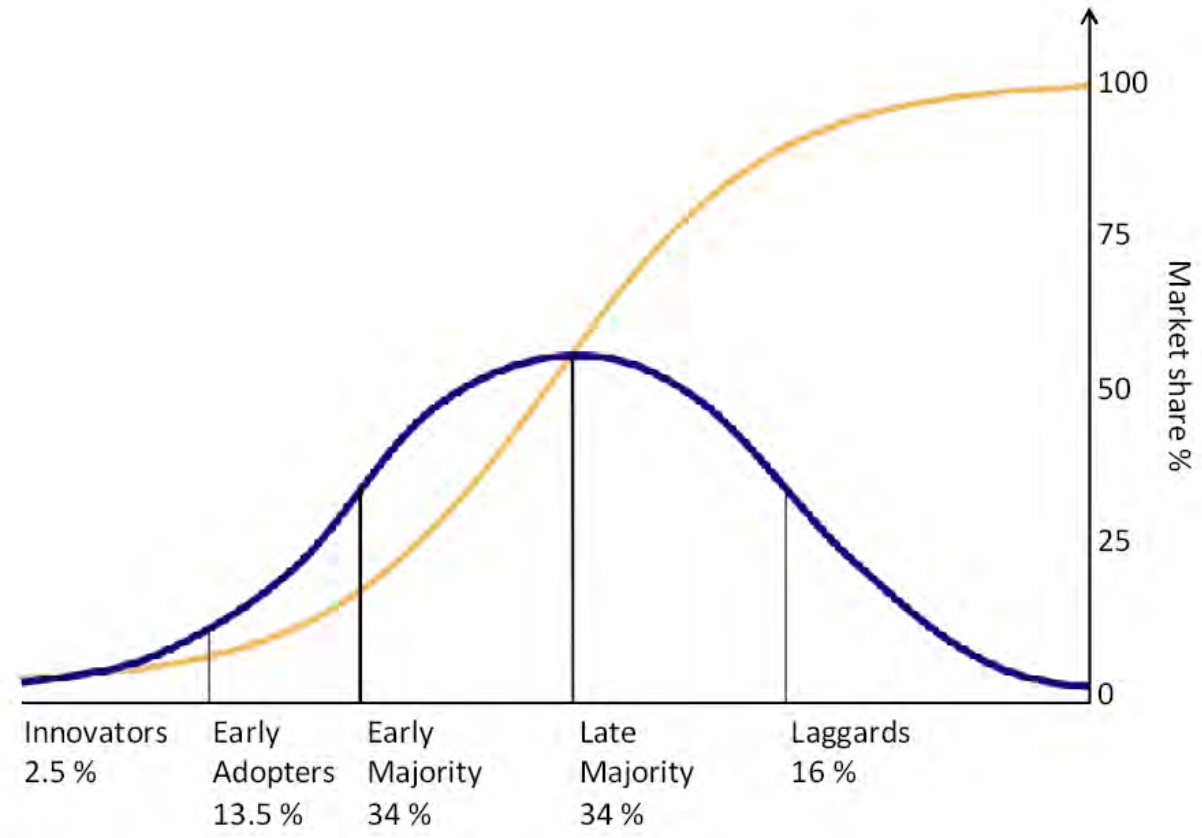


Figure 3.1.3. S-Curve of Innovation Diffusion in Systems with PTP Potential.

The process of an S-curve is context specific, but researchers have identified common patterns and characteristics along different parts of the S-curve, with generalisable lessons. These studies often break down the S-curve into phases (Rotmans et al. 2001, Victor et al. 2019; Systemiq 2021; EEIST 2021; Henderson and Sen 2021). Here, we consider the S-curve in three phases of the tipping points process, in each of which the system dynamics, leverage and roles of key actors may differ:

- **Phase 1. Emergence:** Visionaries recognise a problem or opportunity and conceptualise a better way to do things. Innovators move the concept from the laboratory, models and sketches to working prototypes or pilots.
- **Phase 2. Acceleration**
  - » Diffusion in niche markets: Early adopters form niche markets, connecting supply and demand. Performance increases and costs decline but the innovation remains at a premium and is not widely available.
  - » Diffusion in mass markets: The innovation reaches the mass market as it outperforms incumbents in costs and performance. This is the steep part of the S-curve.
- **Phase 3. Stabilisation**: Growth slows as the innovation reaches market saturation. The innovation may be transferred to new markets or help catalyse further innovations and forms the basis of a reconfiguration of socio-economic systems.

Understanding where a system sits on this curve is crucial to identifying the key leverage points to accelerate adoption—we return to this in chapter 3.2.

Trends in key indicators such as changes in the market share of sustainable technologies, price and performance metrics, capital investment, or social media data can help identify where on the S-curve a system is. Data can also provide insights into the effects of policies or other interventions, the likelihood that the system will progress to the next phase of the tipping points process and potential barriers to progress.

Analysis of longitudinal data may provide early indicators of tipping opportunities. Just as early warning indicators—such as critical slowing down or the rate at which a system recovers from shocks or perturbations—can signal the approach of an ESTP, **early opportunity indicators** may signal the proximity to a PTP. These indicators detect the loss of resilience of the incumbent state following a shock to the system (e.g. price shocks). If the system recovers rapidly, the incumbent state is likely resilient. If it is slow to recover, this may signal growing engagement with, investment in or market share of sustainable alternatives (see Box 3.1). For example, economic or sociopolitical pressures and weakening performance or legitimacy of an incumbent technology (e.g. ICEVs) or behavior can lead to a growing exploration of alternatives (e.g. EVs).

Loss of resilience alone does not guarantee that tipping will occur but the nature of fluctuations in the system can give clues as to whether a tipping point may be approaching (Kuehn, 2011; Bury et al., 2021). Further, it can point to windows of opportunity or critical periods for action by key stakeholders (see chapter 3.2).

Box 3.1. Detecting early opportunity signals for tipping in battery electric vehicle (BEV) adoption

Changes over time in statistical properties of key indicators such as market share can indicate changes in resilience through 'critical slowing down', in which a system becomes more sensitive to perturbations and takes longer to recover from shocks as it loses resilience.

For example, in the current market where vehicles powered by internal combustion engines (ICEVs) are incumbents and have the majority of market share in most national jurisdictions, market share of ICEVs vs BEVs should become more susceptible to fluctuations in demand and take longer to recover from shocks as the incumbency of ICEVs becomes less resilient under pressure of competition from BEVs.

Starting in 2020 market share of ICEVs in Chinese and European markets showed critical slowing down prior to abrupt declines and corresponding rapid increase of market share of BEV and hybrid vehicles (Mercure et al 2024, GTPR 2023). In the UK, the share of BEVs in viewing figures for online advertising of second hand vehicles shows a similar statistical trend, with increasing spikes of interest over time which are also becoming more persistent (Boulton et al 2025).

3.2 System Interactions and Tipping Cascades

It is important to keep in mind that systems do not exist in isolation. Their interactions mean that crossing tipping point thresholds in one system can lead to tipping in others, potentially causing a domino or cascading effect (Sharpe and Lenton, 2021; Eker et al., 2024). For example, the self-reinforcing economies of scale and learning by doing that have dramatically improved the cost and performance of batteries influence the tipping point for renewable power generation by helping to solve the supply/demand balancing problem. The decline in price of renewable energy in turn brings forward the tipping point in electric vehicle sales. It also brings forward the tipping point for producing affordable green hydrogen, which in turn improves the economic case for green steel and for green ammonia for fertilisers and shipping fuel (Lenton et al., 2023). In contrast to negative tipping cascades in Earth systems, positive tipping cascades in social systems offer the potential to generate rapid and broad beneficial change.

At the same time, this interdependence between systems means that efforts to reach a PTP in one system may be dampened by feedbacks in another system. An example are rebound effects where incentives to invest in energy efficiency are reduced when abundant affordable renewable energy is available. Another example is the temporary constraint that energy related grid congestion places on further demand electrification or household level renewables.

3.2 Acting on positive tipping points

Authors: Sara M. Constantino, Steven R. Smith, Yuki Numata, Laurens Speelman, Tom Powell, Rune Baastrup, Ilona M. Otto, Nadia Ameli,, Claudia R. Binder, Malcolm Rogge, Courtney Howard, Rasmus Mikkelsen, Sebastian Villasante, Timothy M. Lenton, Bjørn Bedsted, Morten Friis, Floor Alkemade, Viktoria Spaiser, Hywel Williams, Tristan Cann, Sibel Eker, Laura Pereira

Reviewers: Iain Black, Fenna Blomsma, Peter Lefort, Martina Ayoub, Kingsmill Bond, Owen Gaffney.

Key Messages:

Policy design needs to match the phase of a positive tipping process

- Effective sequencing of interventions is important to activate positive tipping points. Different opportunities exist to overcome barriers and enable scaling at different phases of an S-curve of adoption. Effective policy design needs to match the system's tipping phase.
- Policy mixes need to be appropriate to the scale, context, sector, actor, and phase of transition, to effectively catalyse and facilitate positive tipping dynamics (see Figure 3.2.4).

Positive tipping points need to be well governed to ensure a rapid and just transition

- Governance can create the enabling conditions for positive tipping, including easing access to finance, providing the necessary infrastructure to support rapid deployment, and cultivating sufficient stakeholder engagement and public support for policies to be approved and implemented.
- Rapid transition benefits from governance that is collaborative, localised and tailored to what communities say they want through participatory methods.
- Governments need to be aware of the potential for unintended consequences from positive tipping points including financial and political instability, stranded assets (including human assets) and perceived (in)justice of the transition.

Cross-cutting factors can support positive tipping points

- Patterns of capital allocation that enable sustained financial flows into emerging low-carbon technologies and sectors can help overcome lock-ins, reduce perceived risk and build market confidence, particularly in underinvested regions and markets.
- Digitalisation and AI have the potential to accelerate positive tipping points by managing complex systems from renewable energy smart grids and transportation systems to social deliberation processes.
- Climate communications in the format of film, journalism, performance art and other media can be instrumental in generating the political momentum for positive change, particularly when connected to targeted policy advocacy and trusted messengers.

Coordination and coalitions can catalyse positive tipping points

- Coordinated cross-sectoral action at 'super-leverage points' can unleash positive tipping cascades. Coordinated mandates across interacting sectors (e.g. power, transport and heating) can bring forward tipping in all.
- Coherent, committed, ambitious coalitions can challenge incumbencies and catalyse positive tipping towards majority adoption of social and technological innovations.

3.2.1 Introduction

Identifying conditions and actions to bring about positive tipping points is key to decarbonising our society at the scale and pace needed to reduce the impacts of climate change and avoid ESTPs (Otto et al., 2020; Lenton et al., 2023; Ong et al., 2025; Meldrum et al., 2023). Creating the conditions for PTPs requires strengthening enabling conditions that promote desirable self-reinforcing (positive) feedbacks, while overcoming balancing (negative) forces. Recent efforts have thus focused on identifying these enabling conditions and 'leverage points' or 'sensitive intervention points' — points in a system where small interventions can create significant and self-reinforcing change (Mealy et al, 2023; Farmer et al 2019; Meadows, 2008)—and the actions that can be taken to increase the likelihood of crossing PTPs.

In this chapter, we discuss some of these enabling factors and leverage points, illustrated with examples from specific key systems for decarbonisation, organised as follows:

- Overview of the types of measures that can be taken to enable positive (reinforcing) feedbacks and overcome negative (balancing) feedbacks (see 3.2.2).
- Consideration of how the strength, sequencing, and combination of measures can accelerate change within and across systems (see 3.2.3).
- Examination of how a domino effect of positive tipping cascades can accelerate change across sectors, demonstrated in a model of four interacting sectors – renewable power, residential heating, light road transport (cars) and heavy road transport (trucks) (see 3.2.4).
- Discussion of some key social and political considerations to enable positive tipping (see 3.2.5).
- Discussion on the importance of coalition-building to facilitate positive tipping (see 3.2.6).

This chapter aims to be useful to policymakers, financial investors, insurers, business leaders, media organisations and civil society organisers, all of whom have a vital role to play in accelerating decarbonisation and managing potential risks and unintended consequences.

3.2.2. Enabling positive feedbacks and overcoming balancing feedbacks

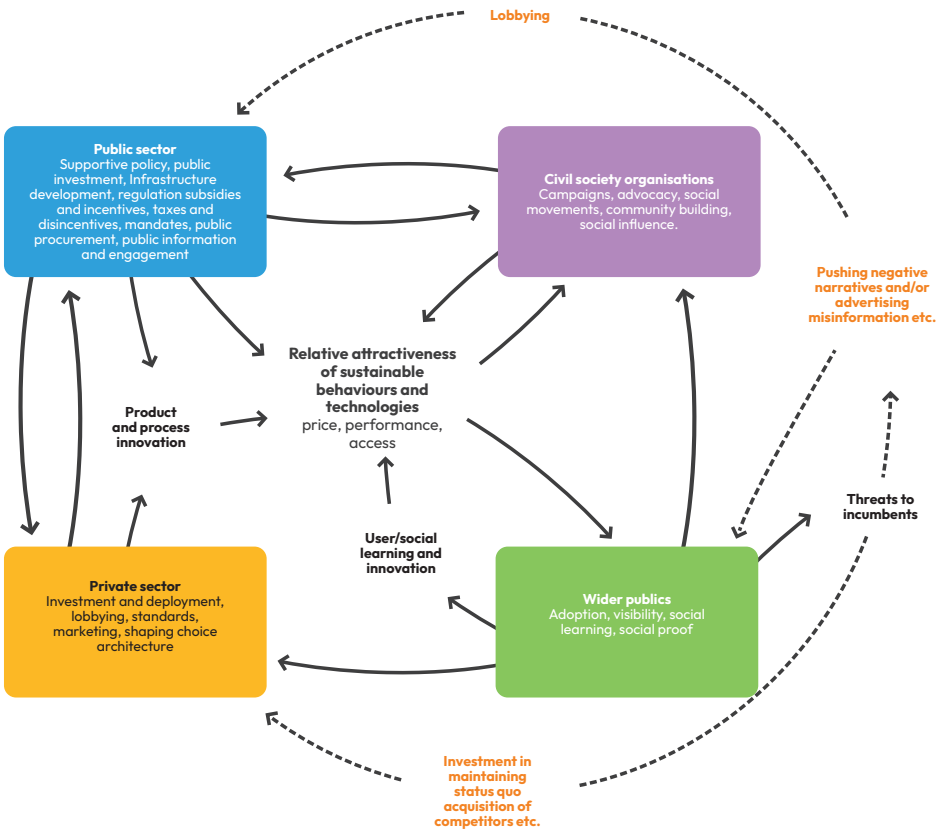


Figure 3.2.1: Generic diagram of the reinforcing feedbacks among the public and private sectors, civil society organisations, and the wider publics of adopters who influence the relative attractiveness and prevalence of sustainable technologies and practices. Colours correspond to different actor groups. Also shown are some of the balancing feedbacks that might emerge in response to the growing adoption of a new technology or practice. Solid lines indicate positive causal relationships, and dotted lines indicate negative relationships.

3.2.2.1. How different actors can enable positive feedback

Enabling conditions improve the relative attractiveness, accessibility and/or affordability (discussed in greater detail in Chapter 3.1) of a desired innovation, increasing its likelihood of adoption (Figure 3.2.1). Creating these enabling conditions, while overcoming the balancing forces maintaining the status quo, often depends on specific, deliberate and to some extent coordinated measures by actors from multiple sectors of society. For example, a transition to a low-carbon society requires lowering the costs of clean technology, incentivising private investment in clean energy, building clean energy infrastructure, encouraging low-carbon lifestyles and norms, and building social and political support for rapid change, all of which have potential for reinforcing and cascading feedbacks (Sovacool et al., 2025; Willis, Curato and Smith, 2022; Boswell, Dean and Smith, 2022). This "all hands on deck" perspective emphasises that: the conditions for change can start at many points in a system, with different actors having agency to bring about systemic change.

There are many ways that positive, self-reinforcing feedbacks can emerge—and that balancing forces can be overcome. For example, bottom-up demand-side pressures—driven by innovators and entrepreneurs or new needs or knowledge that lead to changes in the priorities of the public—can create opportunities for social or political change while putting pressure on incumbents to adapt. Bottom-up pressures may be especially important in contexts with strong incumbent industries and governments resistant to change.

At the same time, top-down actions by governments or businesses can also incentivise shifts away from incumbent technologies and practices towards low-carbon ones. Public policy can be critical to create the conditions for private capital investments in new industries when there are powerful incumbents, high costs to entry, and technological, political or market risks or uncertainties. Between these two ends, there are meso-level forces, such as organised civil society groups (e.g. unions, environmental groups, media) that can also be critical for seeding and supporting change.

Importantly, bottom-up and top-down forces can reinforce each other. For example, the Cool Biz campaign initiated by the Japanese Ministry of the Environment in 2005 introduced a lighter and cooler summer dress code. At the same time, it raised office air conditioner thermostats to 28°C. The combination of these two measures saved energy and lowered CO^2 emissions. This approach has since been adopted by the South Korean Ministry of Environment, the British Trades Union Congress, and the United Nations, demonstrating how successful pilots can spread through social learning.

Below, we describe some of the measures that the different types of actors shown in Figure 3.2.1 can take to create enabling conditions for PTPs. In Box 3.2.1, we describe these actions in the concrete case of UK EV adoption.

Public sector

The **public sector** can create **supportive policy** environments to rapidly increase supply and demand for low-carbon technologies and weaken the dominance of incumbent technologies, practices and norms.

Supportive environments start with **agenda setting**—the process by which some issues gain political traction while others fade—which is influenced by civil society organisations, the public, and the private sector, among others (Kingdon, 1995). **Policy windows**, created by **focusing events** such as crises (e.g. extreme weather, pandemics, financial crisis), political shifts, or other factors, can create opportunities for policy entrepreneurs to overcome institutional frictions and introduce new items onto the agenda (Giordono et al., 2020). Institutions have balancing feedbacks that sustain the status quo (e.g. fragmentation, veto power). Focusing events can change how policies are perceived and, in some cases, lead to rapid and punctuated policy change that overcomes institutional friction (Baumgartner and Jones, 1993).

If the issue rises to the government agenda, governments can create positive feedbacks and overcome balancing feedbacks through the use of different combinations of policy instruments such as **regulation** and **mandates**, **taxes** and **subsidies**, **public finance** and **direct investment, public procurement** and **guarantees**, **infrastructure** development, **public education** and **information provision**, ultimately shaping the relative strength or prevalence of new and incumbent industries, technologies and practices. Different policy instruments are critical at different stages along the innovation and adoption curve.

The **policy feedback** literature describes how the direct effects of policies can create feedbacks from the public and concentrated interest groups. **Credible** climate policies that deliver **tangible** and **short-run** benefits to industries and people that are **traceable** to the policy can create new interest groups and constituencies that support the policy (e.g. through voting or lobbying). Recent work suggests that **sequencing policies** so that benefits are realised early and often can increase subsequent support for more ambitious climate policy (Montfort et al., 2023). In contrast, starting with ambitious and broad policies right away can result in the repeal or discontinuation of a policy (Sewerin et al., 2023). For example, taxes on carbon emissions have been historically challenging to pass. Many governments instead adopted green industrial policies, thereby mobilising private capital and creating new 'green' constituencies and coalitions (Meckling 2021; Meckling et al., 2015). To the extent that this policy feedback is successful, it could ease the path for future carbon taxes.

Governments can use **public finance** or direct investment to support research & development into high risk technologies or public goods; develop **public-private partnerships** and introduce **tax credits** to reduce the cost of capital and incentivise private investment in low-carbon technologies and sectors. How policies are '**packaged**' or combined matters, and supply-side policies are more likely to create positive feedbacks when coupled with policies that strengthen demand for new technologies and practices. For example, building supportive **infrastructure** (e.g. public transit systems, bike lanes) and using **mandates**, **regulation** and **standards**, **public procurement, public education** (including correcting misinformation), **nudges** (e.g. defaults) and **consumer subsidies** create demand for low-carbon products and technologies. At the same time, governments can introduce **regulation** or **taxes** to dissuade investment in or use of incumbent fossil fuel-based technologies.

Policy instruments differ in terms of their sociopolitical **feasibility**, **impact**, **costs**, **efficiency, speed, distributional** and **equity** implications. Governance thus needs to be collaborative and tailored to the preferences of communities through participatory methods to avoid backlash (British Academy, 2025).

Private sector businesses

Private sector businesses play a key role in creating positive feedbacks to accelerate low-carbon transitions. Recent work suggests that climate governance can function like a conveyor belt that starts with voluntary pledges by companies and other non-governmental actors that eventually lead to standardisation and eventually mandatory regulation (Hale, 2018). In this sense, action by businesses can lead climate policy, while allowing for early experimentation and demonstrations of feasibility that may reduce political resistance.

As sellers, businesses can pursue **cost reduction** and **quality improvement** of their products, in turn increasing the affordability, attractiveness, and availability of their products to downstream buyers or consumers (Deloitte & RMI 2022). They can further shape demand through marketing tactics, including behavioural nudges and using influencers to adopt and promote their products (Thaler & Sunstein 2008). As buyers, businesses can have large impacts on upstream markets. Buyers' coalitions, also known as buyers alliances, are increasingly common in the clean technology space (e.g., CEBA, SABA, Sustainable Steel Buyers Platform). These coalitions unlock early-stage market growth by aggregating the demand of multiple corporate buyers. This creates a reliable source of demand, thus reducing their market risk, critical in early stages of product development, while allowing buyers to leverage their collective buying power to negotiate favorable rates (RMI 2024).

Businesses can also shape the policy environment (UN Global Compact, We Mean Business, and WRI, 2018) and public narratives, and the financial sector can shape access to capital across systems (see 3.2.2.3 on cross-cutting influences). This can be done directly through **lobbying**, **campaign finance**, and **participation in climate meetings** and other official modes of policy engagement; or indirectly, through **white papers**, **voluntary targets** and commitments (e.g., America is All In), **open letters** (e.g., BlackRock letter on stakeholder capitalism), and other mechanisms that influence public perceptions and priorities and political actions.

Whether these measures create the enabling conditions for PTPs depends on market and product characteristics—in particular, whether they are characterised by economies of scale or learning-by-doing dynamics—as described in chapter 3.1. Additionally, the PTP potential of these measures can depend critically on some of the public sector actions described above. For example, early investment and demand creation by governments can help the private sector overcome large initial fixed costs or risks.

Civil society organisations

Civil society organisations and **social movements** can accelerate the low-carbon transition through various measures—from **community-building** to **climate litigation** (see 3.2.2.3 on cross-cutting influences)—that mobilise groups for shared action (Ganz, 2024; Han, 2014). As illustrated using the pilot study to promote sustainable eating habits in Brondby, Copenhagen (Box 3.2.2. PTP theory operationalised at the local scale), a whole systems approach to PTPs begins with identifying, recruiting and developing adaptive leadership, building community around that leadership, and creating a strong and coordinated learning environment across sectors (Ganz, 2010). In seeking to expand its influence on policy, movements and social innovators need to go beyond local, grassroots, and peripheral networks and actively cultivate political "insiders", developing relationships with policymakers and other influential actors (Piggot, 2017; Newell, 2005).

Cross-cutting factors like the **media environment** in which people are embedded shape the beliefs and behaviours of individuals and communities across societal roles (see section on broader publics, below). Persuasive information campaigns can be directed either in support of decarbonisation and more sustainable behaviours or, as in the case of misinformation campaigns, in opposition to climate action. Due to their reach, media campaigns and narratives can create rapid changes in public beliefs, norms and behaviors.

Change agents, social entrepreneurs, and **innovators** can influence innovation diffusion by creating **social movements**, shaping **policy**, or affecting **markets** by encouraging **early adoption** of new technologies. They differ from the broader public in that they are often those who are less risk averse, have more resources, a strong commitment to a cause, and less tendency to conform and so are willing to go against existing social norms (Mittal et al., 2024). Civil society organisations can work with these opinion leaders to proactively shape norms, beliefs, and behaviors—by increasing the acceptability, legitimacy, and attractiveness associated with these outcomes.

Civil society - wider publics

Civil society - wider publics can also create or reinforce the enabling conditions for PTPs in low-carbon technologies and practices through their roles as consumers, investors, citizens, members of organisations, and role models (Nielsen et al. 2021; Hampton & Whitmarsh 2024; Caggiano et al. 2024). For example, consumers influence the private sector through **purchases** and **boycotts**, **shareholder activism**, and **financial** decisions; citizens can shape political and policy outcomes through **voting**, **advocacy**, or participation in **social movements**; and individuals exert **social influence** on their families, peers, and colleagues through the social networks and organisations they are a part of. Social influence can lead to non-linear increases in the adoption of new technologies and shifts in beliefs and opinions (Constantino et al. 2022).

Early adopters of new low-carbon technologies and practices—the adopters that follow the entrepreneurs and innovators described in the previous section—can have direct effects on emissions, but also widespread indirect effects through their influence on others. They often have the social and material resources to engage with new technologies and practices early on, and to withstand associated risks (Rogers 2003). For example, adoption of electric vehicles or rooftop solar was initially costly, risky and uncertain until costs dropped and the market share — and supporting services (e.g. charging stations) — increased. Early adoption increases the perceived **attractiveness** or **appropriateness** of new or alternative behaviours, technologies or beliefs by increasing their **visibility** and creating early **social proof** that they are viable or desirable, which is especially important for new, unknown or costly technologies. They can also signal the **direction a norm** is headed ("trending" or "dynamic" norms). Early adopters of rooftop solar have been shown to predict subsequent adoption among their neighbors (Graziano and Gillingham, 2015; Gillingham and Bollinger, 2021).

Visibility and social proof can be strategically increased through events like solar parties that bring together adopters with peers who have not adopted (Hecher et al., 2025; Hecher et al., in prep.) or the introduction of artefacts that render visible certain behaviours or beliefs (e.g. "I voted" stickers, yard signs, symbols on clothing). Early adoption can also be **strategically seeded** through targeted interventions and policies (e.g. targeted spillovers or education campaigns) to increase the likelihood of spillovers to others (Nyborg et al., 2016). Indeed, research on political movements, technology adoption, and norm change finds that there is a **critical mass** of adoption, ranging from 10% to 43% of a population, after which the fraction of adopters can increase rapidly (Everall 2025; Granovetter 1978; Chenoweth and Stephan 2011; Rogers 2003; though see Efferson et al., 2020).

Different **network configurations** can facilitate or impede the spread of new norms and behaviors. For example, 'small world' networks or 'tiny publics' may be effective configurations for the establishment of new social norms (Fine 2012). Rooftop solar has been shown to spread according to a **complex contagion process**: multiple points of social proof are required before an individual adopts (Centola 2021; Constantino et al. 2022). Where an individual sits in a network — and characteristics of the behaviour and how it spreads — contribute to their **agency** to influence others.

Growing public adoption of a new technology or practice can increase its perceived attractiveness, legitimacy and acceptability, while also creating a dedicated constituency that reinforces the new behaviour or technology through the various roles described above. When governments are **responsive** and **legitimate**, acting on broad public preferences, rather than on the interests of a few (Gilens 2024), changes in public opinion can, in turn, shape political and policy outcomes. Additionally, the same social forces — social learning, conformity etc. — that create rapid initial change also sustain new social norms once they emerge and take root (Young 2024).

Box 3.2.1 Policy sequencing to enable a PTP in UK electric vehicle adoption.

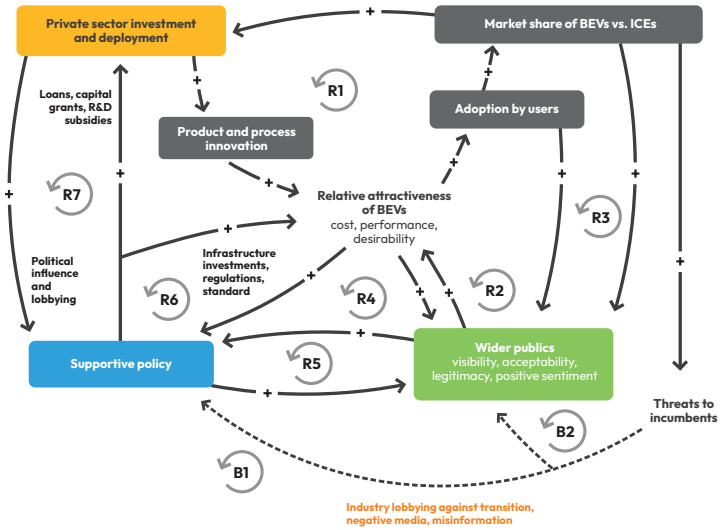


Figure 3.2.2. Systems map of key reinforcing (R) and balancing (B) feedback loops in the UK light-duty road transport system. Reproduced from Adapted from Geels and Ayoub, 2023, and Lenton et al., 2025.

The UK light-duty road transport system exhibits reinforcing feedbacks (R) that are strong enough to overwhelm balancing feedbacks (B), supporting self-propelling change from ICEVs to BEVs.

Reinforcing feedbacks include:

- Increasing returns to adoption due to economies of scale, learning-by-doing, and technological reinforcement (R1).
- Diffusion of information and social norms that support BEVs (R2, R3).
- Policy feedbacks (e.g. zero emission vehicle mandates) and political momentum that is reinforced by co-benefits such as public health (R4-R7).

Balancing feedbacks that reinforce the status quo include:

- Industry lobbying against policies that support BEVs or constrain ICEs (B1).
- Misinformation campaigns supported by media, politicians and influencers (B2).

The UK electric vehicle fleet has expanded rapidly in recent years and is now firmly in the accelerating phase of the tipping process (see Figure 3.2.4), the market share for new BEV sales reached almost 20% in 2024 when the total cost of ownership for a mid-sized BEV became comparable with an ICEV. Multiple analyses and forecasts indicate that the upfront cost of EVs will reach parity with ICEVs by 2026 for mid-sized vehicles and around 2028 for luxury models. This shift is driven by falling battery costs, which are predicted to fall below $100 per kWh threshold by 2026, making EVs as cheap to manufacture as their petrol-powered counterparts.

Public sector: effective advocacy coalitions resulted in the 2008 Climate Change Act and climate-related transport policy, which increased new investment, R&D, coordination between automakers, policymakers and research organisations, recharging infrastructure, and purchasing incentives. Policymaking also experienced a tipping point in 2015 as governments realised the need for an integrated transport decarbonisation and industrial strategy.

Policies became more focussed on supporting manufacturing, supply chains, mass EV adoption and rapid charging infrastructure. The 2017 Clean Growth Strategy led to new capital grants and subsidies for automakers and battery makers to build manufacturing plants. At the same time, new EU car emissions regulations required automakers to at least part-electrify new cars by 2020. Despite some success from these policy stimuli in terms of new car and battery plants, the UK's industrial and policy environment and Brexit-related trade complications have led some auto and battery makers to close or avoid UK-based operations in favour of continental European and Asian production (Geels and Ayoub, 2023). Better infrastructure promotes EV adoption (Buhmann and Criado, 2023) but almost half (47%) of UK consumers believe there are too few few charging points (Autotrader Consumer Research, May 2023).

Private Sector: Automakers initially made defensive R&D investments in the 2000s in response to successful first movers (e.g. the Toyota Prius) and early climate-related policy and public pressures. Over the course of the 2010s (particularly from 2015), increasing demand (especially from international markets such as China), policy pressures, and the aftermath of the 'dieselgate' scandal led to more concerted efforts by automakers to improve battery capacity, size efficiency, range (average range grew 75% from 2015 - 2023) and charging speed (increased from 50kW in early 2010s to 350 kW in 2024 (IEA, 2024)). This increased the attractiveness and reduced the cost of EVs through economies of scale and learning-by-doing (Geels and Ayoub, 2023).

3.2.2.2. Overcoming balancing feedbacks that sustain the status-quo.

To positively tip adoption of a desired technology or practice, it may be important to not only create enabling conditions for positive feedbacks but also to remove or weaken system structures that strengthen incumbents and maintain the status-quo. Balancing effects can arise from path dependencies — for example, large infrastructural systems such as roads are difficult to quickly replace with alternatives such as bike lanes or pedestrian paths — institutional inertia and the reinforcing dynamics of prevailing social norms. Yet, they can also result from deliberate efforts by incumbents. For example, the fossil fuel industry draws on the tactics used by the tobacco industry to undermine efforts towards a just low-carbon economy (Malone, 2022). These tactics include intentionally promoting lock-in, political resistance, discourse that promotes delay and uncertainty, and political resistance (Lamb et al., 2020). In recent years these have been extended to include the funding of fake or disingenuous grassroots organisations that openly oppose actions that threaten incumbents (aka 'astroturfing').

Lock-ins describe mutually reinforcing path dependencies in technologies, institutions, infrastructures, and mindsets (habits, social norms, customs and beliefs) (Seto et al., 2016). For example, institutional investments in incumbent technologies and infrastructure, or education and human resources (e.g. professional training and standards), create long-term commitments that constrain the adoption of alternative trajectories in the future (William and Bonvillian, 2015). Carbon-intensive technologies and practices are particularly prone to entrenchment due to their large capital costs, feedbacks between socioeconomic and technical systems, and the longevity of associated infrastructure.

Political resistance to rapid transitions can come from incumbent industries and their workforces, who fear the prospect of closure and unemployment, and from ideological libertarians who distrust the impositions and perceived costs associated with climate policy. While the goal of accelerating decarbonisation may tempt governments to keep markets open to cheap imported products (often Chinese), this can strengthen resistance from domestic manufacturers and workers unions (Meckling and Nahm, 2018). Incumbent industries can create and exacerbate this resistance by intentionally producing and promoting narrative "**discourses of delay**", centred on claims of excessive economic cost, doubts about the integrity of science and scientists, loss of personal freedom/government interference, and the value of waiting to act (Coan et al., 2021; Lamb et al., 2020; Guenther, 2024). Finally, lobbying efforts by incumbent industries, and fears of backlash, can also create pressure for governments to keep policies such as fossil fuel subsidies intact.

To counteract this resistance, all actors (and governments in particular) have a crucial role to play in communicating the long-term benefits of rapid transitions, including their relatively low cost compared to the much higher cost of inaction and putting people at the heart of change using public participation (Devine-Wright et al., 2022). Regulation of misinformation would help to counteract some of the strategic efforts by incumbents to create political resistance. An integrated trade, industrial and regional development strategy that supports affected communities, re-trains for new skills, and re-purposes manufacturing towards healthier, better paid jobs in the new economy (e.g., offshore wind in the UK and Denmark) could ultimately lead to a deeper, faster and fairer transition by neutralising political resistance (Geels and Ayoub, 2023).

3.2.2.3. Cross-cutting influences on enabling and balancing feedbacks

Some factors can mediate or have cross-cutting influence on the dynamics described above and in Figure 3.2.1, with the potential for both positive and negative influence. Here, we highlight four: private finance, artificial intelligence, the media environment, and climate litigation.

Private Finance: The financial sector has an important role in facilitating the economic activities involved in positive tipping, and is being pressured to respond accordingly. For example, the Science-Based Targets Initiatives' recent net-zero standard for financial institutions rules out support for companies developing new coal, oil and gas projects (SBTi, 2025). Patterns of capital allocation that enable sustained financial flows into emerging low-carbon technologies and sectors can help overcome lock-ins, reduce perceived risk and build market confidence, particularly in underinvested regions and markets. Early, well-aligned investment creates positive feedback loops that reinforce other enabling conditions and accelerate transitions (Ameli et al., 2025). This requires significant changes in the normative guidelines, rules, and governance in the financial sector, including recognising the values of nature and conditioning financial profit on doing no harm (IPBES 2024).

Additionally, global warming and worsening weather extremes are accelerating risks to capital—including to fixed assets and human capital—leading certain regions to become uninsurable (e.g. home insurance in Florida) (Trust et al. 2025; Lamperti et al., 2019). Without insurance, mortgages and loans and other credit markets can no longer function, creating the potential for climate-driven systemic market failure and losses beyond the capacity of states to financially absorb or adapt. By realistically pricing systemic risks, private finance has the potential to trigger PTPs by unleashing considerable financial flows towards decarbonisation and nature conservation (Ameli et al., 2025) and away from activities precipitating ESTPs across many systems. Growing risks and financial losses could motivate decision makers to find solutions, however they could also have the opposite effect by accelerating the breakdown of global economic and political institutions.

Artificial Intelligence: Depending on who controls its use and to what ends, artificial intelligence could accelerate PTPs across systems in the following ways:

1. *Managing complex systems:* Modeling and optimisation can help manage the complex systems that are critical to climate adaptation and mitigation, such as the food system (Ayed and Hanana, 2021), renewable energy/smart grids (Ukoba et al., 2024), or transportation (Hosseini et al., 2025). AI can increase the efficiency of these systems (e.g. by using intelligent load management in smart grids, see Wang et al., 2024), and increase reinforcing feedbacks.
2. *Supporting technological innovation:* Machine learning tools can enable faster discovery and development of new technologies. For instance, by optimising the design of wind turbines (Ribeiro et al., 2025), or reducing supply chain issues with critical minerals.
3. *Promoting behavioural change:* Generative AI chatbots can be effective in challenging conspiratorial views (Costello et al., 2024), reducing the influence of climate change denial and delay on adoption of pro-climate behaviours. Large language models can also be effective in persuading people to change behaviour (Spaiser and Nisbett, 2025), though this introduces obvious ethical implications and risks (Chaudhary and Penn, 2024). Bespoke AI assistant tools could help democratise access to up-to-date climate science (see Biswas et al. 2025), increase climate awareness (Vaghefi et al., 2023), or assist in social deliberation processes such as citizen climate assemblies, including the Global Citizens' Assembly. Deployed at scale and customised to mobilise climate action, such AI tools could strengthen positive feedbacks.
4. *Monitoring social, technological, economic, and political dynamics* using large-scale data analysis, AI could provide early recognition of when social systems might be susceptible to PTPs or harmful tipping. For example, machine learning can be used with ecological monitoring and citizen science to automate biodiversity tracking (Plas et al., 2025), while analysis of vehicle advertisements can be used to detect tipping towards large-scale electric vehicle adoption (Boulton et al., 2025). Better monitoring and understanding of target systems might help to identify opportunities and optimal timing for interventions.
5. *Modeling and simulation tools:* AI can explore a wide range of options including the effectiveness of different policy interventions or activism scenarios. Generative AI-enhanced agent-based models could simulate different international climate negotiation strategies (Vezhenevets et al., 2023). AI-enhanced digital twins could be used to model urban sustainability transformations.
6. *Digital Public Infrastructure:* other digital technologies augmented by AI can enable a rapid transition towards climate and other Sustainable Development Goals with the deployment of digital public infrastructure (DPI). The current, fragmented approach to knowledge acquisition and financial, technological and capacity-building resources have held back structural transformation and exacerbated inequalities. Open, safe, and inclusive DPI could allow AI to promote a more shared prosperity at relatively low cost and without impinging on the sovereignty of nations, communities, or individuals (Zuckerman, 2020).

However, AI technologies also come with substantial risks for PTPs. Data centres are known for their substantial water and energy consumption, and have been linked to increases in planned fossil fuel capacity in certain markets. It will be vitally important to minimise these negative environmental impacts as the AI market grows, through a holistic set of measures such as energy and water efficiency, demand flexibility, alternative transmission technologies, and renewable energy sources (Numata et al., 2025). AI tools could also be used to spread climate misinformation (Noor 2025). And concerns have been raised with respect to data and technology ownership (Strowel 2023; though there are recent promising developments). Ultimately, these technologies are here to stay, we have therefore to find ways to utilise them to empower humans to tackle challenges such as preventing ESTPs while minimizing their burdens on the earth system.

The Media Environment: The mass media has a powerful role in shaping public discourse, perceptions and responses to the climate and nature crisis, including how the policy agenda is set at all levels of governance. As is the case with other cross-cutting influences, this power can be used to build public and political support to accelerate climate mitigation, or for the opposite ends: to undermine public trust in climate science and the need for rapid action (Falkenberg, 2022; Ruiu, 2020; Bolzen and Shapiro, 2017). A study of 59 countries finds that global media coverage of climate-related stories has grown significantly in recent years, from around 47,000 articles in 2016-17 to around 87,000 in 2020-21 (IPCC, 2022). In scrutinising the actions of governments, corporations, and other actors, the media can shine a light on corruption, scandal and injustice and hold drive the public to hold actors accountable for their policies and actions.

Other forms of media, such as films and books, also have the potential to 'tip' public opinion in a profound way—as, for example, Harriet Beecher Stowe's Uncle Tom's Cabin did in the case of the abolitionist movement, helping precipitate the American Civil War. Films such as Al Gore's An Inconvenient Truth, Leonardo Di Caprio's Before the Flood and Don't Look Up!, Sir David Attenborough's BBC documentary Climate Change—The Facts, Franny Armstrong's The Age Of Stupid (2009), and Saci Lloyd's The Carbon Diaries (2015); books such as Kim Stanley Robinson's Ministry of the Future (2020); opinion pieces in newspapers and magazine articles such as David Wallace-Well's The Uninhabitable Earth (2017) have raised awareness about the climate and nature crisis but have remained unconnected to the wider movement.

Occasionally, an artwork does coordinate advocacy on a broader scale and can be instrumental in creating momentum for meaningful change and a critical mass of committed actors. A recent example is the film Ocean, produced by Silverback Films and Open Planet Studios and narrated by Sir David Attenborough. This film's release was perfectly timed to put pressure on political leaders to ban bottom trawling in Marine Protected Areas (MPAs) and to conserve 30% of the world's oceans by 2030, as agreed in the Kunming-Montreal Global Biodiversity Framework.

Social Media is a powerful tool for spreading information about climate and nature issues. However, while social media algorithms can result in the quick spread of information and awareness and mobilise support for climate action, they can also spread misinformation and increase polarisation by creating information silos, increasing homophily, and promoting the spread of extreme content. Polarisation, to the extent that it reduces support for general public goods and is leveraged to delay a transition away from incumbent systems, is a barrier to decarbonisation. Additionally, as online social networks replace more local or place-based ones, civic capacity and the incentive to contribute to local public goods can become weaker (Zhang, 2025).

Climate Litigation: Strategic climate litigation can enable the conditions for PTPs by generating court decisions that require governments to accelerate efforts to address climate change, such as developing more stringent national climate plans (Averchenkova et al., 2024; Higham et al., 2022) and implementing mandates for private sector actors. They can also enable PTPs by creating climate-related risks for the private sector, thereby incentivising them to adopt more sustainable business practices. Climate litigation efforts also shape public discourse on climate change and the rights of future generations (Wewerinke-Singh & Ramsay, 2024) in ways that may support policies to enable PTPs.

As of 2024, 2967 climate cases had been brought in almost 60 countries. Over 226 new cases were launched in 2024 (Setzer & Higham, 2025). This expansion looks set to continue, as evidenced by the release in 2025 of advisory opinions on climate change by the International Court of Justice (ICJ) (Obligations of States in respect of Climate Change), the Inter-American Court of Human Rights (IACtHR) (Climate Emergency and Human Rights), and the International Tribunal on the Law of the Sea (ITLOS) (Climate Change and International Law). These legal opinions have laid the groundwork for greater scope for liability for both state and non-state actors. In its 2025 Advisory Opinion, the ICJ explicitly acknowledged that a State may be liable where, "it has failed to exercise due diligence by not taking the necessary regulatory and legislative measures to limit the quantity of emissions caused by private actors under its jurisdiction" (IJC, 2025, para. 428). By this finding, the ICJ opened the door for new claims against states for failure to regulate the fossil fuel industry with respect to production, consumption, granting licenses, and providing subsidies (para. 427).

A growing number of cases are being brought by individuals and civil society organisations (CSOs) against states (Leghari v. Federation of Pakistan, 2015; KlimaSeniorinnen, 2024) and local authorities (Finch on behalf of the Weald Action Group v. Surrey County Council, 2024). One of the leading cases of this kind, State of the Netherlands v. Urgenda Foundation, led to the phase-out of coal power stations in the Netherlands and stricter climate policies (Urgenda, 2019). Cases are also being brought against businesses. In Luciano Lliuya, a Peruvian farmer sought compensation for loss and damage from a German energy company in German courts (Luciano Lliuya v. RWE). The court dismissed the specific case; however, it held that businesses are potentially liable to pay compensation for historical emissions that contribute to climate change today. Other forms of climate litigation include anti-greenwashing cases (FossielVrij NL v. KLM, 2024) and shareholder rights litigation (Client Earth v. Shell plc et al., 2024).

At the same time, some industry actors and governments have used litigation to slow down or halt action on climate change (Setzer & Higham, 2025). Arguably, this adverse reaction is a manifestation of 'balancing forces' that seek to maintain the status quo, dampening progress towards PTPs. To enable PTPs, such balancing forces must be countered with renewed climate litigation efforts, creative advocacy, and greater financial support for individuals and CSOs engaged in climate litigation. It is recommended that advocacy organisations strive for greater coordination of strategic litigation efforts for enabling PTPs; at the same time, it should be recognised that diverse and autonomous approaches will be taken in different regions and countries. As climate litigation efforts evolve, the use of ESTPs science should be tracked, and this data used in developing strategies for future cases that can help to enable PTPs.

Box 3.2.2 PTP theory operationalised at the local scale: creating the conditions for a shift to sustainable eating habits in Brøndby, Denmark.

A new project in the Danish suburban municipality of Brøndby exemplifies the operationalisation of positive tipping point theory to promote rapid, sustainable dietary change at the local/municipal level. Initiated in 2025, this project relies on community engagement, leadership development, and gastronomic innovation to promote the adoption of plant-rich diets among Brøndby's 40,000 culturally diverse residents.

In Brøndby, tipping point theory is translated into action by first identifying and empowering informal local leaders who can effectively influence their social networks to adopt sustainable eating habits. Community leaders receive specialised training in sustainable cooking and community mobilisation, thus enabling them to normalise plant-rich diets within their social circles. These interventions aim to initiate a 'complex contagion' process, where behaviours spread within communities due to normalisation and social reinforcement.

By combining food joy and appealing plant-rich meals in routine community settings including schools, workplaces, canteens, and community events, the project ensures sustainable dietary choices are visible, accessible, and socially desirable. Such visibility is amplified through strategic communication efforts and public events, including the high-profile "Brøndby Challenge", reinforcing community commitment and broadening the movement.

The Brøndby Project has been developed jointly by the Danish not-for-profit foundation Democracy x, culinary entrepreneur and co-founder of the New Nordic Kitchen movement Claus Meyer, the Global Systems Institute at the University of Exeter, and the municipality of Brøndby. It is designed to offer a replicable/adaptable framework for municipalities globally, demonstrating (if successful) how carefully designed community interventions can effectively promote positive tipping points towards sustainability.

3.2.3 Policy sequencing, packaging and stringency

Different policy instruments or actions have distinct outcomes, and are often tailored to the specific national context and sector (Grubb et al., 2024) (see Figures 3.2.3. and 3.2.4). Creating the enabling conditions for PTPs and achieving rapid decarbonisation goals requires multiple policies and actions to bring about rapid systemic change. However, the overall effectiveness of different combinations of policies depends on how different interventions interact, and how they are sequenced (Stechemesser et al., 2024; D'Arcangelo et al., 2023). Once policymakers understand where in the transition phase a system is (see 3.1), they can begin to identify the most effective (1) combinations of policies ("policy packages" or "policy mixes"), (2) sequences of interventions ("policy sequencing"), and (3) intensity of such efforts ("policy stringency") to accelerate progress—or create lock-in and resilience once desired change has been achieved.

Policy packages refer to the combination and interaction of multiple instruments over time. Complementary and reinforcing policy packages or mixes can increase the potential impact of decarbonisation efforts. For example, multiple measures may be necessary to solve different market failures or enhance both the supply and demand of a new technology. Redundant or conflicting policies can increase mitigation costs or administrative complexity. For example, public investment and regulatory instruments can both enhance and detract from each other. Public investment in alternative infrastructure and technology can increase the acceptability of standards or bans. At the same time, investment in R&D or infrastructure development can fail due to permitting regulations that hinder expansion of new technologies (e.g. limitations on cross-jurisdiction permitting in the U.S. have slowed the build out of regional transmission lines necessary to support wind and solar).

Policies will interact differently in different contexts and sectors, and the research on policy mixes is still nascent (OECD, 2025; Meadowcroft and Rosenbloom, 2023). However, the specific mix of policy instruments should be tuned to the transition phase (see below) and to political and public readiness or appetite for change. Strategic policy mixes can increase sociopolitical acceptance for climate policy and decarbonisation by including provisions that compensate potential losers (e.g. workforce retraining or cash transfers in coal communities), increasing the salience and presence of co-benefits (e.g. local health benefits), and integrating climate and social policy (Bergquist et al., 2020).

Some policies or interventions will only be effective when introduced sequentially. How **policies are sequenced** can therefore enhance or detract from policy effectiveness (Meadowcroft and Rosenbloom, 2023). Policies that create the enabling conditions for a subsequent intervention to be effective should be introduced first. In particular, policies that deliver credible and tangible benefits that are traceable to a policy quickly can garner greater support among the public, as was the case for Social Security in the US (Jacobs and Mettler, 2018). How the extent of benefits or costs are sequenced can have large repercussions for the resilience of a policy. Additionally, green industrial policy that creates strong economic interests in the green transition can be self-reinforcing if those interest groups start to lobby for continued or more stringent transition policies (Meckling, 2021).

Increasing **policy stringency** in the short term, self-propelling feedbacks can be unleashed earlier, thereby reducing the need for policy intervention and public investment in the longer term and enabling tax revenues to be better spent on other priorities. Tax and subsidy combinations can be designed to bring forward the crossing of the cost parity threshold between clean technologies and fossil fuels, while being revenue neutral for the government. For example, a tax of $160 on the sale of each mid-range internal combustion engine car in Europe in 2023 could fund a subsidy of $1,600 on the purchase of each mid-range electric vehicle, achieving ownership cost-parity while maintaining revenue neutrality (Lam et al., 2023).

In the financial sector, increasing the capital requirements for banks holding fossil fuel assets is another powerful tool to raise the cost of capital for high-carbon activities and accelerate the phase-out of fossil fuel finance (Ameli et al., 2024). At the same time, stringent policies can be more difficult to pass and can create backlash, even when they are carefully designed to offset costs, as was the case with the Canadian carbon tax and dividend policy (Mildenberger et al., 2022). Starting with policies that are targeted, specific, and create upfront tangible benefits (e.g. subsidies) can create appetite for more stringent climate policy in the future (Fesenfeld et al 2022; Sewerin et al., 2023).

3.2.3.1 Tuning the policy or intervention to the phase of the transition

Considering the phase of the s-curve a transition is in can help to identify which measures might be most relevant. In Figure 3.2.4. and in the text below, we describe which public policy measures may be most effective at different points along the tipping trajectory.

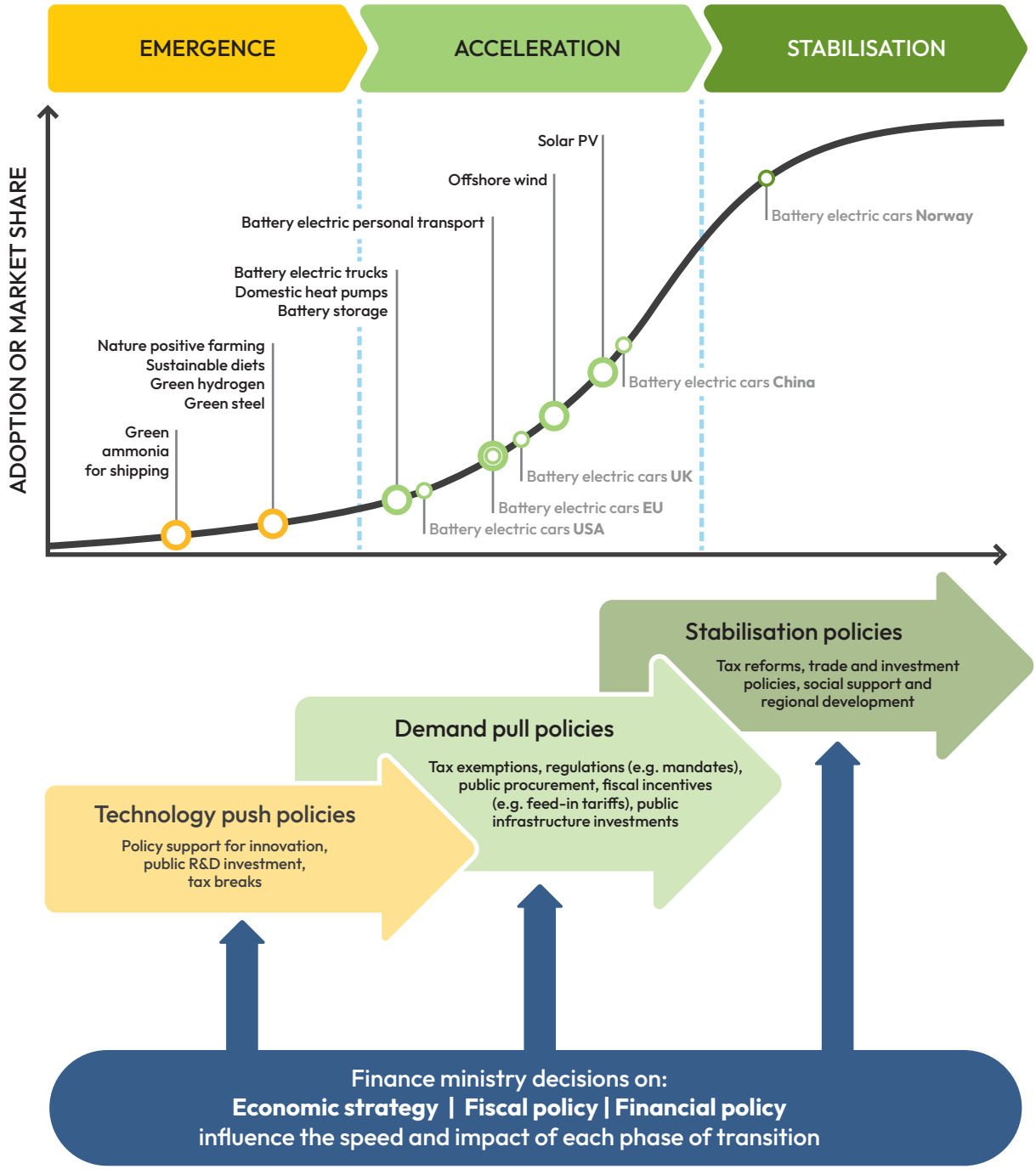


Figure 3.2.4. Sequencing policy interventions along a transition curve to enable PTPs. Based on Figure 2 of Sharpe et al., 2025, modified to show sector update assessments from Chapter 3.3. for global adoption of key transition technologies (orange circles, black text), and market share of battery electric cars in 5 key markets (USA, EU, UK, China and Norway) to illustrate potential different states of adoption in different markets or jurisdictions'

Phase 1: Emergence. The early stages of a transition are characterised by the emergence of an innovation, or set of innovations, with the potential to address an identified problem or need. At this stage, innovations are vulnerable to inconsistent messaging, uncertain policy and market environments, and barriers to commercialisation (e.g. high fixed costs before economies of scale can be realised).

Important interventions at this stage include: building awareness and support among key stakeholders through public engagement and media campaigns and setting clear and credible policy goals. Additionally, early public investment in R&D and skills development (e.g. workforce development) as well as tax breaks can help de-risk and incentivise private investment to support early stage innovation. Roadmaps and targets can help direct investment and coordinate R&D activities. Creation of niche markets, which provide a space for early commercial products to improve, can be facilitated through public procurement or green industrial policy (Meckling 2021).

Niche markets can also depend on early adopters to increase the visibility and create the social proof necessary for those who are less certain or committed to adopt the technology or practice. In this early stage, one challenge can be achieving sufficient early adoption to destabilise status quo practices, behaviours and norms, which can themselves be self-reinforcing through the same social dynamics that eventually lead to destabilisation (Constantino et al., 2022; Young et al., 2024). Strategic policy introduced by businesses and governments can incentivise early adoption through targeted education or subsidies and taxation, among others (Nyborg et al., 2016). For example, businesses might promote the use of bikes or public transport, encourage different dress codes and energy and water conservation, among other actions.

Phase 2: Acceleration. The middle stage of a transition is characterised by accelerating diffusion of behaviour, technology or new norms to a wider population—and weakening strength of incumbent technologies and industries.

In this phase, policies such as continued and broad use of subsidies and taxes, purchase incentives (i.e. to increase affordability), and development of supportive infrastructure can be critical to support broad adoption. Regulations and mandates that force the private sector to reallocate investment from the old to the new technology can drive innovation, economies of scale, and learning, improving the attractiveness and affordability of new technologies.

However, passing mandates can prove politically challenging unless there is already public acceptance for the new or alternative technologies or strong enough private sector interest or an organised civil society response. Designing policies, such as public education efforts, that create new constituencies that support the alternative behaviour or technology, or that create lock-in to the alternative while simultaneously breaking out of lock-in to the incumbent way of doing things, can create positive feedbacks that are important for transitioning from phase 2 to phase 3 (Trachtman et al., 2025).

Phase 3: Stabilisation. In the late stages of a transition, the new regime can become stabilised or resilient due to system characteristics or strategic actions to “lock in” or entrench desirable change through the same reinforcing feedbacks described in the previous section. For example, economies of scale or network effects, where benefits to use of a technology increase in the number of adopters of that technology (e.g., electric vehicles become more desirable as more people adopt them and more charging stations are built), create reinforcing feedbacks that can make it costly or difficult to revert to prior or alternative technologies.

Stabilisation can also happen through long-term infrastructure investments (e.g. the build out of renewable energy and decommissioning of coal plants, expansion of trains and bike paths etc.) which reduce the accessibility of alternatives, the emergence and institutionalisation of new social norms (Young 2024), the creation of strong coalitions and constituencies that benefit from the new regime in phases 1 and 2 and so have incentives to ensure its continuation (e.g. new workforce, firms and trade associations, consumers), and supportive and potentially increasingly stringent policy measures (e.g. building codes, emissions standards, carbon prices). These measures need to be coupled with continued efforts to promote the phase-out of fossil fuels and weaken the role of incumbents in resisting changes (e.g. to infrastructure) and in shaping policy and public narratives, including through misinformation.

Dampening effects are present at each of these phases as existing actors respond to protect their self interest. Precautions to avoid or reduce unintended consequences and measures to deliver widespread benefits that are salient and linked to the transition to a new behaviour or technology and that ensure that those who stand to lose from the transition are engaged in the process through participatory decision-making and compensated for their losses can help to reduce backlash and increase continued support for the transition.

3.2.4 The domino effect of positive tipping cascades

Policies and other actions that promote sustainable transitions in one sector can sometimes accelerate transitions in other sectors, creating a domino effect or cascade (Sharpe and Lenton, 2021; Eker et al., 2024). The improvements in battery technology in the last few decades, for instance, cascading from consumer electronics to buses, cars and then into stationary electricity storage in the power sector and long-haul transport, is a good example of positive tipping across multiple sectors and countries (Walter et al. 2023).

These cross-sectoral interactions reinforce the feedback loop of demand increase, cost reduction and quality improvement, and have led to rapid adoption of batteries to replace fossil-fuel based energy supply.

A model of four sectors—renewable power, residential heating, light road transport (cars) and heavy road transport (trucks)—show a that coordinated policy mixes (and mandates in particular, see Figure 3.2.5) can significantly bring forward tipping points in these sectors (by 2-8 years) and increase the potential for tipping cascades (Nijsse et al., 2024).

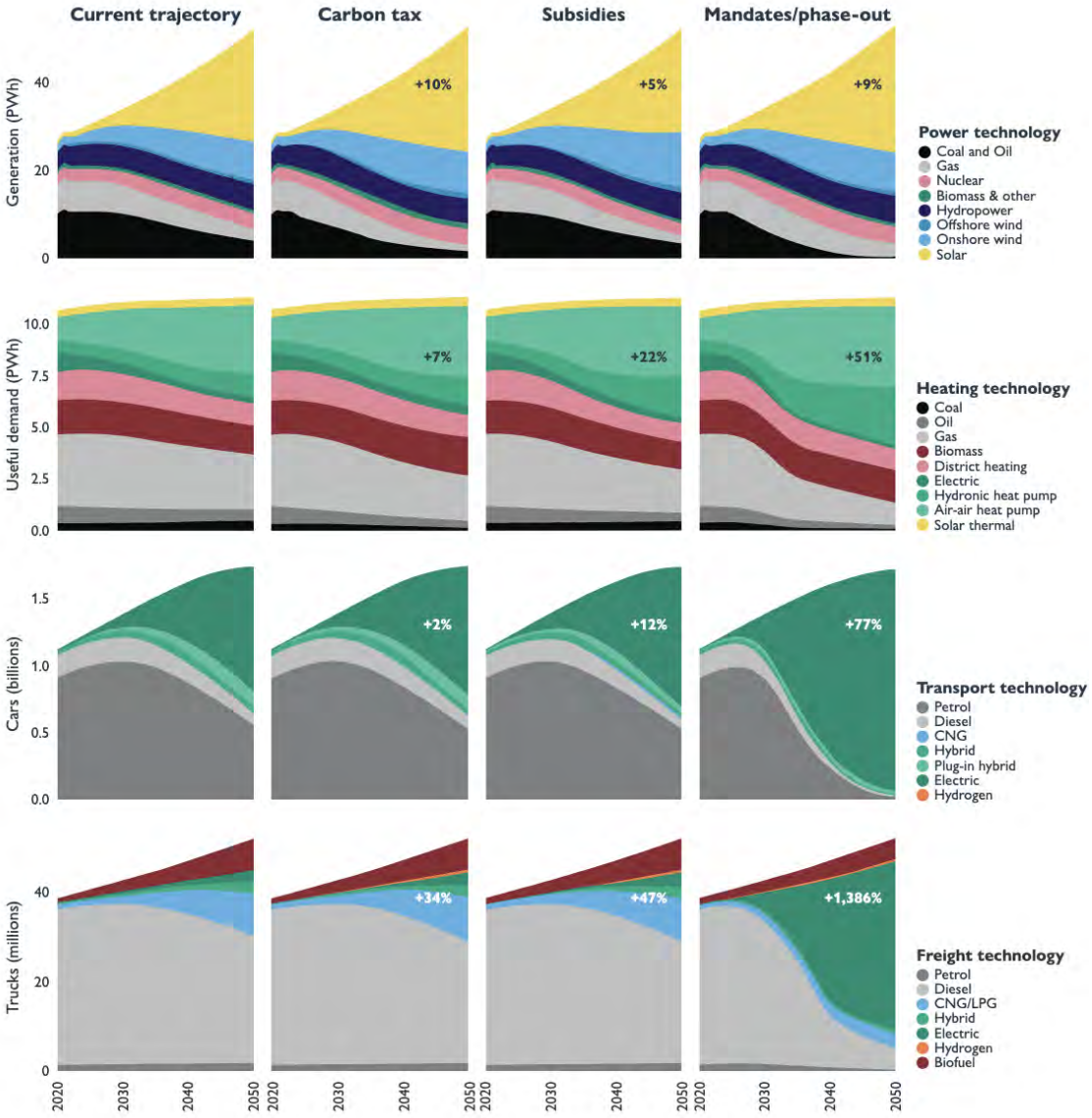


Figure 3.2.5.. Effect of different policy instruments on the global technology mix in four sectors. Percentage growth is shown for selected green technologies: in the power sector it is the sum of wind and solar; in the heating sector it is all types of heat pumps; in the transport sector it is all types of full electric vehicles (Nijsse et al., 2024. Reproduced with permission).

Other policies can further enhance the effectiveness of technology deployment policies, for example: policies to reduce energy demand to help power system balancing; policies to improve home insulation to lower heating and cooling demand; policies to increase heat pump efficiency; and building standards requiring that houses act as thermal batteries (OECD, 2025). Such demand-side measures can amplify the effectiveness of supply-side policy mixes and trigger positive tipping cascades. Furthermore, the common drivers of social and behavioural changes for demand-side mitigation, such as environmental identity, social norms, and self-efficacy, can create spillovers across different consumption domains (Maki 2019; Behn 2025). Behavioural changes in one end-use sector, such as residential energy, can cascade into other sectors such as food and mobility. In addition to their cross-sector cascades for decarbonisation, demand-side measures can also improve energy security, enhance quality of life, and reduce the costs and risks associated with carbon removal technologies (Creutzig et al., 2022).

3.2.5. Social and political considerations when enabling PTPs

Creating the enabling conditions for PTPs involves some degree of anticipation and influence over the evolution of a system—as well as some level of agreement about the alternative desirable system state. This report defines PTPs as those that contribute to rapid decarbonisation. However, what is "positive" is a normative question, and even with the goal of decarbonisation, there are many possible pathways—and these will be supported and contested by different actors (Pereira et al 2024).

Identifying shared goals and where to intervene can thus be challenging when considering complex social-ecological systems with emergent dynamics, diverse viewpoints and priorities, and inevitable tradeoffs. Strategic foresight and scenario building can help practitioners to understand system dependencies and anticipate different potential system responses (Ramirez and Wilkinson, 2016). For example, strategic foresight tools can help governments to better understand, project and anticipate market developments, technological trends, or how changes in public opinion or behaviour might evolve, as well as how interlinkages between systems might change. This is important as deliberate attempts to create rapid change are likely to be met with backlash without additional considerations about distributional consequences, impacts on social identities and communities, and psychological aversion to rapid change.

Ensuring a just transformation can increase the sociopolitical viability of PTPs, while also achieving important normative goals. Just sustainability transformations have distributional, procedural and recognitional dimensions. It is critical that the distributional consequences of a transition are considered, and that measures are developed to ensure that those who face losses are adequately compensated and that social outcomes, including equity, are prioritised alongside decarbonisation goals (Bennett et al 2019, Avelino et al 2024, EEA 12/2024). In addition to identifying different potential transformation scenarios, practitioners can use scenario building methods to consider the potential distributional consequences of different interventions, and preferences about inevitable tradeoffs that emerge.

Decision-making processes that enable broad participation are key to achieving procedural justice, and are likely to increase sociopolitical acceptance. Asking the question "transforming towards what?" requires broad inclusion of diverse voices and not just experts to guide what aspirational futures could be enabled (Juri et al 2025). Community engagement is increasingly viewed as critical to create social & democratic legitimacy for strategic efforts to alter the status quo. Measures to bring individuals and communities on board in early stages—and to give them a say in the decision-making—can increase the social acceptance of necessary changes and, depending on who is represented in these efforts, ensure greater benefits and equity. Participatory scenario development is one tool to build anticipatory governance and futures literacy as well as generate useful outputs in terms of the futures that people both aspire towards as well as those they want to avoid (Pereira et al 2021).

Deliberative democratic methods can also be used to take regular 'temperature checks' of ongoing efforts at systems change—allowing flexible and adaptive responses as well as identification of unintended consequences. For example, the Global Citizen Assembly takes a two-pronged approach to community engagement in decision-making by creating a Global Mini-Public and Community Assemblies. The Global Mini-Public is a transnational deliberative mechanism to legitimise global-scale decisions, facilitate long-term thinking and demand justice across scales and borders. In contrast, Community Assemblies are local deliberative spaces to support the local deliberation of Earth System risks that foster local stewardship in the management of these risks. Together, the two levels could create a two-way knowledge bridge: community assemblies can feed insights and lived experiences into the global mini public, anchoring global decisions in local realities, while the global mini public can return globally deliberated visions and mandates to local communities, creating a reflexive learning loop across scales (Curato et al. 2025). These tools for community engagement could advance polycentric Earth System governance by supporting a multi-level governance architecture, aligning local agency and global coordination in response to interconnected tipping point risks. Ultimately such approaches can foster cross-scale and trans-local networks of learning, knowledge co-production, cooperation and capacity building. It is important that politicians commit to implementing the recommendations of these assemblies.

3.2.6 Building Coalitions to Facilitate PTPs

Efforts to create PTPs are often met with resistance to change, as well as specific counter-measures from powerful, well-financed incumbents trying to maintain the status quo. The power asymmetry in the incumbents' favour can be difficult to overcome. Coalitions, which are broadly defined as "alignments of disparate groups across government, business and civil society, united by common interests" (Roberts et al., 2018; Rayner & Bonnici 2021) are vital in the creation (or undermining) of PTPs for rapid decarbonisation. Actors who are limited in what they can achieve individually can strengthen their combined agency by forming broad, deep, and interconnected ecosystems of influence (Laybourn-Langton et al., 2021; Weible, 2018; Schmidt, 2015). Coalitions allow actors across scales and sectors to pool their resources, learn from each other, and build collective and strategic capacity to bring about PTPs in the face of strong incumbent interests and substantial uncertainty (Matti et al 2025; Ganz 2009).

Coalitions can be detrimental when they are not well organised. Common pitfalls include dilution of goal strategy, lack of clear decision structure or ownership, and difficulty achieving consensus (Tulder et al., 2018). Coalitions with coherent and unified goals tend to have the most decisive influence on policy (Weible and Sabatier, 2018). When coalitions have a shared interest in the new technology they can reinforce the new technology or behaviour through policy feedbacks (Meckling et al., 2015; Rosenbloom et al., 2019). Furthermore, clear roles and learning feedback loops that allow the coalition members to adapt and learn as they pursue their shared goal (Zack et al 2023).

Steps to consider in building coalitions for PTPs:

- **Map and model:** define the system, its boundaries and its current state and create a map of the field including actors.
- **Identify and define:** identify actors with aligned values and interests around a decarbonised future state and complementary resources. Identify formal and informal leadership among key actors. Define clear goals and a shared approach and theory of change to guide the work
- **Convene:** bring together coalition partners to build trust and design shared working and decision-making structures with clear roles and commitments from coalition partners (Zack et al 2023).
- **Work with friction:** accept that systems change takes energy and includes systems learning where conflicting interests compete over scarce resources, make sure to develop mechanisms for transparency, accountability and conflict resolution (Zack et al 2023, Rayner & Bonnici 2021).
- **Invest in capacity building and learning:** develop the necessary environment (Heifetz 1998) to enable adaptive learning and new roles required by the uncertain nature of systems transformation. (Rayner & Bonnici 2021, Zack et al 2023)
- **Include citizens and outside actors:** Involve citizens and other stakeholders early on to identify shared visions and to counter inertia and zero-sum-logics, contribute to shared will formation, and broader norms change.

As described in the first Global Tipping Points Report (2023), recent work suggests that broad consensus-building may not be the most effective way to catalyse rapid climate action. Pioneering, high-ambition small-group coalitions committed to ambitious climate and nature goals may be able to initiate self-propelling virtuous cycles of cooperation involving specific sectors and corporate partners. These 'climate clubs' could lead others to follow (Sharpe, 2023).

Box 3.2.3 below describes an emerging coalition for positive tipping points in climate and health.

Box 3.2.3 A Climate and Health Coalition for PTPs

Opportunities exist for the health sector to bring together a powerful, well organised coalition of actors committed to a joint programme of rapid climate action and improved health.

The health sector, which employs more than forty-six million people, is responsible for approximately 5% of greenhouse gas emissions and 10% of Global World Product. Health professionals tend to be trusted messengers, well-placed to articulate the health and wellbeing benefits of a rapid transition to a sustainable future. However, until recently they were largely unaware of the systemic risks to health and healthcare provision posed by intensifying heatwaves, wildfires, floods, hurricanes, tornadoes and other climate-related hazards.

In Glasgow, November 2021, local and national-level initiatives coalesced into an international movement via the WHO CoP26 Health Programme. At CoP26, The UK National Health Service (NHS) was an early mover in announcing a comprehensive, evidence-based net-zero strategy for the health sector, demonstrating that ambitious decarbonisation was possible. By the end of CoP26, fifty-two countries had signed up to this WHO-led movement, which has now grown into a coalition of over eighty countries. These country level commitments can enable normative shifts at all levels of health bureaucracy and wider society, shifting working practices, financing, and power dynamics in transformative ways. Global networks such as the Global Climate and Health Alliance and the WHO–WMO Climate and Health Joint Programme, are now engaging with countries to accelerate towards climate-resilient, sustainable, low-carbon health systems.

3.3: Progress on Positive Tipping Points in Key Systems

Authors: Tom Powell, Steven R. Smith, Femke Nijsse, Timothy M. Lenton, Kai Greenlees, Floor Alkemade, Hatty Wylder-Hopkinson, Emma Bailey, Sara Constantino.

Reviewers: Lukas Fesenfeld,Laurens Speelman, Sibel Eker, Ilona Otto, Owen Gaffney, Viktoria Spaiser.

Key messages

- **Renewable energy is scaling rapidly but unevenly. Solar PV is doubling capacity every 2–3 years and growth of wind power is also strong. Reducing planning delays, providing grid infrastructure, and finance can accelerate change.**
- **Battery prices have plummeted by 84% in the last decade and capacity is growing exponentially, underpinning mobility and power sector transitions.**
- **Electric vehicle adoption is accelerating in leading markets. China has become the dominant manufacturer. Norway has near total adoption. Price parity, battery performance, and charging availability are key determinants of mass adoption.**
- **Policy mandates and coordinated finance and investment are essential for bringing forward positive tipping points in the energy system.**
- **Heat pumps are a critical lever for decarbonising buildings, but face high upfront costs and other barriers including a shortage of skilled installers. Improved policy incentives, financing (e.g. cheap loans) and consumer trust are vital.**
- **Affordable green hydrogen could unlock hard-to-abate sectors such as those requiring industrial heat (eg steel and cement). Current costs are 2–3 times higher than grey hydrogen but learning curves could lead to price parity.**
- **Clear policy supported by financial incentives can enable farmers to switch to more sustainable production methods and build resilience to extreme weather events.**
- **Widespread support for rapid decarbonisation can be strengthened when benefits are evenly distributed, e.g. through lower bills, better health outcomes and improved quality of life.**
- **Supportive policy and public procurement can help to normalise and spread sustainable behaviours, e.g. through promoting active transport, sustainable eating.**

Introduction

This chapter provides short updates on progress towards positive tipping points in 11 key sectors or systems essential to mitigating the threat of Earth system tipping points, which have been highlighted in previous reports (Meldrum et al., 2023; GTPR 2023).

ENERGY & POWER: **SUPPLY**

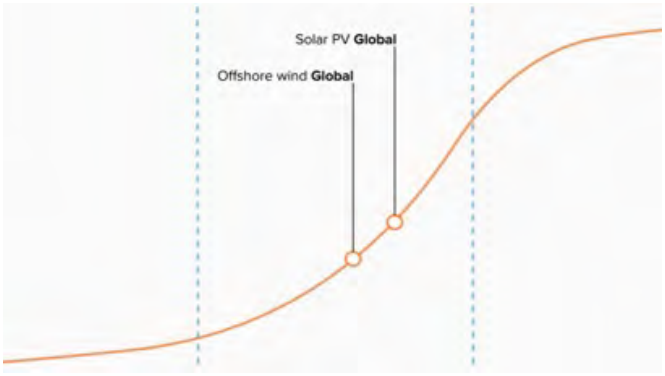


Renewables, especially solar PV and wind power, offer the only affordable solution to rapidly decarbonise energy grids and provide plentiful, low-cost power. Growth in renewable energy generation firstly reduces demand for new fossil fuel based generation as global electricity demand grows, and will replace existing coil and gas generation capacity as older infrastructure is decommissioned.

Deployment of solar and wind power are essential for enabling emission reductions in end-use sectors like transport, heating and industry (see below). The potential to do so is growing every day through innovation in, for example, electric vehicles, heat pumps and industrial processes.

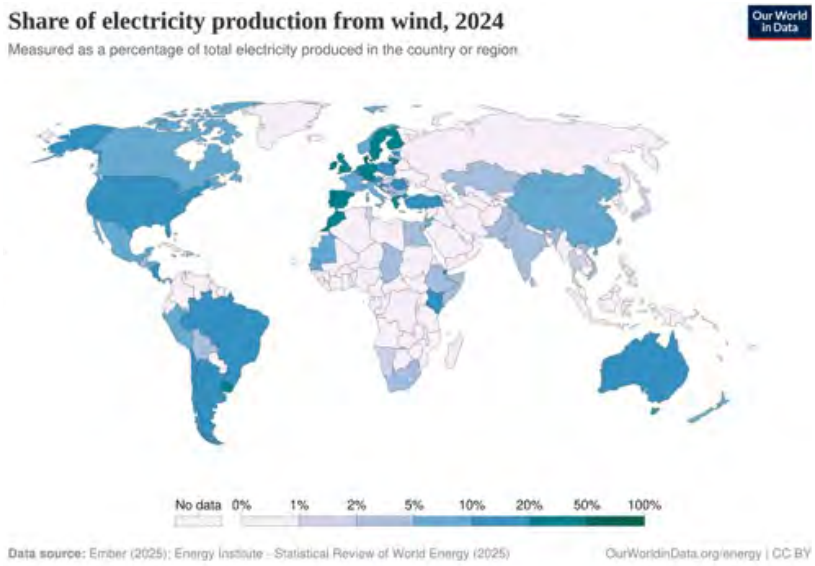
SOLAR PV AND WIND GENERATION

Replacing all electricity generation with renewable sources could **remove 26% of current global greenhouse gas emissions from fossil generation, and more through enabling electrification in other sectors.**



Progress:

Combined, solar PV (1865 GW) and wind (1133 GW) provided 15% of global electricity generation capacity in 2024. **Solar PV is the fastest growing source of energy generation in history** (Ember, 2025a) and dominates growth in electricity generation capacity, increasing by over 30% (452GW) globally in 2024, meeting 40% of the global increase in electricity demand (IRENA, 2025). 99 countries have doubled (or more) the amount of electricity they produce from solar power in the last five years, from emerging economies to those with the largest power systems, and 20 countries now generate more than 15% of their electricity from solar power (Figure 3.3.1a). Wind deployment (7.9% capacity growth in 2024) is also projected to continue with steady or slightly accelerated growth, with 19 countries generating more than 15% of their electricity from wind in 2024 (Figure 3.3.1b).



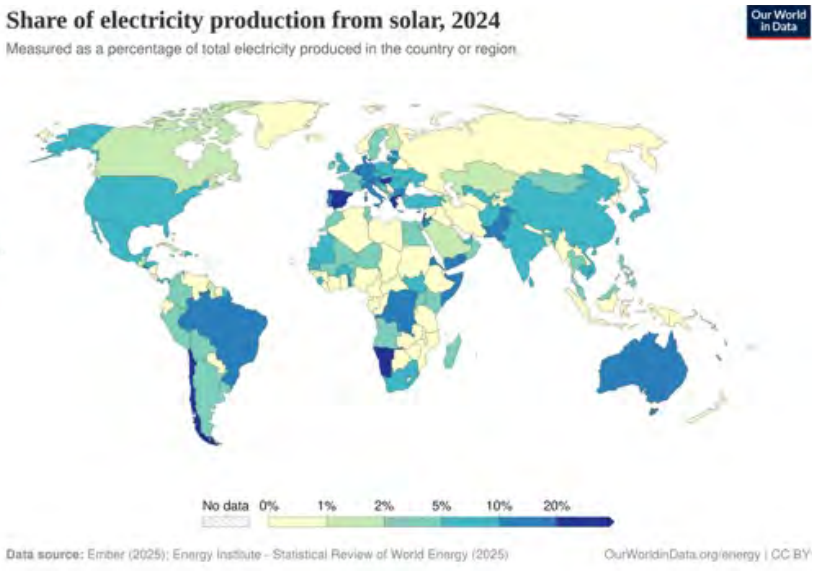


Figure 3.3.1: The share of electricity production from (a) solar and (b) wind power in world countries in 2024 (Ember (2025); Energy Institute - Statistical Review of World Energy (2025) – with major processing by Our World in Data).

- **China:** tripled solar PV capacity additions in 2 years from 2022 to 2024, installing 277 GW last year. China also realised a new record in wind capacity additions of 79 GW (IRENA, 2025). New fossil capacity additions fell in 2024 compared with previous years, despite growth in electricity demand (Ember, 2025a). China dominates global production and innovation in renewable technologies; with more than enough supply for its domestic market, it is now actively investing in building new offtake markets in South-East Asia, Africa and Latin America (RMI, 2024).
- **USA:** installed a record of 50GW new solar PV capacity in 2024, with a moderate increase in wind capacity (5.1 GW). Combined, wind and solar overtook coal power for the first time in 2024, generating 17% of the USAs electricity (Ember, 2025a). This growth trend is expected to continue, with solar and battery storage expected to contribute over 80% of new capacity additions in 2025 (U.S. EIA, 2025).
- **EU:** installed 66GW of new solar PV capacity in 2024 (4% increase from 2023), and 16 GW of new wind capacity (Wind Europe, 2025). Fossil generation fell in the EU while both power demand and electricity exports grew as clean energy growth significantly outpaced demand growth (Ember, 2025b).
- **India:** energy demand is set to more than double by 2050. While early in its transition, dependence on fossil fuel imports provides a strong incentive for renewables deployment, and capital is rapidly shifting into renewables deployment and manufacture. India doubled solar capacity additions in one year from 2023 to 2024, adding 23 GW (RMI, 2025a).
- **Emerging markets and global South:** low costs of renewables are enabling very rapid deployment in many countries in the global South, which stand to gain by reducing fossil fuel imports while increasing electricity access. Capital expenditure on generation is swinging rapidly to renewables (87% of capex in 2024), and deployment is accelerating rapidly, even outpacing that in the global North in terms of generation share vs. fossil fuels. New markets can emerge and grow very fast. Pakistan emerged rapidly as one of the world's largest markets for solar panels in 2024, importing 17 GW of panels (Ember, 2025a). Low cost exports of solar panels from China, which is actively building new markets in the global South, are a key driver of growth (RMI, 2024).

Reinforcing or enabling change



- **Renewable energy costs continue to fall while products improve in quality** (e.g. more efficient solar cells, larger wind turbines) driven by economies of scale and learning by doing, especially due to very high production volumes in China.
- **Battery storage is getting much cheaper** and markets are being designed to make them profitable. This **technological reinforcement** improves the business case for solar developments, making them more competitive against fossil fuels and even cheaper than gas generation in some markets (e.g. Germany)(Ember, 2025b). The world's first 24-hour solar PV project is due to come online in Abu Dhabi in 2027, enabled by low-cost battery storage. **Digitally enabled smart-metres and consumer interfaces** enable consumers to save money by shifting demand to periods of abundant supply.
- **Energy insecurity** and volatile/rising pricing of fossil fuels have increased the rate of solar deployment in some countries. Of the 15 countries with the highest solar shares in 2024, 7 were in the EU, where energy independence from Russia is an important driver.
- Although gross solar production and installation statistics are dominated by **China**, solar is experiencing rapid growth worldwide, with 99 countries doubling their installed capacity in the last 5 years. 21 countries generate more than 15% of their electricity from solar power, up from 3 in 2020. As well as China among BRICS nations **Brazil** and **India** both now sit in the top 5 solar generators globally, alongside USA and Japan.
- In the **Global south**, the modular and distributed nature of renewables, as well as low costs and high generation potential, are driving faster electrification than ever before, which in turn brings opportunities for faster, cleaner economic development.

Balancing or resisting change



- **Policy barriers** remain in many markets, including complex permitting and auction processes for renewables, a lack of support for enabling flexible storage and demand-side flexibility.
- **Grid infrastructure investment** often lags growth in renewable deployment, creating bottlenecks. Battery storage and demand flexibility may mitigate this need for grid expansion .
- **Negative electricity prices** harm the business case for renewables. Per kWh, solar sometimes only get 60% of the income compared to an average asset (Ason and Dal Poz, 2024, Hillion, 2025).
- **Continued investment in, and subsidies for fossil fuels** slow down the growth of renewables.
- **Growth in total electricity demand still outpaces clean energy deployment**. Demand from electrification of sectors like transport and heating, as well as demand from data centres and crypto mining contribute to this demand growth (RMI 2025b). Hotter than average temperatures in 2024 were a significant cause of increased electricity demand, and drove increased fossil generation resisting phase out (Ember 2025a).

Enabling policies:	
	• **Effective system planning and regulatory frameworks** to enable rapid deployment, flexible storage and demand-side flexibility.
	• **Minimal feed-in-tariffs** or contracts for difference to protect renewables from price volatility and provide a stable long-term investment climate (Ason and Dal Poz, 2024).
	• **Improving grid flexibility and rapid deployment of storage capacity.**

Sources:

Ason, A. and Dal Poz, J. (2024) 'Contracts for Difference: the Instrument of Choice for the Energy Transition', Oxford Institute for Energy Studies Working Paper [Preprint], (ET34). Available at: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2024/04/ET34-Contracts-for-Difference.pdf.

Ember (2025) European Electricity Review 2025. Available at: https://ember-energy.org/latest-insights/european-electricity-review-2025.

Ember (2025) Global Electricity Review 2025. Available at: https://ember-energy.org/latest-insights/global-electricity-review-2025/the-big-picture/.

Ember (2025); Energy Institute - Statistical Review of World Energy (2025) – with major processing by Our World in Data. "Share of electricity generated by solar power" [dataset]. Ember, "Yearly Electricity Data Europe"; Ember, "Yearly Electricity Data"; Energy Institute, "Statistical Review of World Energy" [original data]. Retrieved September 15, 2025 from https://archive.ourworldindata.org/20250909-093708/grapher/share-electricity-solar.html

Ember (2025); Energy Institute - Statistical Review of World Energy (2025) – with major processing by Our World in Data. "Share of electricity generated by wind power" [dataset]. Ember, "Yearly Electricity Data Europe"; Ember, "Yearly Electricity Data"; Energy Institute, "Statistical Review of World Energy" [original data]. Retrieved September 15, 2025 from https://archive.ourworldindata.org/20250909-093708/grapher/share-electricity-wind.html

Hillion, P. (2025) 'Use and Abuse of the LCOE: A Market-Based Valuation Framework', INSEAD Working Paper, 2025/15/FIN. Available at: http://dx.doi.org/10.2139/ssrn.5117985.

IRENA (2025) Renewable Capacity Highlights 2025. International Renewable Energy Agency. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2025/Mar/IRENA_DAT_RE_Capacity_Highlights_2025.pdf.

RMI (2024) Powering Up the Global South. Available at: https://rmi.org/insight/powering-up-the-global-south/.

RMI (2025) Empowering India. Available at: https://rmi.org/insight/empowering-india/ (Accessed: 10 September 2025).

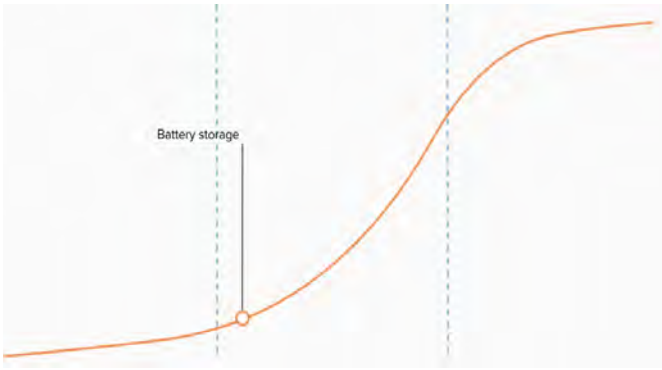
RMI (2025) Fast, Flexible Solutions for Data Centers. Available at: https://rmi.org/fast-flexible-solutions-for-data-centers/.

U.S. EIA (2025) Solar, battery storage to lead new U.S. generating capacity additions in 2025. U.S. Energy Information Administration. Available at: https://www.eia.gov/todayinenergy/detail.php?id=64586 .

Wind Europe (2025) Wind energy in Europe: 2024 Statistics and the outlook for 2025-2030. Wind Europe. Available at: https://windeurope.org/data/products/wind-energy-in-europe-2024-statistics-and-the-outlook-for-2025-2030/.

BATTERY STORAGE

Battery storage is essential to accelerate deployment of renewables by overcoming challenges of intermittent supply. **Global energy storage capacity must increase sixfold to 1,500 GW by 2050, of which 1,200 GW is expected to be provided by batteries** (IEA, 2024)



Progress:

Average price of lithium ion battery packs dropped to $115 USD/kWh in 2024, down 20% on the previous year and 84% lower than average cost in 2014, driving large increase in installed storage capacity (Figure 3.3.2). Globally, installed battery capacity nearly doubled from 86 GW in 2023 to 159 GW in 2024 (Ember, 2025). Batteries can be installed both in utility scale systems (accounting for ~65% of installations), and in domestic or small-scale 'behind-the-meter' systems (~35%)(IEA, 2024).

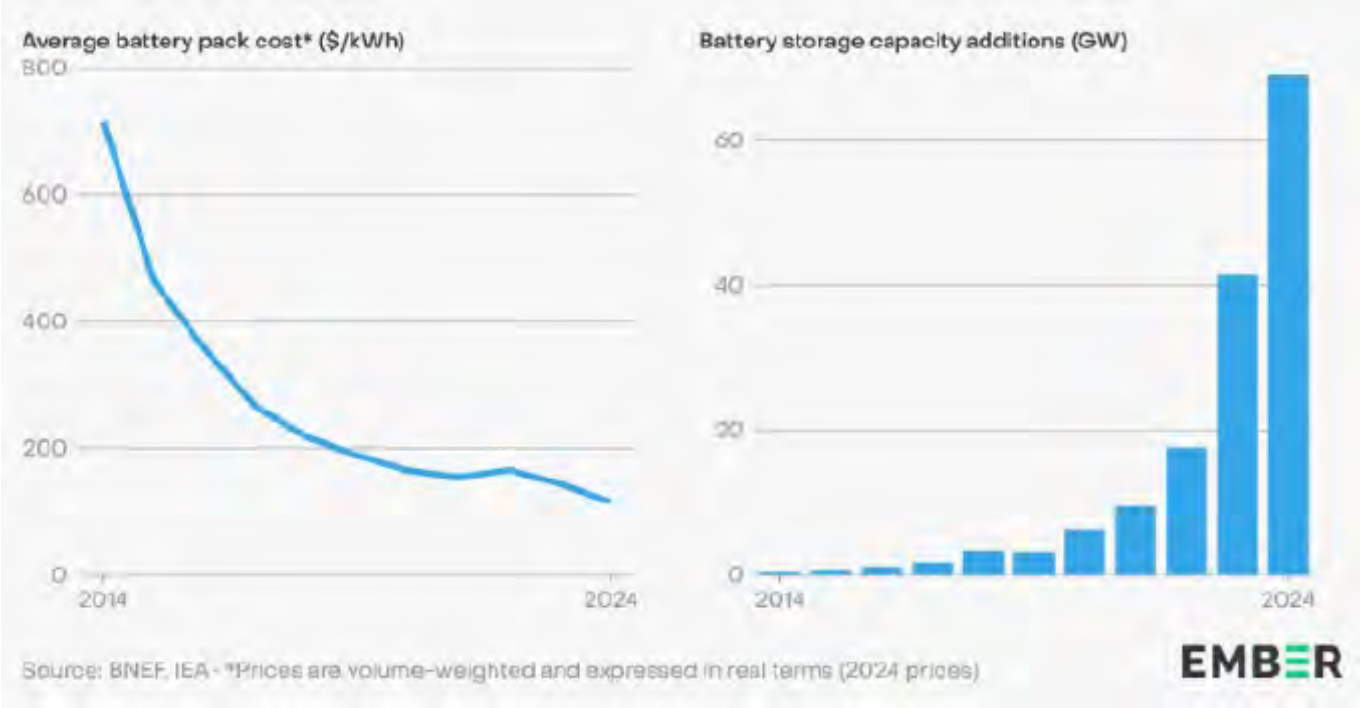
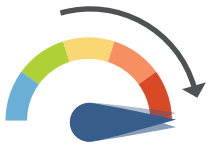


Figure 3.3.2: Battery storage installation has grown rapidly as battery prices have fallen (reproduced from Ember, 2025).

- China dominates battery supply chains, producing more than three quarters of batteries globally, and is also the world leader in battery storage installations, accounting for 55% of global capacity additions (23 GW) in 2023 (IEA, 2024). Provincial level mandates to pair battery storage with new solar pv and wind developments, as well as a growing market for commercial-scale behind-the-meter storage systems have been key drivers.
- The **USA** is the second largest market, with 8 GW added in 2023, a doubling year-on-year driven by market reforms, falling battery costs and domestic production, and an investment tax credit under the Inflation Reduction Act (IEA, 2024). **California** and **Texas** are significant leaders in battery storage. In 2024 batteries met nearly 20% of California's summertime daily peak loads, up from less than 2% in 2021 and significantly displacing gas generation (Ember, 2025).
- In the **EU** installations increased 70% in 2023 to 6 GW. Nearly 90% of capacity additions in the EU were behind-the-meter storage, mostly in **Germany** and **Italy** where high retail electricity prices and supportive policy incentivise pairing rooftop solar installations with battery storage. The **UK** is Europe's largest market for utility-scale batteries, adding over 1 GW in 2023 (IEA, 2024).
- **Australia, Japan** and **Korea** are also significant leaders in installations. **Chile** is the first country in Latin America to deploy battery storage at scale.
- Capacity growth is expected to broaden into new markets (e.g. in India and sub-Saharan Africa) with significant growth potential (IEA, 2024). Current installations in these markets are primarily used to back up unreliable grid connections (e.g. over three quarters of installations in Nigeria). Installations are expected in increase significantly as electrification efforts increase; over 80% people without access to electricity live in rural and remote areas where mini-grids and stand-alone systems powered by increasingly affordable solar pv offer the cheapest and most pragmatic solution for electrification.

Reinforcing or enabling change



- **Falling prices are driven by economies of scale, and learning by doing**, especially through the exponential growth of markets for battery electric vehicles (RMI, 2023). **Changes in battery chemistry** (e.g. increasing use of lithium iron phosphate, reducing need for nickel and cobalt) as well as improvements in design have played a significant role (IEA, 2025).
- **Falling prices have driven rapid rises in capacity additions** at a rate of 67% per year over the last decade.
- **Co-location with renewable power generation** can improve the business case for developing new utilities by enabling them to be more flexible in meeting demand. Policy to incentivise or mandate co-location is accelerating deployment in some regions.
- **Batteries can provide multiple services**, including **supporting grid-flexibility**, but also providing ancillary and back-up services and congestion management in transmission and distribution systems.
- **Flexible battery storage can enable domestic consumers to reduce energy costs** and increase benefits of rooftop solar installation.
- Low prices for critical minerals also contributed to lower costs last year.
- **Developing circular and recycling systems for critical minerals** can help keep prices stable and lower costs for producers and consumers. It also reduces harm from mining and can improve public support (RMI, 2024).

Balancing or resisting change



- Lack of adequate **regulatory frameworks for battery storage** in many countries slows investment and deployment. Many countries lack appropriate remuneration schemes for battery storage or have other regulatory barriers to market access (IEA, 2024).
- **Slow deployment of smart-meters and slow modernisation of grid management systems**, especially in emerging and developing markets, slows deployment of battery storage.
- **Delays in obtaining planning consent and grid connections** are slowing deployment in many jurisdictions (IEA, 2024).
- **Consolidation of manufacturers and supply chains, especially in China**, may lead to reduced competition and slow price declines (IEA, 2025).
- Concerns about the **availability of critical materials and environmental impacts**
- **Risks and benefits do not always receive balanced media attention, leading to misinformation**, which can slow public acceptance and investment.

Enabling policies:	
	• **Mandates, targets or incentives for co-location** of battery storage with new solar and wind developments. • **Contracts for differences** and other similar mechanisms (e.g. Australia's Capacity Investment Scheme) can provide more stable long-term revenue and lower barriers to investment. • Support for creating **secure, sustainable and resilient supply chains for critical minerals.** • **Feed-in-Tariffs, tax breaks, subsidies, low-interest loans** incentivise behind-the-meter installations. • **Enabling behind-the-meter installations to participate in energy markets** creates benefits for the energy system (e.g. increasing flexibility) and opens additional revenue streams for domestic and small-scale commercial installations (as e.g. in the UK).

Sources:

Ember (2025) Global Electricity Review 2025. Available at: https://ember-energy.org/latest-insights/global-electricity-review-2025/the-big-picture/

IEA (2024) Batteries and Secure Energy Transitions. International Energy Agency. Available at: https://www.iea.org/reports/batteries-and-secure-energy-transitions

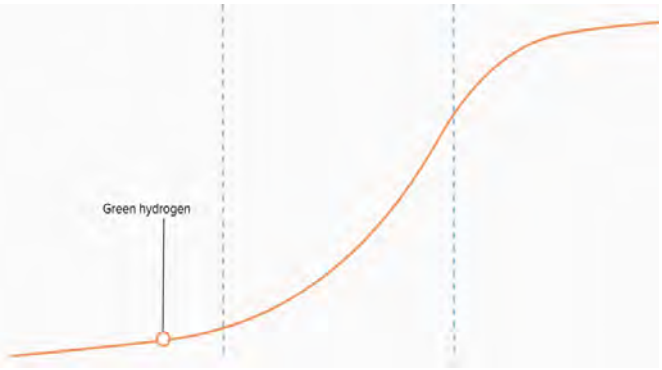
IEA (2025) The battery industry has entered a new phase. International Energy Agency. Available at: https://www.iea.org/commentaries/the-battery-industry-has-entered-a-new-phase.

RMI (2023) X-Change: The Battery Domino Effect. Rocky Mountain Institute. Available at: https://rmi.org/insight/x-change-batteries/

RMI (2024) The Battery Mineral Loop. Rocky Mountain Institute. Available at: https://rmi.org/insight/the-battery-mineral-loop/

GREEN HYDROGEN

Green hydrogen from electrolysis powered by renewable energy could replace grey hydrogen in industrial uses including in chemicals industries, production of steel and cement and manufacture of ammonia for fertiliser. Replacing current global hydrogen production would **remove around 2% of global greenhouse gas emissions.**



Progress:

Green hydrogen production is growing, from 1.0 Mt per year in 2023 to potentially 49 Mt per year in 2030 based on announced projects, or more than half of current hydrogen use in the economy (~97 Mt per year) (IEA, 2024). Global installed electrolyser capacity was nine times larger in 2024 than 2021 (0.2-5.6 GW), and investment in electrolyser installation grew from 0.3 bn USD to 7 bn USD in the same period. Although modelling studies suggest that electricity will play a much larger role than H2 as the main sector-coupling driver for achieving deep CO2 emission cuts towards GHG neutrality, hydrogen might still play a key contribution to decarbonize specific market segments in which electrification is challenging or not yet commercially available, for example primary steel-making (van der Zwaan et al., 2025).

Although green hydrogen is currently more expensive than grey and blue, **it could become the cheapest form of hydrogen with continued government support**. Costs are expected to reduce and – subject to market uptake, electrolyser innovations and lower renewable energy costs – could be 66% lower by 2030 (IEA, 2024).

- **China** is the world's largest hydrogen producer and consumer, and has made green hydrogen a key element of its decarbonisation strategy.
- In **Brazil** green hydrogen is already cost-competitive with domestic fossil-fuel based hydrogen production under current policies (Vercoulen et al., 2025).
- **The USA, European Union, India, Japan, Germany** and other countries have set ambitious hydrogen production targets (IEA, 2024; RMI, 2025*a*, RMI 2025*b*). Net energy importers with strong renewable energy potential like **Chile, Morocco and Namibia** are also emerging as major players in the global green hydrogen market. Affordable green hydrogen could offer transformative industrialisation opportunities for emerging markets and developing economies.

Reinforcing or enabling change



- Green hydrogen electrolysers are becoming more **modular and standardised, enabling fast scaling** at low cost, with high learning rates of 18% cost reductions per doubling of output.
- **Plummeting costs of renewable energy** are also driving costs lower.
- With **policy support** and market uptake, learning-by-doing enables faster, more efficient production.
- Larger, **automated production facilities** could reduce costs by 80% in the longer term.
- **International cooperation on hydrogen storage and transportation standards** could reduce logistical barriers to scaling (Cordonnier and Saygin, 2022).
- Increasing **innovation and development of end-use applications** (particularly in transport and shipping) can help to expand markets.

Balancing or resisting change



- **Costs remain high**. Green hydrogen currently costs 2-3 times more than grey hydrogen. Significant interventions (e.g. carbon pricing combined with mandates) are likely necessary for green hydrogen to be economically competitive in the near- to mid-term (Vercoulen et al., 2025).
- **Thermodynamic constraints**: whereas solar plus batteries provides a huge energy efficiency saving when replacing fossil fuels, hydrogen production doesn't, limiting its uses (Johnson et al., 2025).
- **Lack of finance** for inexpensive renewable energy and infrastructure, especially in emerging markets and developing countries.
- **Storage and transportation challenges** due to relative bulk and safety risk. The high costs of storing and transporting hydrogen limit its usefulness in many potential applications (Johnson et al., 2025).
- Lack of **availability of critical materials** (e.g. iridium) for green hydrogen electrolysers if proton membrane technology continues to be used.
- **Lack of investor certainty** around projected hydrogen demand (OECD, 2024; McKinsey, 2024).

Enabling policies (ETC, 2021):	• The greatest opportunity to scale up green hydrogen quickly is to **create economies of scale for its use in sectors where it can replace grey hydrogen** – ammonia production for fertilisers, crude oil refining, and methanol production. • **Mandates for green hydrogen in steel and ammonia production** are needed to crowd in private investment to build larger, standardised plants and green hydrogen hubs. • **International coordination of policy** across industrial users of green hydrogen can accelerate learning and economies of scale. • **Significant policy support through public investment and financial incentives** to increase the price of fossil fuels and lower the cost of renewable energy will help to reduce costs of green hydrogen production. • **Elimination of fossil fuel subsidies and increased carbon pricing** can make green hydrogen more competitive.

Sources:

Cordonnier, J. and Saygin, D. (2022) 'Green hydrogen opportunities for emerging and developing economies: Identifying success factors for market development and building enabling conditions', OECD Environment Working Papers [Preprint], (205). Available at: https://doi.org/10.1787/53ad9f22-en.

ETC (2021) Making the hydrogen economy possible: Accelerating clean hydrogen in an electrified economy. The Energy Transitions Commission. Available at: https://energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Hydrogen-Report.pdf.

IEA (2024) Global Hydrogen Review 2024. International Energy Agency. Available at: https://www.iea.org/reports/global-hydrogen-review-2024/.

Johnson, N. et al. (2025) 'Realistic roles for hydrogen in the future energy transition', Nature Reviews Clean Technology, 1(5), pp. 351–371. Available at: https://doi.org/10.1038/s44359-025-00050-4.

McKinsey (2024) Global Energy Perspective 2023: Transition bottlenecks and unlocks | McKinsey. McKinsey and Company: McKinsey Energy Solutions. Available at: https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2023-transition-bottlenecks-and-unlocks.

OECD (2024) Leveraging de-risking instruments and international co-ordination to catalyse investment in clean hydrogen. Paris: OECD. Available at: https://www.oecd.org/en/publications/leveraging-de-risking-instruments-and-international-co-ordination-to-catalyse-investment-in-clean-hydrogen_9a377303-en/full-report.html.

RMI (2025a) Green Hydrogen Production Pathways for India. Rocky Mountain Institute. Available at: https://rmi.org/green-hydrogen-production-pathways-for-india/.

RMI (2025b) Hydrogen — Made in America, For America. Rocky Mountain Institute. Available at: https://rmi.org/insight/hydrogen-made-in-america-for-america/.

Vercoulen, P. et al. (2025) EEIST: Can demand for green fertiliser accelerate electrolytic hydrogen supply? Available at: https://eeist.co.uk/eeist-reports/can-demand-for-green-fertiliser-accelerate-electrolytic-hydrogen-supply/.

van der Zwaan, B. et al. (2025) 'Electricity- and hydrogen-driven energy system sector-coupling in net-zero CO2 emission pathways', Nature Communications, 16(1), p. 1368. Available at: https://doi.org/10.1038/s41467-025-56365-0

ENERGY & POWER: **DEMAND**

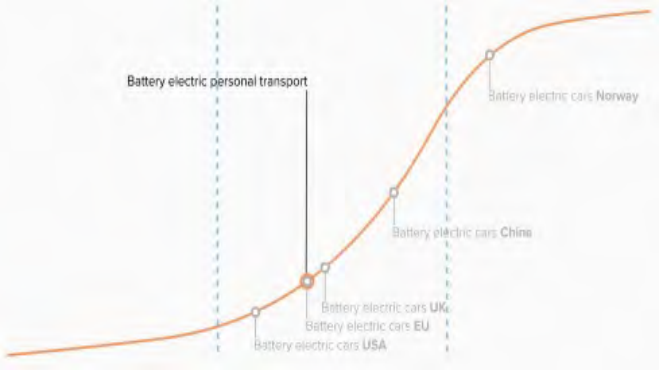


Electrifying energy demand is essential for renewables to replace fossil fuels. Since around 60% of primary energy is used as fossil fuels (mainly oil and gas) in transport, buildings, and industry, electrifying these sectors is crucial to cut greenhouse gas emissions and strengthen energy security (Ember, 2025). In hard to electrify sectors such as shipping and aviation, opportunities exist for the manufacture of green fuels using renewable electricity.

Ember (2025) The electrification imperative. Ember. Available at: https://ember-energy.org/latest-insights/the-electrification-imperative.

BATTERY ELECTRIC PERSONAL TRANSPORT

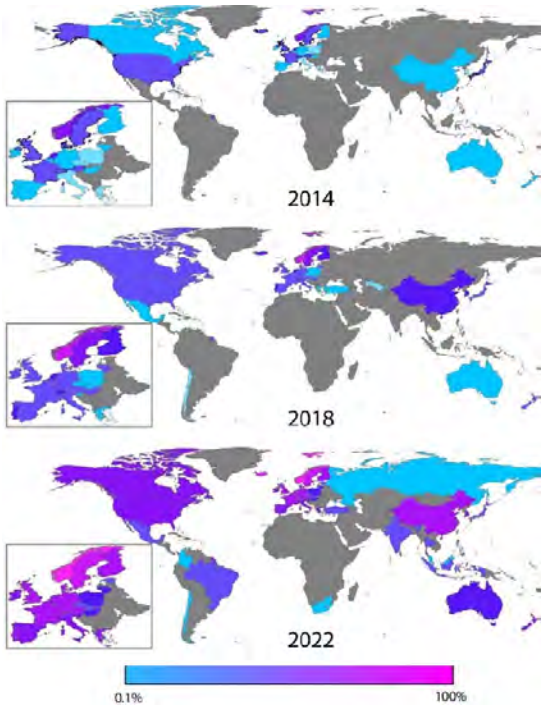
Electrifying cars and 2 and 3 wheeled transport could **remove 9% of current global greenhouse gas emissions** and improve air quality in cities.



Progress:

Sales of battery electric vehicles continue to increase rapidly in key markets, following S-curves driven by cost declines and performance improvements, with deployment spilling over into other markets as a result (Figure 3.3.3). More than 20% of all new cars sold globally in 2024 were battery electric vehicles (BEVs), a 25% increase on 2023 (IEA 2025). The global stock of BEVs has reached almost 58 million, about 4% of the total stock, displacing over 1 million barrels per day of oil consumption. The global average price of BEVs fell in 2024, driven by falling battery prices, but a purchase price gap with conventional vehicles remained in many markets outside China. Public charging stations have doubled in the last 2 years, keeping pace with EV sales. Strong sales growth looks set to continue in 2025.

2- and 3-wheeled vehicles which provide essential personal and commercial transport in cities, and particularly in the global South, are furthest ahead in electrification: in 2024 38% of 2-wheeler sales were electric; in the smaller 3-wheeler sector, this grew to 80% (BNEF 2025). In both sectors cheaper lead batteries are still popular, but lithium-ion vehicles are gaining traction.



- **China**: roughly 1 in 10 cars is now electric (including BEV and hybrid vehicles). In 2024 roughly 11 million electric vehicles were purchased in China (of which more than 6 million were BEVs), more than all global sales in 2022, and electric vehicles have overtaken conventional cars with more than 50% market share since July 2024. The median purchase price of BEVs was around USD 24,000, about USD 700 less than for an internal combustion engine vehicle (ICEV). China accounted for more than 70% of global production in 2024, largely for the domestic market, but numerous Chinese car makers have recently announced foreign direct investment plans signalling a ramping up of overseas production to supply other markets (IEA, 2025).
- **Norway**: with near total electrification of car sales (BEVs 88% of market share in 2024), Norway has passed through the acceleration phase and is now in the stabilisation phase of the S-curve. Norway is now imposing increasingly stringent taxes on conventional cars and hybrid vehicles, aiming to reach 100% BEV market share in 2025. This tipping point in sales will still take several years to convert the whole of Norway's car fleet to electric vehicles; 1 in 3 cars currently in use in Norway was electric in 2024 (IEA, 2025).
- **UK**: BEV sales reached a nearly 20% market share in 2024, driven in part by the introduction of progressively stringent targets under the new Vehicle Emissions Trading Scheme. Including hybrid vehicles, electric cars took nearly 30% market share. Charging infrastructure development has not kept pace however, with the number of vehicles per charging station increasing in 2024 (IEA, 2025).

Figure 3.3.3: BEV adoption (per cent of market share) and spillovers from major markets into peripheral and developing markets from 2014-2022 (adapted from Mercure et al., 2025 (in press).

- **EU**: electric car sales remained around 20% of market share in the EU as a whole for 2024, as policy support was weakened or phased out in key markets including **France** and **Germany**, leading to stalling or declining sales, though initial reports suggest that growth is returning in 2025 (Rueters 2025). Growth in sales continued in 14 out of 27 member states however, including in **Denmark**, where sales of electric vehicles increased 10 percentage points to reach 56% market share. Initial reports suggest
- **USA**: Electric car sales increased to more than 10% market share in 2024, but the rate of growth slowed significantly from 2023. However, this came against a backdrop of stagnating sales in conventional cars, suggesting that electric car sales slightly boosted the overall market (IEA 2025).
- **Emerging markets**: electric vehicle sales doubled or more than doubled in many markets in **Asia**, **Africa**, and **Latin America** in 2024, albeit from low baselines compared to leading markets. **Brazil** is a notable leader in Latin America. In Asia, **Thailand, Malaysia , Indonesia** and **Vietnam** are all seeing rapid growth in sales, driven in part by reductions or exemptions on import taxes for electric vehicles for companies that invest in domestic production. In Africa, **Morocco** and **Egypt** have seen growth in sales, while Ethiopia's ban on imports of petrol and diesel cars has reportedly driven rapid deployment of 100,000 electric vehicles, though it appears that deployment of charging infrastructure and maintenance and repair capacity are struggling to keep pace. In India, levelised costs of 3-wheelers are lower than their ICEV equivalent. With subsidies, payback times are roughly 2 years

Reinforcing or enabling change



- **Falling prices and improving performance**, especially in batteries, continues to make BEVs more attractive to consumers. Cost reductions driven by economies of scale and learning by doing in major markets are making BEVs accessible in emerging markets. In most emerging markets in 2024, the purchase price of the cheapest electric vehicle was lower than the average price of an ICEV. 2 and 3 wheeled vehicles are seeing rapid innovation and accelerated learning as a result of their short lifetimes (~10 years).
- **Increasing model diversity** enables BEVs to compete in more market niches. The number of available models increased 15% year on year to reach 785 in 2024, passing 50% of the combined number of models of ICE and hybrid vehicles. Based on data for announced models, BEV models will reach 70% of combined ICE and hybrid models by 2027. In China, the number of electric models is already greater than the number of ICE and hybrid models, and the price distribution of BEVs closely matches that of ICEVs, with more than half of available electric models below USD 30,000.
- **Market competition and economies of scale in car manufacture** are also leading to price reductions.
- Tax exemptions or reductions (e.g. VAT, import taxes), or trade-in schemes can **reduce purchase and operating costs to make BEVs competitive with conventional cars**. In many countries this is being paired with incentives or requirements for importers to invest in domestic production facilities, boosting investment, jobs and skills as a co-benefit.

Balancing or resisting change



- **Purchase prices for BEVs remain higher than for conventional vehicles in most markets**, with limited availability of affordable car models. The same is true for 2 and 3 wheelers, for instance purchase price of 3 wheelers is on average 55% higher than fossil fueled alternatives in India. As 2- and 3-wheelers are popular in less affluent countries, this can pose an important barrier for uptake.
- Some important markets are phasing out or **weakening supportive policies**, including subsidies and tax incentives, including France, Germany and USA.
- **Delaying or weakening mandates** for the transition to electric vehicles creates uncertainty, slowing investment and innovation.
- **Tariffs and trade restrictions are slowing trade in BEVs**, especially reducing access to markets in the UE, USA and elsewhere for China, which manufactures the highest numbers, and lowest cost, BEVs.
  - » A longer-term effect of this is to drive accelerated investment by Chinese car makers in manufacturing capacity in other markets, including EU, South East Asia and Brazil, which may ultimately accelerate production and sales. Chinese overseas manufacturing capacity is expected to double to over 4.3 million vehicles per year by 2026.
- **Vehicle oversizing increases electricity demand**, making decarbonising electricity more difficult, and may reduce EV support due to greater risks to pedestrians from heavier cars (ACEEE , 2024).
- **Public perceptions remain mixed** and susceptible to misinformation and negative portrayals of BEVs (e.g. on demand, performance, price, environmental and other impacts) in the media (ECIU, 2025).

Enabling policies:

- **Emergence phase**: for countries at the beginning of the S-curve, boosting investment in R&D, reducing import costs, investment in building and scaling charging infrastructure and public procurement of BEVs can help to drive initial market growth.
- **Acceleration phase**: Reducing purchase and operating costs through tax exemptions and subsidies, alongside expanding charging infrastructure and support services, helps sustain and boost BEV growth. In countries with strong vehicle manufacturing industries, support with transition costs and investment in manufacturing will likely be key for public support.
- **Stabilisation phase**: In countries in the later phase of transition, increasing taxes on conventional and hybrid vehicles can help stabilise BEV ownership as the new status quo. Purchase subsidies and trade-in schemes can help offset the purchase price difference in markets where BEVs remain more expensive.
- **At city scales**, low-emissions zones and other local restrictions can drive BEV adoption as well as improving public health and reducing congestion.

Sources:

ACEEE (2024) Electric Vehicle Efficiency: Unlocking Consumer Savings and Environmental Gains. American Council for an Energy Efficient Economy.

BNEF (2025) Electric Vehicle Outlook. BloombergNEF. Available at: https://about.bnef.com/insights/clean-transport/electric-vehicle-outlook/.

ECIU (2025) Releasing the handbrake: unpacking misinformation on Electric Vehicles in UK print media. Energy and Climate Intelligence Unit. Available at: https://ca1-eci.edcdn.com/EV-Media.pdf?v=1756218634.

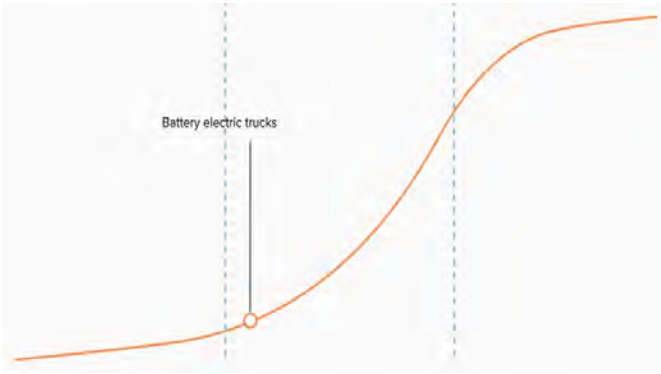
IEA (2025) Global EV Outlook 2025. International Energy Agency. Available at: https://iea.blob.core.windows.net/assets/0aa4762f-c1cb-4495-987a-25945d6de5e8/GlobalEVOutlook2025.pdf.

Reuters (2025) Germany sees record e-car sales in first half of year, data show | Reuters, Reuters. Available at: https://www.reuters.com/markets/europe/germany-sees-record-e-car-sales-first-half-year-data-show-2025-07-16/ (Accessed: 18 September 2025).



BATTERY ELECTRIC ROAD FREIGHT

Electrifying road freight could **remove up to 6% of global greenhouse gas emissions.**



Progress:

Global sales of full electric trucks are growing rapidly, increasing 35% year on year from 2022 to 2023 to reach 0.9% of global market share (Akther et al., 2025). More than 400 models of battery electric truck are available, up from fewer than 70 in 2020, indicating increasing diversity and ability to fulfil different applications and niches. Lifetime total cost of ownership (TCO) has either passed or is rapidly approaching parity with diesel and petrol vehicles in many markets.

- **China** represented over 80% of global sales in 2024 (IEA, 2025). Rapid development and innovation in batteries and trucks, subsidies, procurement requirements and clean air zones in cities have driven deployment and cost reductions.
- **EU**: second behind China in deployment, driven largely by stringent emission standards.
- **India**: Strong progress in electrifying 2- and 3-wheeled vehicles often used for last-mile delivery, with >50% of sales of 3 wheelers electric in 2022. In this sector, the cost of zero-emission vehicles (ZEVs) is already substantially lower than alternatives. For medium- and heavy-duty vehicles, higher purchase prices offer a significant barrier to adoption.

Reinforcing or enabling change



- **Advances in light road transport** have significantly improved battery performance, lowered costs, and driven development of charging infrastructure.
- **Operating costs for battery electric trucks are significantly lower** than for petrol and diesel trucks in many markets:
- For **medium-duty ZEVs**, lifetime cost of ownership is likely already lower than that of petrol and diesel trucks in China, roughly equal in the USA and only slightly higher than diesel trucks in India.
- For **heavy-duty ZEVs**, lifetime costs of ownership are lower than for petrol and diesel trucks in India and China, and slightly higher in USA and Germany.
- 33 countries are part of the Global Memorandum of Understanding on Zero-Emission Medium- and Heavy-Duty Vehicles, committed to reaching a 30% ZEV sales share sales by 2030, and 100% by 2040.

Balancing or resisting change



- Although lifetime cost of ownership is lower for ZEVs in many markets, **purchase costs remain high** (1.5-2 times the cost of petrol and diesel trucks) which can present a barrier to transition for smaller companies who are less able to make large capital investments.
- **Performance of ZEVs is still catching up with petrol and diesel trucks.** Long charging times, lower payloads relative to petrol and diesel vehicles, and lack of supporting infrastructure reduce attractiveness and performance of ZEVs.

Enabling policies:

- **Regulatory policies** including fleet-wide emissions reduction standards and especially ZEV mandates are likely to achieve the fastest transition. City scale zero-emission or low-emission zones can also be effective at growing the market for ZEVs.
- **Subsidy can enable capital-constrained businesses to transition their fleets** and benefit from the lower operating costs of battery operated trucks (Mission Possible Partnership, 2022).
- **International cooperation among the largest markets** (especially China and EU, but also India, Canada and supportive US states) for zero-emission freight can significantly bring forward a tipping point of price-parity in total cost of ownership.
- **Well aligned policy can incentivise supply chain optimisation** that takes charging infrastructure and schedule into account. For example, mandated rest periods, like the 45 minutes required in the EU, can reduce the opportunity cost of longer charging times en route, enabling drivers to add 150–400km of driving range while resting depending on charger capacity.
- **Policy support for battery swapping** makes green trucking more attractive logistically and cost-wise.

Sources:

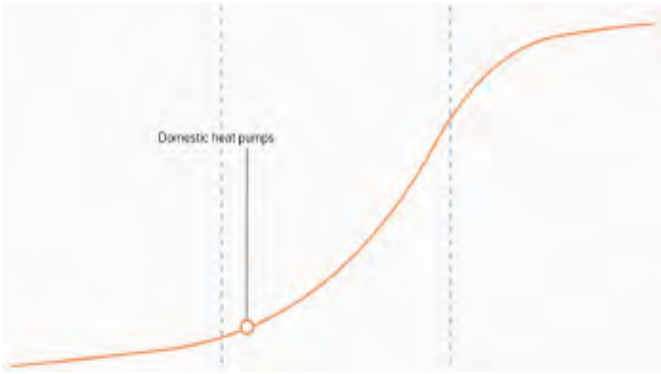
Akther, A. et al. (2025) EEIST: Driving the Transition to Zero-Emission Trucks. Available at: https://eeist.co.uk/eeist-reports/driving-the-transition-to-zero-emission-trucks/

IEA (2025) Global EV Outlook 2025. International Energy Agency. Available at: https://iea.blob.core.windows.net/assets/0aa4762f-c1cb-4495-987a-25945d6de5e8/GlobalEVOutlook2025.pdf.

Mission Possible Partnership (2022) Making Zero-Emissions Trucking Possible. Mission Possible Partnership. Available at: https://staging.missionpossiblepartnership.org/wp-content/uploads/2022/11/Making-Zero-Emissions-Trucking-Possible.pdf.

DOMESTIC HEAT PUMPS

Electrifying home heating could **remove 6% of global greenhouse gas emissions.**



Progress:

Progress: Globally, around 10% of space heating was met by heat pumps in 2021 but the rate of installation is growing rapidly (15% growth in 2021) (IEA 2022). Heat pumps are already less emissions-intensive than fossil fuel boilers in almost all countries. As the electricity supply is decarbonised, this will continue to increase. In some countries, heat pumps are already the largest heating source.

- In **Norway**, 60% of buildings are equipped with heat pumps.
- **China** is the largest market for new sales, while the **USA** has the largest number of residential home installations (IEA, 2022).
- In the **USA**, heat pumps outsold gas furnaces by 30% in 2024, the largest gap ever recorded (IEA, 2025; Knobloch et al., 2020).
- **Total cost of ownership** of heatpumps is already lower than for a fossil fuel boiler in some countries, including **Denmark** and **Italy**.

Reinforcing or enabling change



- **Increasing returns to adoption:** economies of scale and learning curves. The more heat pumps deployed, the lower their purchase price and the better their performance.
- Greater use of heat pumps r**educes dependence on imported fossil fuels**, improving the balance of payments and domestic energy security.
- Heat pump running **costs are typically lower than gas boilers**, reducing exposure to gas price spikes.
- A **stable regulatory environment** with long-term targets (e.g. phase-out dates) increases industry and customer confidence in the transition.
- **Improved building insulation reduces energy demand**, reducing strain on the grid and raising the efficiency of heat pumps.
- **Peer effects of technology adoption** have been observed for heat pumps. As more households in a community adopt, it supports others to adopt, particularly through word-of-mouth dissemination.

Balancing or resisting change



- **High upfront cost** of purchase and installation
- **Higher running costs where there is a high electricity-to-gas price ratio**, often due to subsidy policies.
- Installers' **perception of a lack of heat pump demand from households.**
- **Low rate of training** of new heat pump installers and engineers.
- **A long installation timeline compared to a replacement boiler** increases challenges for 'distress purchases'.
- **Misinformation in the media**, promoted by vested interests, has in some regions created a negative narrative environment and increased uncertainty
- Heat pumps reduce total domestic energy consumption, but total electricity consumption will significantly increase, requiring **significant investment in electricity infrastructure, flexibility, and storage.**

Enabling policies:

- **Mandates on the sale and installation of heat pumps**, regulations for new homes, and the **phase-out of fossil fuel boilers** are likely the most cost-effective measures to increase the market share of domestic heat pumps.
- Rebalance taxes and levies on electricity prices to **reduce the electricity-to-gas price ratio**, such that the efficiency gains of heat pumps result in running cost savings over fossil fuel boilers.
- Interventions for upfront cost: Low- or zero-interest loan schemes to **help households afford the higher upfront costs of heat pumps**. Boiler upgrade schemes offering grants to replace fossil fuel boilers with heat pumps.
- Training for heat pump installers, Incentive schemes and streamlining of certification processes to **build a certified installer base.**
- Subscription-based **"heat as a service" schemes.**
- **Align international policy action in the largest markets** for heating to enable faster cost declines through learning curves and economies of scale.
- **International standards** of heat pump performance requirements help reduce costs by lowering compliance costs for manufacturers.
- **Investing in digital technologies** that allow heat storage systems to operate when electricity demand and prices are low.
- **Public engagement campaigns** and 'one-stop shops' that streamline the customer journey and provide trustworthy information.
- **Customer protection and industry standards** will increase consumer trust in the quality of heat pump installations and increase heating efficiency.

Sources:

Hassett, K. et al. (2024), "Household energy choices: New empirical evidence and policy implications for sustainable behaviour", OECD Environment Working Papers, No. 247, OECD Publishing, Paris, https://doi.org/10.1787/534a14fe-en

IEA. (2022). The Future of Heat Pumps. World Energy Outlook Special Report. https://www.iea.org/reports/the-future-of-heat-pumps/executive-summary

IEA. (2025).Global Energy Review. Global Energy Review 2025

Knobloch, F., Hanssen, S., Lam, A. et al. Net emission reductions from electric cars and heat pumps in 59 world regions over time. Nat Sustain 3, 437–447 (2020). https://doi.org/10.1038/s41893-020-0488-7

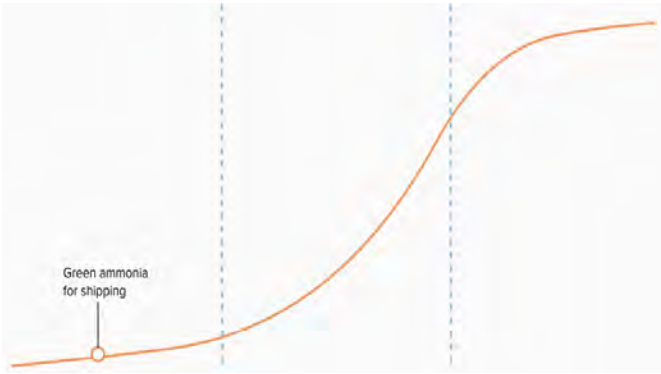
Olympios, A. V., Justo Alonso, M., & pantaleo, A. M. (2025). Heat pumps in Europe: Perspectives and innovation challenges. Progress in Energy.

Zhang, H., Zielonka, N., & Trutnevyte, E. (2024). Patterns in spatial diffusion of residential heat pumps in Switzerland. Renewable Energy, 223(120032).



GREEN AMMONIA FOR FERTILIZER AND SHIPPING FUEL

Use of green ammonia to manufacture fertiliser could **remove 2% of global greenhouse gas emissions**, and could lower costs sufficiently to make it viable as a fuel in long-range shipping, **removing a further 2% of global greenhouse gas emissions** and reducing black carbon emissions.



Progress:

Cost effective production of green ammonia by reacting green hydrogen with nitrogen separated from air could accelerate its use in fertilisers for agriculture (70% of ammonia use), industrial applications including plastics, explosives, and synthetic fibres, and sustainable fuels for long-range shipping (OECD, 2025).

Green hydrogen for ammonia production can only be cost-competitive in regions with plentiful, low-cost renewable electricity supply, and **scaling production is dependent on continuing rapid deployment of renewables**. Forecasts of the compound annual growth rate for green ammonia range from 70% to 88%, driven by environmental concern, strong government support, advances in green hydrogen electrolyser technology, and demand for sustainable fertilisers and alternative fuels. **Cost parity** of green ammonia with conventional ammonia is expected in most markets from 2034 (BloombergNEF, 2024), but will require considerable policy support to do so. Reaching cost-parity for fertiliser production (currently the largest market), can enable further cost reductions that increase competitiveness for other uses including shipping fuels.

- The **Asia-Pacific** region is the leading producer of green ammonia, led by China.
- **Australia** and **India** are emerging as key players due to their renewable energy potential and strong government support.
- **Brazil's** supportive policy environment for green hydrogen production could enable it to become self-sufficient in green ammonia fertilisers for it's agricultural industry (Vercoulen et al., 2025).

In 2025 the **International Maritime Organisation published the first interim safety guidelines for use of ammonia as a shipping fuel** (IMO, 2025), setting in place a risk-assessment and management framework to facilitate early adopters. As of September 2025 **77 ammonia-ready vessels are operational**, and a further 154 ammonia-fueled vessels and 261 ammonia-ready vessels have been ordered and announced (Ammonia Energy Association, 2025). The first operational vessels are small-scale supply ships and tug boats, with ammonia carriers and bulk carriers among the vessels ordered.

Reinforcing or enabling change



- **Falling costs and rapid deployment of renewable energy** generation and storage reduce the cost of green hydrogen more rapidly than improvements in electrolyser technology (Vercoulen et al., 2025).
- **Economies of scale and learning curves:** 18% cost reductions per doubling of output have been experienced for hydrogen electrolysers (IRENA, 2020)
- **Further enabling policies** (e.g. mandates and price mechanisms) are likely to be necessary to make green ammonia competitive in the near to mid-term (Vercoulen et al., 2025).

Balancing or resisting change



- **Current hydrogen policies are insufficient** to start the large-scale deployment of electrolytic hydrogen production globally.
- **Subsidies for fossil fuels and low carbon prices** make it difficult for green ammonia to achieve cost parity.
- **Low-replacement rates of existing plant and infrastructure**, and sunk costs of investments in hydrogen and ammonia production from fossil fuels, slow investment in new infrastructure.

Enabling policies:

- Small group coalition of leading countries could introduce a **blending mandate of 25% green ammonia in fertiliser production** (Meldrum et al., 2023)
- Meet the **International Maritime Organisation's target** to achieve at least 5% utilisation of zero-emission fuels by 2030.
- **Create a clean hydrogen strategy** (as in Japan, South Korea, China, USA, EU, India, Australia and elsewhere).
- **Policies guaranteeing long-term low renewable energy costs.**
- **Public investment in green hydrogen electrolysers and infrastructure** (e.g., ammonia bunkering in ports) (RMI, 2024).
- **Eliminate fossil fuel subsidies and increase carbon price** (Lee and Saygin, 2023).

Sources:

Ammonia Energy Association (2025) LEAD: Ammonia-Fueled Vessels. Available at: https://ammoniaenergy.org/wp-content/uploads/2025/09/AEA-LEAD-Vessels-Executive-Summary-September-2025.pdf

BloombergNEF. (2024). Scaling Up Hydrogen: The Case for Low-Carbon Ammonia. Available at: https://assets.bbhub.io/professional/sites/24/CTC-whitepaper_Ammonia_Final.pdf.

IMO (2025) 'Interim Guidelines for the Safety of Ships using Ammonia as Fuel'. Available at: https://www.bimco.org/media/bxvcygg1/msc1-circ1687-interim-guidelines-for-the-safety-of-ships-using-ammonia-as-fuel-secretariat.pdf.

IRENA. (2020). Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf.

Meldrum, M. et al. (2023), The Breakthrough Effect: How to trigger a cascade of tipping points to accelerate the net zero transition. Available at: https://www.systemiq.earth/wp-content/uploads/2023/01/The-Breakthrough-Effect.pdf

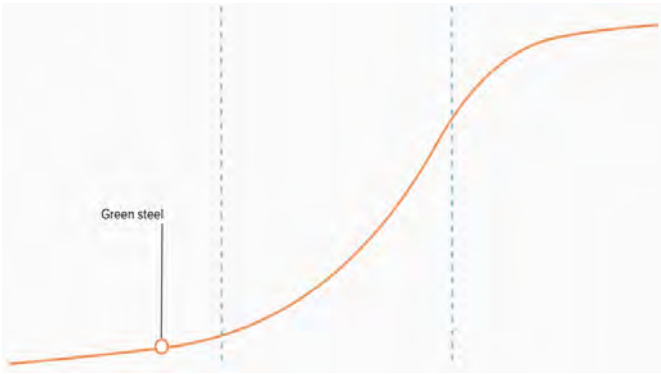
OECD. (2025). Leveraging positive tipping points in the race to net zero. OECD Net Zero+ Policy Paper No. 12. OECD Publishing, Paris. Available at: https://doi.org/10.1787/50b737f8-en.

RMI. (2024). Oceans of Opportunity: Supplying Green Methanol and Ammonia at Ports. RMI and Global Maritime Forum. Available at: https://rmi.org/insight/oceans-of-opportunity/

Vercoulen, P. et al. (2025) EEIST: Can demand for green fertiliser accelerate electrolytic hydrogen supply? Available at: https://eeist.co.uk/eeist-reports/can-demand-for-green-fertiliser-accelerate-electrolytic-hydrogen-supply/.

GREEN STEEL PRODUCTION

Transitioning to green steel production could **remove 7% of global greenhouse gas emissions**



Progress:

Hydrogen-based DRI combined with electric arc furnace technology is rapidly emerging as a key pathway for green steel production, while major steel-producing countries and companies are setting ambitious targets for low- and zero-carbon innovation and investment.

However, the rate of deployment is still slow, with only **11 full scale green hydrogen DRI steel plants planned to be operational by 2030** (Mission Possible Partnership, 2022; Stockholm Environment Institute, 2025).

Reinforcing or enabling change



- Green hydrogen DRI has the largest GHG emissions mitigation potential and could generate reinforcing feedbacks through learning curves and economies of scale. As more green hydrogen electrolysers come into operation, **cost reductions of up to 18% per doubling of output are possible.**
- A positive tipping point becomes more likely once **at least 6% of steel plants adopt DRI** technology (approximately 25 plants).

Balancing or resisting change



- **Green steel production costs are higher** than coal-fired blast furnaces
- **Slow replacement rate** of steel production facilities
- **Low quality of iron ore.** Currently, only 13% of iron ore shipped for processing meets the required quality for DRI steelmaking.
- **Job losses** associated with phasing out old infrastructure.

Enabling policies:

- Policy instruments, including measures to **lower the unit price of green hydrogen and the unit price of renewable energy.**
- Financial instruments to **de-risk investments in emerging markets and developing economies.**
- **Mandates for phasing in green hydrogen DRI technology and phasing our blast furnaces** are likely to offer the fastest and most cost-efficient decarbonisation pathway for steel production.
- **Require green steel for publicly funded construction projects.**
- **Small group coalitions of leading steel producers** (eg China, India, Japan, USA) **coordinate policies** and overcome first-mover risks (Meldrum et al., 2023).
- **Strategic planning and support for workers** who face the risk of job losses during the transition.

Sources:

Meldrum, M. et al. (2023) The Breakthrough Effect: How to trigger a cascade of tipping points to accelerate the net zero transition. Available at: https://www.systemiq.earth/wp-content/uploads/2023/01/The-Breakthrough-Effect.pdf.

Mission Possible Partnership (2022) Making Net-Zero Steel Possible: An industry backed, 1.5oC-aligned transition strategy. Mission Possible Partnership. Available at: https://3stepsolutions.s3-accelerate.amazonaws.com/assets/custom/010856/downloads/Making-Net-Zero-Steel-possible.pdf.

SEI (2025) Green Steel Tracker, Stockholm Environment Institute. Available at: https://www.sei.org/tools/green-steel-tracker/ (Accessed: 18 September 2025).

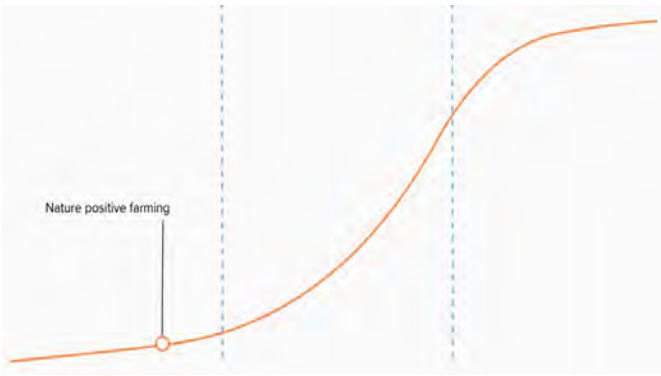


FOOD, LAND USE **& NATURE**

Food production and other land uses are responsible for up to a third of global greenhouse gas emissions, are the largest driver of nature and biodiversity loss, and pose direct threats to critical ecosystems in danger of tipping points (see 4.1 Amazon Case Study and 4.3 Coral Reefs Case Study). Urgent and complementary actions are required to end deforestation, shift to nature positive farming, reduce food waste and shift food demand in overconsuming societies. These are discussed further in GTPR2023, and Chapter 3.5

SHIFT TO NATURE POSITIVE AGRICULTURE

Shifting to nature positive farming could **remove CO2 from the atmosphere, increase soil health** and **build resilience to extreme weather.** System-wide adoption is likely dependent on other shifts in food waste, food demand and supply chain reforms.



Progress:

Absolute global numbers are difficult to report, however a number of initiatives and practices demonstrate effective scaling in different contexts.

- 'Conservation agriculture' (CA), promoted by the UN Food and Agriculture Organisation, has scaled at a rate of roughly 10 M ha per year, almost doubling from 107 Mha in 36 countries in 2008/9 to 205 M ha in 102 countries in 2018/19, roughly 15% of global cropland (Kassam et al 2022).
- Between 2000 and 2023, the global share of organic agricultural land (including crops and pasture) rose from 14.9 M ha to 98.9 M ha farmed by 4.3m farmers in 188 countries (2.1% of total global farmland) (Trávní□ek, et al. 2025). The global organic food market has grown to over USD $136bn in the same time, with the largest markets in USA, Germany and China. 22 countries have 10% or more of their agricultural land under organic management (e.g. Austria at 27%).
- Many smaller scale initiatives have scaled effectively where they offer direct and clear benefits to farmers, e.g. diversified incomes, lower input costs, improved soil health and other synergistic ecological and economic and/or social outcomes.
- The Danish Green Tripartite Agreement passed into law in June 2024. This is an accord between the Danish government, agricultural sector, and environmental groups to achieve climate, nature, and water quality targets through land-use changes and the world's first carbon tax on agriculture (with revenues directed back into agriculture to fund climate and nature positive solutions).

Reinforcing or enabling change



- **Policy, subsidies and incentives:** clear policy goals supported by effective incentives or subsidies help to make alternative farming models economically attractive and overcome transition costs.
- Access to **markets for new or premium products and/or ecosystem services, including carbon sequestration**, can similarly provide economic incentives and drive adoption (e.g. Benjamin and Sauer, 2018). **Valuing natural capital** in farming landscapes can substantially alter the balance sheets for farmers, incentivising investment in resilient and healthy agroecosystems (Alexanderson, Luke, and Lloyd 2024).
- **Lower input costs** can also be an incentive for farmers.
- **Effective labelling and standards, and access to certification.**
- **Concentrated supply chains** can offer more leverage for particular actors (traders, manufacturers, retailers etc.) to set standards, influence farmers and support them to transition to sustainable practices (e.g. Amazon Soy Moratorium (Box 3.5.1), Better Cotton Initiative, and other sector specific initiatives).
- **Increasing ecological and economic resilience**: Restoring ecosystem service provision (e.g. soil health, moisture management), lowering input costs and diversifying farm revenue (e.g. through payments for ecosystem services, mixed cropping etc.) can enhance economic outcomes and provide resilience to extreme weather events and crop failures, providing incentive for vulnerable farmers to transition.
- **Social contagion** among farmers can drive diffusion of nature positive practices among farmers in many contexts (Läpple and Kelley 2013, Padel 2001, Wollni 2014).
- **Network effects** and **information cascades** can also drive change in the networks of farm advisers, agronomists, financial advisers and agricultural training centres that strongly influence decision making among farmers.

Balancing or resisting change



- **Policy and public/private investment lock-ins**: Agricultural policy and incentive structures often prioritise productivity, low food prices, and technology-led solutions at the expense of environmental sustainability (Zhang and Drury 2024).
- **Transition costs for farmers**: Moving to nature positive practices may require capital investment for new equipment, certification or other expenses, and may incur other costs (labour, time, foregone yield). Farmers may need to invest in acquiring **new skills and capacity** to learn new methods of production and access new markets (including payments for ecosystem services and certification).
- **Yield penalty**: In some systems, switching to nature positive farming may incur a yield penalty. In some cases this may be a temporary dip in productivity, leading to long-term neutral or net positive impacts (Pathania et al. 2024).
- **Network effects**: Existing networks of farm advisers, agronomists, sales reps, financial advisers can create strong balancing feedbacks that maintain the system status quo. Peers and families may also have cultural and social expectations at odds with nature positive farming practices (Coon et al. 2025, Pathania et al. 2024)
- **Land Access**: Insecure tenure discourages long-term planning and investment (in equipment or natural infrastructure, such as tree planting as part of agroforestry). (Olabanji and Chitakira, 2025, Pathania et al. 2024).
- **Conflicting and confusing labelling and standards** can create confusion among consumers or be appropriated as marketing tools or 'greenwashing' (Wilson, Hendrickson, and Myers 2024, Bless, 2025)

Enabling policies:

- **Policy to facilitate financial benefits, and offset transition costs**; including subsidy and incentives, and markets for ecosystem service provision (Baker et al., 2025, Hilmi et al., 2024)
- **Set clear, measurable targets** through design of metrics and monitoring frameworks (Baker et al., 2025, HLPE, 2019)
- **Design and implement schemes at landscape scale** (Baker et al., 2025, HLPE, 2019)
- **Targeted and context specific interventions** are more effective at triggering widespread uptake (Kassam et al 2022, Funke and Munyaradzi, 2025). Policy design benefits from **participatory approaches engaging with farmers**, recognising them as crucial agents of change to facilitate collaboration and cooperation (Baker et al., 2025).

Sources:

Alexanderson, M.S., Luke, H. and Lloyd, D.J. (2024) 'Regenerative agriculture in Australia: the changing face of farming', Frontiers in Sustainable Food Systems, 8. Available at: https://doi.org/10.3389/fsufs.2024.1402849.

Baker, D.J. et al. (2025) 'Aligning strategic and participatory approaches to agri-environment scheme design and implementation to enhance nature recovery outcomes', People and Nature, 7(2), pp. 329–345. Available at: https://doi.org/10.1002/pan3.10785.

Benjamin, E.O. and Sauer, J. (2018) 'The cost effectiveness of payments for ecosystem services—Smallholders and agroforestry in Africa', Land Use Policy, 71, pp. 293–302. Available at: https://doi.org/10.1016/j.landusepol.2017.12.001.

Bless, A. (2024). The co-optation of regenerative agriculture: revisiting the corporate environmental food regime. Globalizations, 22(4), 590–612. Available at: https://doi.org/10.1080/14747731.2024.2397260

Coon, J.J. et al. (2025) 'Farmer Perceptions of Regenerative Agriculture in the Corn Belt: Exploring Motivations and Barriers to Adoption', Agriculture and Human Values, 42(3), pp. 1847–1864. Available at: https://doi.org/10.1007/s10460-025-10735-y.

Hilmi, Y.S. et al. (2024) 'Farmers' resilience to climate change through the circular economy and sustainable agriculture: a review from developed and developing countries', Renewable Agriculture and Food Systems, 39, p. e15. Available at: https://doi.org/10.1017/S1742170524000097.

HLPE (2019) Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. Rome: High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security,. Available at: https://openknowledge.fao.org/server/api/core/bitstreams/ff385e60-0693-40fe-9a6b-79bbef05202c/content.

Kassam, A., Friedrich, T. and Derpsch, R. (2022) 'Successful Experiences and Lessons from Conservation Agriculture Worldwide', Agronomy, 12(4), p. 769. Available at: https://doi.org/10.3390/agronomy12040769.

Läpple, D. and Kelley, H. (2013) 'Understanding the uptake of organic farming: Accounting for heterogeneities among Irish farmers', Ecological Economics, 88, pp. 11–19. Available at: https://doi.org/10.1016/j.ecolecon.2012.12.025.

Olabanji, M.F. and Chitakira, M. (2025) 'The Adoption and Scaling of Climate-Smart Agriculture Innovation by Smallholder Farmers in South Africa: A Review of Institutional Mechanisms, Policy Frameworks and Market Dynamics', World, 6(2), p. 51. Available at: https://doi.org/10.3390/world6020051.

Padel, S. (2001) 'Conversion to Organic Farming: A Typical Example of the Diffusion of an Innovation?', Sociologia Ruralis, 41(1), pp. 40–61. Available at: https://doi.org/10.1111/1467-9523.00169.

Pathania, S. et al. (2024) 'The Transition from Conventional Farming to Regenerative Agriculture: Problem, Global Reality, and Future Perspectives', in S. Kumar et al. (eds) Regenerative Agriculture for Sustainable Food Systems. Singapore: Springer Nature, pp. 15–48. Available at: https://doi.org/10.1007/978-981-97-6691-8_2.

Trávníček, J., Schlatter, B.; Helbing, M. and Willer, H. (2025) The World of Organic Agriculture 2025: Summary. In: Willer, Helga; Trávníček, Jan and Schlatter, Bernhard (Eds.) The World of Organic Agriculture. Statistics and Emerging Trends 2025. Research Institute of Organic Agriculture FiBL and IFOAM – Organics International, CH-Frick and D-Bonn, pp. 20-31. Available at: https://www.organic-world.net/yearbook/yearbook-2025.html

Wilson, K.R., Hendrickson, M.K. and Myers, R.L. (2025) 'A buzzword, a "win-win", or a signal towards the future of agriculture? A critical analysis of regenerative agriculture', Agriculture and Human Values, 42(1), pp. 257–269. Available at: https://doi.org/10.1007/s10460-024-10603-1.

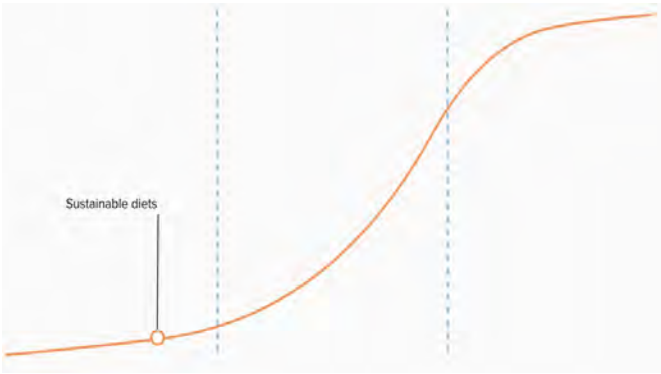
Wollni, M. and Andersson, C. (2014) 'Spatial patterns of organic agriculture adoption: Evidence from Honduras', Ecological Economics, 97, pp. 120–128. Available at: https://doi.org/10.1016/j.ecolecon.2013.11.010.

Zhang, J. and Drury, M. (2024) 'Sustainable agriculture in the EU and China: A comparative critical policy analysis approach', Environmental Science & Policy, 157, p. 103789. Available at: https://doi.org/10.1016/j.envsci.2024.103789.



ADOPTING SUSTAINABLE DIETS

Could remove up to **17% of global greenhouse gas emissions** from the livestock sector. Even small reductions can have powerful impacts for **reducing threats in critical ecosystems.**



Progress:

Progress: Meat consumption globally has continued to rise due to population growth and increasing incomes. **But in some high income countries meat eating has decoupled from economic growth** (including UK, USA, Canada, Australia, Saudi Arabia, New Zealand, Switzerland, Israel) and in some cases has begun to fall (Whitton et al 2021, Stewart et al 2021). Correspondingly, the number of people identifying as 'flexitarian', 'vegetarian' and 'vegan' has increased in many countries, often driven by overlapping concerns around health, environmental impacts and ethics of overconsumption of meat (Dagevos, 2021; Rosenfeld et al., 2020). In the **UK**, vegetarian food orders at quick-service restaurants increased by 64% and vegan food by 56% from 2023-2024 (Good Food Institute, 2024). If the 60% of the world's population who currently overconsume were to adopt sustainable diets, they could more than offset the approximately 15% increase in global GHG emissions associated with undernourished countries moving towards healthier diets (Li et al 2024).

Plant-based alternatives to livestock products - seen as an important enabler of diet shifts in overconsuming countries (Meldrum et al., 2023) - have shown strong growth in leading markets over the last decade, with global sales rising from $18bn USD in 2015 to $29bn in 2024, with sales of plant-based meats growing faster than milk alternatives and other products (Good Food Institute, 2024). However, sales of these products have slowed in recent years with some regions (including USA) experiencing consecutive years of sales declines. Many of these **products do not yet meet consumers' expectations on taste or price**, and Meat alternatives were between **24-115% more expensive** than the meat benchmark across European countries in 2023 (Siegrist 2024). Consumer concerns over nutrition and sustainability are also slowing sales. 'New-generation' processed plant-based alternatives tend to contain more salt and sugar than processed meat products, but are also richer in fibre and lower in calories and saturated fat (Food Foundation 2024).

Reinforcing or enabling change



- **Social contagion:** Social networks and expectations strongly influence dietary choices and norms (Higgs, 2015). More plant-based meals are consumed by those whose family and friends exhibit the same preference (Sharps et al., 2021), and seeing others consume a more sustainable option in a restaurant encourages uptake (Salmivaara et al., 2021).
- **Reinforcement through nudging and choice architecture:** When more meat-free options are available, people eat less meat, e.g. doubling the proportion of vegetarian meals on a menu increases vegetarian sales by 41-79% (Garnett et al., 2019). Strong messaging on co-benefits for health may also positively affect consumer choices.
- **Policy feedback to consumers:** Politically acceptable policies (e.g. changing dietary guidelines in Denmark, Norway, Germany, Canada, New Zealand, Switzerland) can raise awareness and shift social norms and behaviours, increasing public support for further interventions (Fesenfeld and Sun, 2023).
- **Increasing returns to adoption** help increase the quality, diversity and affordability of plant-based meat alternatives, e.g. plant-based milks, plant-based meat alternatives, precision fermentation, sustainable aquaculture production. It is worth noting, however, that traditional foods like fermented soybean products (tofu, tempeh etc.) other pulses etc. are already available and readily compete with meat products.
- **Learning-by-consuming:** A positive experience of eating plant-based meat encourages further consumption (Fesenfeld et al., 2023).

Balancing or resisting change



- **Existing policy and subsidies** skewed to maintaining livestock production and other unsustainable models of production and consumption:
  - In the EU 4x as much farming subsidy goes into animal products as plant ones. EU cattle farmers get >50% of income directly from subsidy. The EU spends almost 2x as much promoting meat and dairy products as fruit and vegetables. VAT on plant-based milk is higher than on dairy milk in several European countries.
  - Currently most countries have food based dietary guidelines (FBDGs) with significant environmental impacts (Springman, 2020) and only 38 countries explicitly reference environmental sustainability in their FBDGs (Aguirre-Sánchez et al., 2023)
- **Vested interests** in livestock production are a powerful lobbying group: The meat and dairy industry spend 190x more on lobbying than the alternative protein industry in the USA (and 3x more in the EU) (Vallone and Lambin, 2023). In Europe they have undertaken litigation to rule that plant-based milk alternatives cannot be called 'milk'.
- **Low public investment in alternatives:** £33m invested in alternative proteins in the EU and USA combined for 2014-2020, versus £35bn supporting meat and dairy production (Vallone and Lambin, 2023). UK spending on a flagship healthy eating campaign (£5.2m per year) is dwarfed by annual advertising of unhealthy products (£143m per year).
- **Institutional support is lacking** in many jurisdictions where national governments have rejected recommendations that would support changing diets, or actively stymied alternative proteins (e.g. Italy backed a ban on cultured meat). FAO has failed to recommend reducing livestock and dairy consumption.
- **Livestock products retain strong cultural value** in many countries.
- **Infrastructural and institutional incumbencies** in food supply chains, from farm practices, skills and machinery to supermarkets present barriers to systemic change.

Enabling policies:

- **Introduce dietary guidelines that are compatible with the Paris agreement, the CBD and public health goals.**
- **Innovation and investment to improve the attractiveness of plant-based alternatives** in terms of taste, freshness and nutritional value.
- Phase-in of policies including **public food procurement, mandates, taxes and subsidies in favour of plant-based food supply and demand.**
- **Support for farmers to transition to alternative business models** and nature-based solutions, including through growing markets for provision of ecosystem services.
- **A holistic, cross-departmental and cross societal approach to food/agriculture/land-use policy and planning**, as seen in the Danish Green Tripartite Agreement of 2024. System-wide interventions can include local government, business, civil society organisation, local leaders, influencers and communities.

Sources:

Aguirre-Sánchez, L. et al. (2023) 'Climate Change Mitigation Potential in Dietary Guidelines: A Global Review', Sustainable Production and Consumption, 40, pp. 558–570. Available at: https://doi.org/10.1016/j.spc.2023.07.015.

Dagevos, H. (2021) 'Finding flexitarians: Current studies on meat eaters and meat reducers', Trends in Food Science & Technology, 114, pp. 530–539. Available at: https://doi.org/10.1016/j.tifs.2021.06.021.

Fesenfeld, L.P. et al. (2023) 'How information, Social norms and experience with novel meat substitutes can create positive feedback and demand-side policy change', Food Policy, 117(102445), pp. 1–13. Available at: https://doi.org/10.1016/j.foodpol.2023.102445.

Fesenfeld, L.P. and Sun, Y. (2023) 'Enabling Positive Tipping Points in Public Support for Food System Transformation: The Case of Meat Consumption', in D. Resnick and J. Swinnen (eds) The Political Economy of Food System Transformation: Pathways to Progress in a Polarized World. Oxford University Press, p. 0. Available at: https://doi.org/10.1093/oso/9780198882121.003.0011.

Food Foundation (2024) Rethinking Plant-Based Meat Alternatives. The Food Foundation. Available at: https://foodfoundation.org.uk/sites/default/files/2024-08/Rethinking%20Plant-Based%20Meat%20Alternatives.pdf.

Garnett, E.E. et al. (2019) 'Impact of increasing vegetarian availability on meal selection and sales in cafeterias', Proceedings of the National Academy of Sciences, 116(42), pp. 20923–20929. Available at: https://doi.org/10.1073/pnas.1907207116.

Good Food Institute (2024) 2024 State of the Industry: Plant-based meat, seafood, eggs, dairy and ingredients. The Good Food Institute. Available at: https://gfi.org/wp-content/uploads/2025/04/2024-State-of-the-Industry-Plant-based-meat-seafood-eggs-dairy-and-ingredients.pdf

Higgs, S. (2015) 'Social norms and their influence on eating behaviours', Appetite, 86, pp. 38–44. Available at: https://doi.org/10.1016/j.appet.2014.10.021.

Li, Yanxian et al. (2024) 'Reducing climate change impacts from the global food system through diet shifts', Nature Climate Change, 14(9), pp. 943–953. Available at: https://doi.org/10.1038/s41558-024-02084-1.

Meldrum, M. et al. (2023) The Breakthrough Effect: How to trigger a cascade of tipping points to accelerate the net zero transition. Available at: https://www.systemiq.earth/wp-content/uploads/2023/01/The-Breakthrough-Effect.pdf.

Rosenfeld, D.L., Rothgerber, H. and Tomiyama, A.J. (2020) 'Mostly Vegetarian, But Flexible About It: Investigating How Meat-Reducers Express Social Identity Around Their Diets', Social Psychological and Personality Science, 11(3), pp. 406–415. Available at: https://doi.org/10.1177/1948550619869619.

Salmivaara, L. and Lankoski, L. (2021) 'Promoting Sustainable Consumer Behaviour Through the Activation of Injunctive Social Norms: A Field Experiment in 19 Workplace Restaurants', Organization & Environment, 34(3), pp. 361–386. Available at: https://doi.org/10.1177/1086026619831651.

Sharps, M.A. et al. (2021) 'The role of perceived descriptive and injunctive norms on the self-reported frequency of meat and plant-based meal intake in UK-based adults', Appetite, 167, p. 105615. Available at: https://doi.org/10.1016/j.appet.2021.105615.

Siegrist, A. et al. (2024) 'Comparing the nutritional value and prices of meat and milk substitutes with their animal-based benchmarks across six European countries', Food Research International, 197, p. 115213. Available at: https://doi.org/10.1016/j.foodres.2024.115213.

Springmann, M. et al. (2020) 'The healthiness and sustainability of national and global food based dietary guidelines: modelling study', BMJ, 370, p. m2322. Available at: https://doi.org/10.1136/bmj.m2322.

Stewart, C. et al. (2021) 'Trends in UK meat consumption: analysis of data from years 1–11 (2008–09 to 2018–19) of the National Diet and Nutrition Survey rolling programme', The Lancet Planetary Health, 5(10), pp. e699–e708. Available at: https://doi.org/10.1016/S2542-5196(21)00228-X.

Vallone, S. and Lambin, E.F. (2023) 'Public policies and vested interests preserve the animal farming status quo at the expense of animal product analogs', One Earth, 6(9), pp. 1213–1226. Available at: https://doi.org/10.1016/j.oneear.2023.07.013.

Whitton, C. et al. (2021) 'Are We Approaching Peak Meat Consumption? Analysis of Meat Consumption from 2000 to 2019 in 35 Countries and Its Relationship to Gross Domestic Product', Animals : an Open Access Journal from MDPI, 11(12), p. 3466. Available at: https://doi.org/10.3390/ani11123466.

PUBLIC OPINION & ENGAGEMENT

Growing public support for decarbonisation efforts are important for multiple reasons. First, politicians and business leaders are, in many contexts, accountable to and dependent on the public (e.g. through voting, consumer decisions). Public support for pro-climate actions can thus encourage leaders to implement bold climate and nature-related policies, and businesses to make longer term investment decisions or to structure their businesses to reduce their footprints.

Second, structural changes to our infrastructures, economies and livelihoods, and institutions require public support and buy-in to be effective. Third, the public will also have to change how they work, travel, eat, heat/cool their homes and so on — and since people look to each other when deciding how to act or what to care about, these changes can spread, creating new social norms and shared values. How we turn growing public concern about climate change into action is context and group specific and is an area of active research. In more polarised contexts, it may involve avoiding mention of climate change altogether and focusing on immediate and local economic and health co-benefits.



PUBLIC SUPPORT FOR PRO-CLIMATE AND PRO-NATURE ACTIONS

Public support provides an essential mandate for effective policy actions, but is vulnerable to politicisation and polarisation.

Progress:

The public perception that we are in a climate crisis is growing. The share of people globally who consider climate change a major threat increased from 54% in 2016 to 62% in 2017, to 71% in 2022 (Pew Research Center, 2022). In a 2023 survey, 93% of respondents stated that "climate change poses a serious and imminent threat to the planet" (Edelman Trust Barometer, 2023). Half of these respondents said that their views had changed over time. In 2024, the Peoples' Climate Vote found that 80% of people want their country to do more on climate change and 72% want their country to move away from fossil fuels quickly (UNDP, 2025). The increasing appetite for national action on climate change was echoed in a 2022 survey of 40,000 people across 20 countries that are collectively responsible for 72% of global CO2 emissions, where 80% of people agreed that "their country should fight climate change" (OECD, 2022). The sense of urgency for personal action also appears to be growing: in a 2023 global survey, 80% of people agreed that "we are heading towards an environmental disaster unless we change our habits quickly" (IPSOS, 2023).

- Across many countries, women are more likely than men to consider climate change a major threat, especially in wealthier countries (Bush and Clayton, 2023). Education is also correlated with greater concern (Pew Research Center, 2022).
- In the UK, the biggest change was observed among those over 65 years old: in 2013, only 36% said that humanity was causing climate change. By 2021 that figure had more than doubled to 74% (YouGov, 2021).
- In the US, only 22% of those on the political right say global climate change is a major threat to their country, compared with 85% of those on the political left - a Left-Right difference of 63% (Pew Research Center, 2025).
- However, most other countries are much less polarised. For example in South Korea, 79% of those on the political right say global climate change is a major threat to their country, compared with 87% of those on the political left - a Left-Right difference of only 8% (Pew Research Center, 2025).

Reinforcing or enabling change



- **Emergence of new social norms** aligned with sustainability and low carbon practices (e.g. repair cafes, libraries of things, active travel)
- **Positive political feedback** (e.g. declarations of climate emergency).
- **Positive policy feedback**: falling costs, positive experiences, and increasing adoption of clean technologies builds support for more ambitious policy.
- **Growth in green economy** jobs or local health benefits of reduced pollution.
- Establishing a **clear collective vision of a desirable post-carbon future.**
- **Replace GDP growth with 'good growth'** - economic growth needed for human development and wellbeing within safe planetary boundaries and just social foundations - as the primary measure of economic progress.

Balancing or resisting change



- **Disinformation campaigns** from right-wing political parties and media, funded by the fossil fuel industry and think tanks, sow doubt about the science, exaggerate the cost of climate policies, or call for delay.
- **Entrenched norms, habits, customs and social identities** that rely on carbon-intensive practices.
- **Affective political polarisation** where pro-climate actions or sustainability norms become associated with certain political groups, leading other groups to reject those actions or beliefs.

Enabling policies:

- Well designed, impartial climate assemblies, information campaigns, and education that enable people to understand the real risks and opportunities, discuss the difficult decisions and trade-offs, and make incremental or rapid change a conscious choice.
- The recommendations of climate assemblies to be given legal status in government policymaking such that the public co-create the transition.
- Accessible and affordable low-carbon alternatives.
- Correcting misperceptions by communicating public concern and support for pro-climate policies to the public and elected officials.

Sources:

Bush, S.S. and Clayton, A.. (2023) 'Facing Change: Gender and Climate Change Attitudes Worldwide', American Political Science Review, 117(2), pp. 591–608. Available at: https://doi.org/10.1017/S0003055422000752

Edelman Trust Barometer. (2023). Special Report: 'Trust and Climate Change': Available at: https://www.edelman.com/trust/2023/trust-barometer/special-report-trust-climate

IPSOS. (2023). Global Trends Survey. Available at: https://www.ipsos.com/sites/default/files/2023-Ipsos-Global-Trends-Report.pdf

OECD. (2022). Fighting climate change: International attitudes towards climate policies. Available at: https://www.oecd.org/en/publications/fighting-climate-change-international-attitudes-toward-climate-policies_3406f29a-en.html

Pew Research Center. (2022). Spring 2022 Global Attitudes Survey: Available at: https://www.pewresearch.org/global/2022/08/31/climate-change-remains-top-global-threat-across-19-country-survey/

Pew Research Center. (2025). Climate Change Remains Top Global Threat Across 19-Country Survey. Available at: https://mlgp4climate.com/uploads/MLGP%20Library/Useful%20Documents/English/L664%20eng.pdf

UNDP, 2025. The People's Climate Vote. (2024). Available at: https://peoplesclimate.vote/

YouGov. (2021). 72% of Britons think climate change is a result of human activity, up 20pts since 2013. Available at: https://yougov.co.uk/politics/articles/39131-72-britons-think-climate-change-result-human-activ

3.4 Renewable power and electrification: from tipping in technology adoption to system transformation

Authors: Floor Alkemade, Nadia Ameli, Claudia R. Binder, Maria Anna Hecher, Francesco Pasimeni,

Reviewers: Martina Ayoub, Claudia Binder, Laurens Speelman.

Key Messages:

Electrification presents key positive tipping point opportunities

- **Electrification is a decarbonisation multiplier: electrifying heating, transport, and industry both reduces emissions and stimulates investment in new renewables. It increases the overall efficiency and flexibility of the energy system.**
- **Integration can accelerate the self-propelling growth of renewable electricity generation, but requires urgent grid upgrades, energy storage, and demand flexibility.**
- **New digital technologies that can optimise energy balancing and storage between commercial and domestic energy providers need to be accelerated.**

Targeted policies can accelerate electrification

- **Decoupling renewable electricity pricing from fossil fuel-linked marginal pricing could significantly benefit consumers and accelerate change.**
- **Co-adoption strategies can trigger positive tipping: bundling complementary technologies increases value, reduces risk, and speeds clean technology diffusion.**
- **Policy should target households during key renovation and purchasing moments.**

Electricity generation by renewables has shown continued growth since the GTPR2023. Wind and solar are now the fastest-growing energy generation technologies in history. The world has passed the 30 per cent renewable electricity milestone, and in the EU, almost 50 per cent of electricity was generated by renewables in 2024, a record (IEA 2024, Wiatros-Motyka et al., 2024, IRENA 2024), See Section 3.3 and Figure 3.4.1 below for an overview.

Countries outside of the EU where the growth of clean power exceeded electricity demand growth include Australia, Korea, the United Kingdom, the US, Argentina, Japan, South Africa, Brazil, and Mexico (IEA 2024). For the first time, China's emissions were down 1.6 per cent year-on-year in the first quarter of 2025 due to its growth in clean power generation (Carbon Brief, 2025). In these countries, renewable energy developments are increasingly market-driven rather than subsidy-driven; investment in renewable energy technologies is attractive even without support from subsidies. This sometimes leads to tensions. Specifically, in developing countries where electricity demand still needs to grow to meet essential needs, we observed that fast growth in distributed renewables sometimes threatens the business case for electricity grids. While these tensions between distributed and centralised solutions are common to energy transitions around the world, they play out differently in different countries and bring different energy justice concerns.

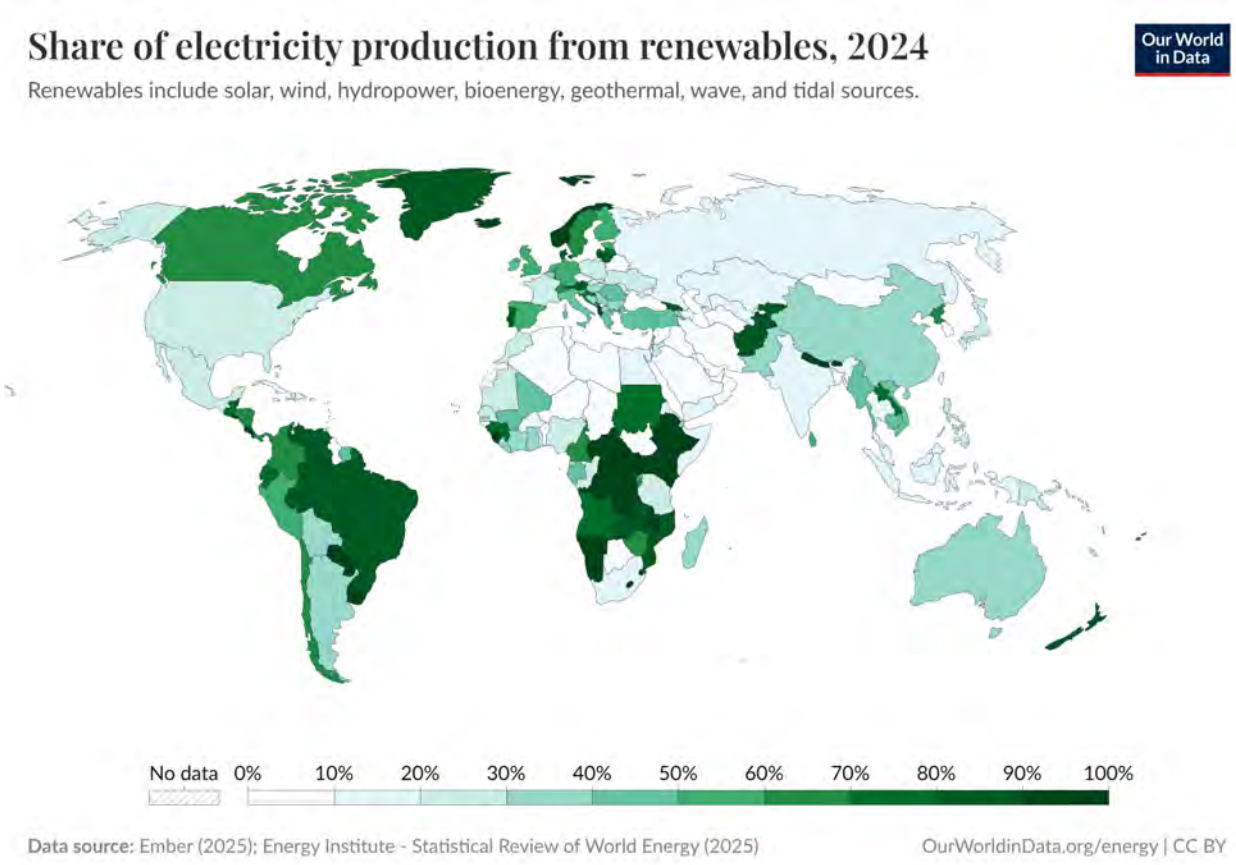


Figure 3.4.1: Share of electricity production from renewables 2024 (Our World in Data).

Now that the progress in these technologies is increasingly self-propelling due to technology-induced tipping (see Section 3.3), the challenge for the energy transition moves from bringing down the cost of individual technologies to ensuring system integration. Specifically, the growth in clean generation capacity needs to be complemented by an acceleration in the electrification of demand to bring down carbon emissions from fossil fuels. Increasing demand flexibility will be helpful here. When users are able to shift their electricity demand in time and space, for example, by smart steering strategies for EVs or heat pumps, it will be easier to match renewable energy supply with demand, and the need for investment in additional renewables and storage capacity will be lower (see Section 3.3). Barriers to this system transformation include power system integration, finance and investment, lack of human capital, but are also found in the deployment of smart meters and the implementation of demand flexibility at the household level (IRENA, 2024).

Despite these barriers, there are several possibilities for positive feedbacks that can induce further tipping on the demand side. Specifically, demand electrification often comes with increased energy efficiency, further supporting emission reductions (Breyer et al., 2022; Rissman et al., 2020, IEA 2024). Electrification is also key to maintaining a strong business case for building new wind and solar generation and creating incentives to invest in additional capacity. Moreover, for a range of applications, electrification also opens up opportunities to increase demand flexibility, further supporting the integration of variable renewable energy generation capacity. Electric vehicles and stationary batteries that provide grid services are key examples here. Dutch grid operator Stedin, for example, estimates based on ongoing experiments that 500 shared electric vehicles can provide 10 per cent of the required grid flexibility in Utrecht, a city with 370000 inhabitants and currently around 900 shared vehicles.

This development is greatly stimulated by the game-changing price reductions observed for batteries. In December 2024, energy research provider BloombergNEF reported that Lithium-ion battery pack prices dropped 20 per cent from 2023 to a record low of US$115/kWh (see Section 3.3). They also signalled an expected overcapacity from Chinese suppliers. Together, these developments support a positive feedback loop between increased electricity generation by renewables and demand electrification.

However, the demand electrification of key demand sectors housing, transport and industry proceeds at different speeds. In housing, the high upfront investment costs for heat pumps and the required renovations (insulation, changes in pipework) act as barriers to adoption. In industry, demand electrification is slow, partly due to the lack of cost reductions in necessary technologies - such as for green steel, green chemicals and green cement (Ember, 2025) and partly due to technological and policy uncertainty. For example, investment decisions on electrolysers are delayed by uncertainty about markets, business models and regulation despite technological learning (Galetti et al., 2025). The electrification of transport is economically attractive but depends on the build-out of charging infrastructure and policy support (IEA Global EV Outlook 2024, Hoekstra and Alkemade, 2025). Differences in support lead to very different growth rates for electric vehicles in different countries. While both are very rich countries, Norway is an example of a high support, high growth country, while Switzerland has a limited number of EVs, charging stations and purchase subsidies in place.

3.4.1 Opportunities for positive tipping in household demand

Households are responsible for a large part of emissions caused by electricity use, heating, transportation and indirectly by consumption (Ivanova et al., 2020; Pang et al., 2019). Changes in the choices of households, therefore, also affect the other sectors. The level of household energy demand differs between countries, and within countries between income groups, but electricity, heating, and land transportation are significant emission sources across the board (IPCC 2023). The large differences between countries indicate that there is room to move towards more sustainable lifestyles, either enabled by better technologies or by reducing demand (Akenji et al., 2021). Examples of such changes are increased building insulation or behaviour change. Below, we zoom in a bit more.

For the EU's household demand electrification, we observe fast changes in some countries. The electrification of heating (responsible for around 60 per cent of final energy consumption in the EU residential sector) benefits from the fast decarbonisation of the electricity supply. However, demand for heating still tends to be met by natural gas boilers. In 2022, natural gas accounted for 42 per cent of global heating energy demand, with a 30 per cent share of the heating mix in the European Union (Eurostat) and over 60 per cent in the United States (EIA n.d.). When low-carbon, sustainable heat sources are available, this may be a preferred option. However, when this is not the case, electrification of heating demand through heat pumps can lead to a considerable reduction in energy demand. Section 3.3 illustrates how the fast growth in heat pump adoption can reduce the emissions from heating considerably (IEA, 2022). Nevertheless, the shift to low-carbon heat sources requires changes in technologies and infrastructure in houses and neighbourhoods. In the EU, heat pumps are expected to play a significant role in the building sector. Heat pumps can supply cooling as well as heat for space heating and tap water. The demand for cooling is increasing, and meeting that demand with traditional air conditioners is already leading to significant increases in energy use.

As of 2023, there were more than 21.5 million heat pumps installed in the EU (European Commission 2024). The share of heat pumps for domestic heating varies from around 90 per cent in Sweden and Finland to around 10 per cent in Hungary. Between 2013 and 2022, heat pump sales experienced continuous growth, reaching a peak in 2022 when they increased by 44 per cent compared to the previous year. However, 2023 saw a slowdown, with a drop of 7 per cent compared to the record year. Despite this fast growth, heat pumps only represent a small share of new installations in Europe (6 per cent in 2021 - European Heating Industry), and gas boilers remain the dominant technology. In countries with fast growth, we observe several drivers and feedback loops. Sufficient insulation is a key condition for the economic attractiveness of heat pump adoption. Here, we see an advantage of stricter housing regulations (often in countries with colder climates). But sometimes other non-technology factors play a role. For example, in the Netherlands, the adoption was driven by the decision to phase out natural gas and concerns about the affordability and availability of natural gas following the war in Ukraine.

3.4.2 Barriers & intervention points

Tipping through demand electrification depends on the supply of electricity from renewables. The levelised costs of energy from renewables outcompete (in new-for-new comparison) or are competitive compared to fossil fuel-generated energy (Nijsse et al., 2023). As wind and solar energy are available at no cost, but fossil generation does not have this advantage, the outlook with continued technological learning is favourable. However, there are some barriers that slow down market-driven progress:

First, in many countries, renewable energy prices are linked to fossil fuel prices. Specifically, under marginal pricing, natural gas is often price-setting. In the EU, for example, natural gas was the price-setter 63 per cent of the time in 2022, with only a 20 per cent share in the electricity mix (JRC, 2023). This prevents consumers from fully benefiting from the energy transition, reducing the attractiveness of investing. Here, decoupling is necessary to ensure that benefits are passed on to consumers (Draghi, 2024). Power purchase agreements (PPAs) and contracts for difference may help here. The use of PPAs is more advanced in the US compared to Europe. Moreover, as discussed above, the fast-decreasing costs of battery storage may be a game-changer in the power sector, reducing the need for gas-fired power plants during peak times.

Second, while renewables' operational costs are typically low compared to fossil fuel-based technologies, capital expenditures are often higher. This is true for heat pumps, electric vehicles, and grid-scale wind and solar. Finance instruments that are connected to the building rather than to the owner are explored in pilot projects as a potential solution.

Specific barriers to electrifying household heating demand are the lack of technologies for heat longer term heat storage and the cumbersome installation process of heat pumps, and the high upfront investment costs, as well as concerns about running costs (see section 3.3).

Accordingly, interventions need to be part of a systemic policy mix (Alkemade et al., 2024; Kern et al., 2019). As an example, leverage points in the transition to heat pumps in Sweden included a carbon tax on heating oil and the availability of cheap electricity. Another leverage point is minimum energy performance standards for buildings (EU, Canada). Building renovations often happen when a building changes hands; this provides a natural opportunity to attach levers. Energy performance requirements play an important role in ensuring that renewable supply can keep pace with the growth in energy demand. This especially holds for buildings and technologies where energy-efficient alternatives are available at comparable prices (like air conditioning). A key driver that receives limited attention is the health co-benefits that come with better-insulated homes and the phase-out of gas-fired stoves (Breysse et al., 2011; Jarvis et al., 1996).

For countries that observe a fast growth in renewables supply, this means support for the electrification of demand and the build-out of the supporting infrastructure, including electricity grids and charging infrastructure. A move toward energy autonomy at the household scale supports this transition at the national level as it reduces the demand for grid capacity. A key energy justice concern is to divide the costs of grid expansion in a fair way.

3.4.3 Co-adoption of technology as a driver of positive tipping

To go from social tipping in the adoption of specific technologies like heat pumps, electric vehicles or rooftop solar PV to a full system transition towards sustainable and affordable energy for all (Sustainable Development Goal 7), requires a systems approach (Campfens et al., 2025). Connecting tipping in one energy behaviour to tipping in other behaviours or at larger scales leads to increased resilience of the new system, reducing the reversibility of the tipping behaviour. Here, the concept of co-adoption is increasingly studied.

The co-adoption of technologies unlocks the full potential to reduce household emissions, enhance energy efficiency and contribute to a more resilient energy system. This is for example, when renewable energy from photovoltaics provides electricity for both the heat pump and the EV (Priessner and Hampl, 2020; Stauch, 2021; Agnew and Dargusch, 2017; Quoilin et al., 2016; Truong et al., 2016), while an energy management system optimises energy flows, increasing the level of energy self-consumption and balancing the energy grid (Liang et al., 2022; Shen et al., 2023). Marketing research suggests that consumers positively evaluate bundles of complementary products as they offer greater value through complementarity, reduce perceived risk, and enhance convenience by saving time and effort spent on a purchase (Stremersch and Tellis 2002).

Leveraging integrated technology solutions is essential whenever households inquire about stand-alone technologies like photovoltaics or renovate their building. These not only accelerate technology adoption but potentially support the advancement of less mature technologies, such as EVs and reduce the risk that people will revert to the older unsustainable technologies (Reinders et al., 2010; Plananska and Gamma, 2022).

Examples are when people co-adopt electric vehicles, heat pumps, home insulation and solar PV because the synergies between the technologies enable households to benefit more from the energy transition and or adopt a sustainable or energy-independent lifestyle. Several countries have schemes that stimulate co-adoption, from purchase price subsidies (Germany, The Netherlands) to tariff incentives (Australia). Social tipping is more likely to scale up when there is a diversity of drivers, appealing to different groups of adopters. For households, we observe such diversity (Martinez-Alcaraz, et al., 2025). Energy affordability is a key and universal driver, but concerns about climate, concerns about energy security and the desire to be energy independent (both on the national and on the local scale – independent from large energy suppliers) also play a role in household energy decisions. Cost reductions and performance improvements through learning remain a main driver of the energy transition, as this creates affordability for a larger group of people.

Policy actions:	• Focus on systemic approaches, leveraging co-benefits and the momentum generated by quick cost reductions. • Reduce uncertainty for firms and consumers that consider switching by providing stable, long-term support.
Business and finance actions:	• Focus on modularisation and standardisation • Design innovative finance models that help reduce risk for adopters
Wider publics and civil society actions:	• Share success stories and positive experiences. Emphasise co-benefits

3.5. Positive tipping points in food systems, land use and nature

Authors: Tom Powell, Mike Barrett, Timothy M. Lenton, Hatty Wylder-Hopkinson, Franziska Gaupp, Sara Constantino, Steven R Smith, Talia Smith

Reviewers: Kate Findlay, Lukas Fesenfeld

Key Messages

Positive tipping points in agricultural commodity supply chains can end deforestation and conversion

- Triggering positive tipping points in the sustainable production and consumption of agricultural commodities requires mutually reinforcing actions in three areas: Clear policy signals and enforcement; coordination across supply chains and between key markets; and finance to support transitions in production.
- Legal protections for tropical forests and their inhabitants need to be established and enforced.
- Standards for sustainable commodity production (e.g. soy, beef, cocoa, cotton, palm oil) and trade need to be developed and enforced. Successful moratoria (e.g. Amazon Soy) show that regulation and monitoring are essential for compliance, and that alternative options for producers must be available (and financially viable).
- Demand-side interventions in import markets must align with domestic policy in major producing countries to ensure success, and should make efforts to support producers in meeting new standards through provision of transition finance.
- Policy and market structures currently incentivise harmful practices. Subsidies and procurement should change towards sustainable production and consumption, thereby supporting sustainably productive landscapes that include standing forests.

Positive tipping points can rapidly restore nature and biodiversity

- Ecosystem restoration can positively tip degraded systems back to health, through interventions like keystone species reintroduction, nutrient reduction, and clumped planting that activate natural reinforcing feedbacks.
- Recovery of food and water resources can be positively tipped through promoting community governance of common pool resources including groundwater, forests, fish stocks and the creation of marine protected areas.
- Positive tipping points in the spread of nature-positive farming, conservation and regeneration initiatives... / Scaling nature-positive initiatives depends on local benefits and governance. Community management, equitable benefit-sharing, and leveraging ecological feedbacks enable rapid spread. Combining local agency with supportive policy increases durability.

Introduction

Agriculture and associated land use contribute a quarter of global greenhouse gas emissions, of which half result from forest loss and degradation (Crippa et al., 2021). When energy use and other supply chain emissions are included, the food system as a whole contributes a third of GHG emissions globally. In terrestrial, freshwater and marine ecosystems food production is a key driver of nature loss and ecosystem degradation, especially in critical ecosystems like the Amazon and coral reefs where its impacts, compounded by climate change, increase the risk of tipping points leading to their irreversible loss (see Section 2). Deforestation is also a major human health risk, increasing the risk of zoonotic disease spread (Chin et al., 2020; Morand and Lajaunie, 2021) and exposing hundreds of millions of people to increased heat stress in the tropics (Reddington et al., 2025).

Meeting the goals of both the Paris agreement and the Kunming-Montreal Global Biodiversity Framework (GBF) (Leclère et al., 2020) requires urgent acceleration of shifts to sustainable and equitable production, trade and consumption across food supply chains globally. As the GBF makes clear, such changes will also require major shifts away from financial investments in unsustainable production towards financing the transition to sustainability.

Positive tipping point opportunities to transform food production and consumption can operate synergistically to increase food security, restore ecological health to agro-ecosystems, reduce pressure on natural ecosystems and ultimately create opportunities for nature restoration by reducing the overall land footprint required for food production. Nature regeneration, and initiatives that promote it, can in turn be positively tipped. The opportunity is to move the food system from problem to solution.

In this chapter, we summarise current knowledge of actions and amplifying feedbacks that could reduce the most significant drivers of deforestation and degradation. We identify potential interventions that policy makers, civil society actors and retailers can take to accelerate a just transition. We then assess the potential for positive tipping points to accelerate nature recovery and restoration of ecosystems services in both managed and natural landscapes by working with reinforcing feedbacks that occur in nature and societies.

3.5.1 Ending deforestation in agricultural commodity supply chains

Half of all habitable land is currently used for agriculture and, of this, 80 per cent is used to raise livestock, including the land used to produce animal feed (Ritchie and Roser, 2019). Whilst most agricultural production is not currently directly driving deforestation, most deforestation is driven by agricultural expansion (Rajão et al., 2020; Pendrill et al., 2022). A demand side tipping point based on lowering global demand for livestock products would help protect forests (Box 3.5.1) but is not alone sufficient, or sufficiently rapid, to protect critical biomes from existential threats arising from deforestation and degradation; especially in the Amazon rainforest (see 4.1 Amazon Case Study). In tropical forest biomes which produce cash crops like soybean, palm oil, coffee and cocoa, urgent action is required to tackle commodity driven deforestation. This includes the need to establish and enforce legal protections for tropical forests and their inhabitants, develop and ensure standards for sustainable commodity production and trade, finance the transition to sustainable production, and support sustainably productive landscapes that include standing forests.

Box 3.5.1. Shifting to sustainable diets

GTPR 2023 highlighted the powerful synergy between efforts to shift to sustainable production and supply chains, and demand-side shifts that reduce the overall impacts and spatial footprint of food production including reducing food loss and waste and reducing consumption of livestock products in overconsuming countries. Of these, the latter holds the strongest potential for tipping dynamics due to its strong association with peer influence and social norms which can spread via contagion.

While globally meat consumption has continued to rise due to population growth and rising incomes, in some over-consuming regions there are signals that consumption of animal products has peaked and is decoupling from economic growth (e.g. in USA, UK, Canada, Australia, Saudi Arabia, New Zealand, Switzerland, Israel; (Whitton et al., 2021). At the same time, purchases of plant-based meals have increased in some markets, especially in Europe (where Germany and UK are the largest markets), and a near doubling of investment over the last decade in plant-based 'alternative proteins' demonstrates a growing sector with increasing market power, albeit one in which momentum has slowed in recent years.

These trends have in part been driven by overlapping concerns for consumers around health, environmental impacts and ethics of overconsumption of animal products (Rosenfeld, Rothgerber and Tomiyama, 2020; Dagevos, 2021). Other significant interventions include resetting of national dietary guidelines in some countries (e.g. Denmark, Germany, Norway) to reduce recommended consumption of animal products. However, the political economy of shifting consumption patterns remains complex and contentious due to significant public investment in livestock farming, transition risks for farmers and wider rural economies, and strong cultural value associated with food and farming landscapes.

Further information on enabling factors and barriers for shifting diets is given in Chapter 3.3.

Effective action can generate systemic change. Different actors, from consumers to policy makers, traders, producers, investors and civil society organisations, can play important roles in developing, demonstrating and propagating models for nature positive value chains. When successfully established, these have potential to tip the wider system behaviour through **network effects** (see Section 3.2.3 and Appendix 1: Glossary), where actors participating in nature positive value chains benefit more than those not participating; through **contagion**, for example by national and regional level bodies adopting standards to align with international agreements or transnational standards, and through **introducing path dependencies** in legislation, infrastructure and information flows (Fesenfeld et al., 2022; Sewerin, Fesenfeld and Schmidt, 2023).

Current supply chain commitments have mixed success. To date, a number of zero-deforestation commitments (ZDCs) have been implemented with mixed results, from international pledges like the Glasgow Leaders' Declaration on Forests and Land Use (The National Archives, 2021), to commitments at national level or relating to specific commodities and supply chains (Box 3.5.2), but these have so far failed to reverse deforestation (Lambin and Furumo, 2023).

Box 3.5.2. Enabling conditions for success of the Brazilian Amazon Soy Moratorium

The Amazon Soy Moratorium (ASM), considered one of the more successful ZDCs, was signed in 2006 following an NGO campaign linking major traders responsible for 90 per cent of the trade in Amazon-produced soy with deforestation. Under the ASM, traders agreed not to purchase soy from newly deforested areas in the Brazilian Amazon Biome. Deforestation in key soy producing areas fell as a result and between 2006 and 2014 only 1 per cent of new forest clearing in the Brazilian Amazon biome was associated with soy expansion (Lambin and Furumo, 2023). Instead, soy cultivation intensified while expansion in the Amazon biome was concentrated in forest areas cleared before implementation of the ASM.

The success of the ASM can be attributed to a number of enabling conditions (Lambin and Furumo, 2023):

1. **Alignment with existing regulation:** The ASM provided a market mechanism to reinforce the already existing Brazilian Forest Code, while adding few additional requirements for producers.
2. **Alternatives available to producers**: Availability of land already cleared before the ASM was imposed, opportunities to intensify through e.g. double cropping, and opportunities for expansion in other areas (e.g. the Cerrado) meant that opportunity costs to producers were low.
3. **Concentrated supply chains, and large export market with demand for zero deforestation products:** A 'naming-and-shaming' campaign by NGOs in key export markets had power to influence traders, who in turn were able to exert powerful direct influence on producers.
4. **Reinforced by government action:** The introduction of the ASM was accompanied by Brazilian government policies that expanded protected areas, increased enforcement efforts, supported satellite based monitoring and created a Rural Environmental Registry.

Despite the success of the ASM in reducing soy-related deforestation in the Amazon biome the simultaneous expansion of soy production in the Cerrado, which is also a globally significant biodiversity hotspot, demonstrates the importance of integrated regional policy and supply chain solutions, based on systems understanding to account for risks of displacement and leakage. In this case, a parallel Cerrado soy moratorium was strongly opposed by producers' associations.

The importance of continued government support for monitoring and enforcement is also clear. Reduction of resources for enforcement of land use regulations has been associated with an increase in non-ASM compliant soybean cultivation from 0.07 per cent in 2008 to more than 6 per cent in 2019 (Lambin and Furumo, 2023).

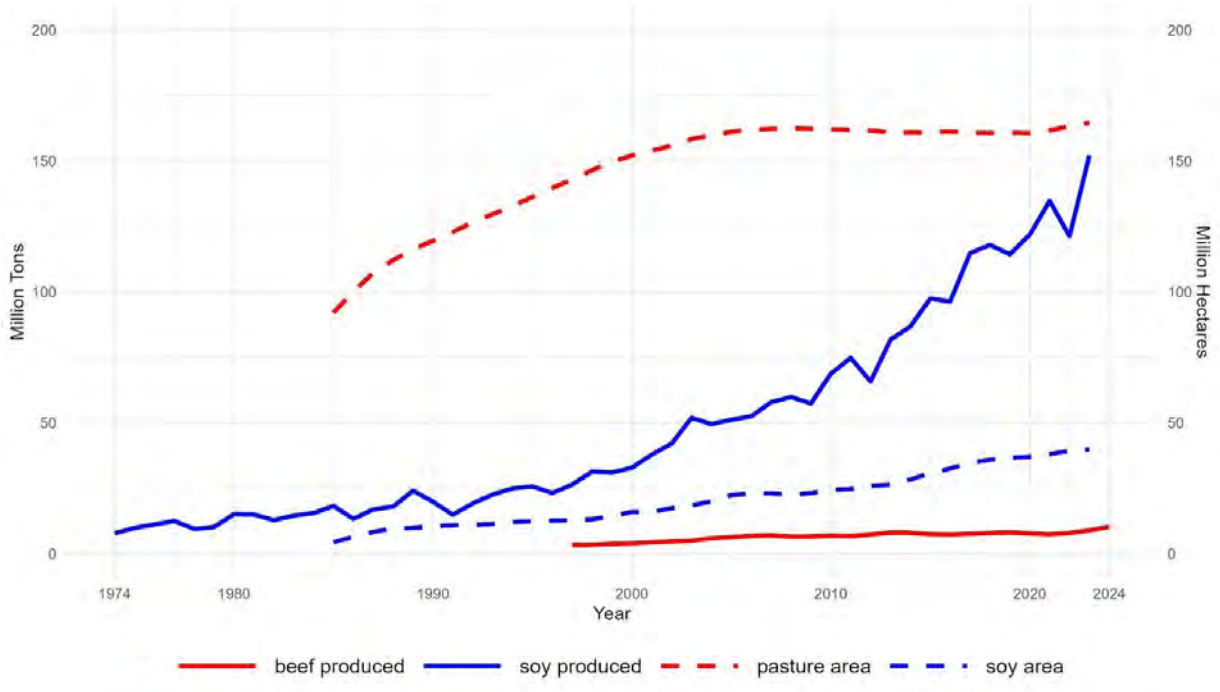


Figure 3.5.1. Soy and Beef production through time, compared with soy and pasture area through time, across Brazil, based on estimates of production from IBGE and Mapbiomas 9.0 land use (Global Land Use and Environment Lab (GLUE) at the University of Wisconsin - Madison (UW) & Land Conservation Association (LCA), 2025).

The relative success of the Amazon Soybean Moratorium (ASM, Box 3.5.2) demonstrates that policy and market-based interventions can reduce deforestation under the right conditions. Other comparable initiatives have been less successful where these conditions have not been met. For example:

- The **Brazilian cattle agreement** (CA), in which slaughterhouses and meatpacking companies signed an agreement to stop purchasing cattle from properties with illegal deforestation to convert forest into cattle pasture, was modelled on the ASM but has been less successful. The more complex nature of cattle supply chains with more actors and individual animals likely to move several times between farms before they are slaughtered makes compliance and monitoring less reliable (Lambin and Furumo, 2023).
- Under the **Indonesian forest moratorium**, the Indonesian government suspended granting of new concession licenses for logging, timber plantations and palm oil within certain areas such as dryland forests and peatland forests from 2011-2021. However, low compliance and weak enforcement in key areas including peatlands has undermined its moderate successes (Groom, Palmer and Sileci, 2022).

Demand side initiatives are emerging. Importing countries have started to propose and adopt regulations against commodity-driven deforestation. In the EU, regulation on deforestation-free products (EUDR) entered into force in June 2023. Traders must prove that commodities that enter or leave the EU do not originate from recently deforested land and have not contributed to forest degradation (Cesar de Oliveira et al., 2024). Similarly, the UK has committed to legislation which prohibits the use of illegally produced forest risk commodities (Participation, 2021). However, concerns have been raised that mis-alignment with domestic policy in Brazil and other Amazon countries may lead to increased barriers to producers and traders, and at worst provide loopholes that weaken the ASM and incentivise expansion of soybean production into recently deforested areas (Oliveira et al., 2024). When implemented effectively, demand side trade measures can help provide long term preferential market access.

Coordination is required across major markets, including domestic markets in exporting countries for such demand-side initiatives to be successful. For example, while they constitute a significant export market the EU and UK markets combined are significantly smaller than both the Chinese market, and the domestic markets of Amazonian soy producing countries (Lambin and Furumo, 2023). Since non-ASM compliant soy makes up only a small percentage of total cultivation (<10 per cent), if key export markets are not aligned on standards it is likely that this soy will simply be redirected to less discriminating markets, with little effect on overall production.

Financing transition costs for producers is essential. Regulating trade alone is insufficient as producers may face costs to the transition, such as investments in restoring abandoned or degraded land for production. It will be essential to make it accessible and profitable for producers of all scales to transition to sustainable production, and it is not reasonable to expect the burden of these costs to be met by producers alone. Countries applying higher standards through trade measures must back these with finance to meet the costs of transition.

Transition costs are not evenly distributed. Smallholder farmers, for example, are unlikely to have technical capability and financial resources to comply with externally imposed regulations like those introduced by the EU and UK (Cesar de Oliveira et al., 2024). This needs to be addressed through domestic public policies as well as EU, UK and other international investments and implementation of cooperation mechanisms that lower the administrative and financial burden of small-scale farmers.

Effecting qualitative, systemic shifts to sustainable supply chains requires coordination between government policy in producing and exporting countries and major consumption markets, private sector actors across the supply chain, public and private finance, NGOs and civil society.

1. Foremost, local laws protecting forests, and the rights of indigenous peoples, need to be established (where absent), rolled out, or enforced, depending on the context – which requires political will and enforcement capacity.
2. Existing farmland needs to be optimised and finance made available to meet the costs of transition, for example in accessing and rehabilitating abandoned and degraded land and in increasing productivity.
3. Market signals need to reinforce action to prevent deforestation, by providing incentives and disincentives. These should take the form of exclusive market access for legal produce and preferential market access for sustainable products (avoiding unfair cheaper competition and rewarding responsible producers and that provide a long term assurance of market access).
4. NGOs and civil society organisations can promote demand for deforestation-free products, hold producers and policy makers accountable, and protect the interests of vulnerable actors like smallholder farmers.

These should not be regarded as a menu of options, but rather a list of mutually reinforcing actions that, if taken together, can trigger positive tipping. **Success lies in multiple complimentary interventions:**

Policy actions:

In countries which are producers and exporters of tropical forest risk commodities:

- Enforce legal protections such as preventing illegal deforestation in protected areas, setting uncontrolled fires and incursions/occupation into indigenous lands.
- End public finance/subsidies for unsustainable production
- Facilitate and incentivise development and adherence to sustainable production standards
- Facilitate compliance with laws protecting forests through effective monitoring and enforcement
- Implement policies to avoid marginalization of vulnerable actors such as extension services to help farmers meet sustainability standards
- Provide legal and regulatory frameworks that support the growth of high-integrity ecosystem service markets (e.g. green bonds)
- Support growth of sustainable bioeconomies

In countries which are importers of tropical forest commodities:

- Work with exporting countries to develop and enforce supply chain standards and regulations that discourage or prohibit imports of deforestation-linked commodities while supporting sustainable practices and economies in exporting countries and regions.
- Form coalitions/blocs across major markets with consistent standards and requirements.
- Provide financial means, technical assistance and capacity building for smallholders to access international markets
- Increase demand for deforestation-free commodities through public procurement policies, labelling requirements, investors standards and information campaigns

Business and finance actions:

- Provide private and public finance to meet the costs of transition to sustainable production
- Develop and lobby for strong standards and regulation that level the playing field for progressive companies
- Ensure supply chain accountability and transparency
- Commit to disclosure and natural capital accounting
- Traders and producers: make zero-deforestation commitments including measures to enable monitoring and traceability
- Retailers: commit to reducing the environmental footprint of products sold (e.g. major UK retailers committed at COP26 to halving environmental impacts by 2030 (BBC, 2021)).

Wider publics and civil society actions:

- Advocacy and campaigning, communicating and building awareness to grow demand for deforestation-free products
- Independent monitoring, accountability and standard setting
- Legal action
- Collaborate with business and other partners to enable consumers to make informed choices, e.g. through traceability of product ingredients
- Protect the interests of vulnerable groups including smallholder farmers, indigenous peoples and other forest dwellers.

3.5.2 Positive tipping points for restoring nature and biodiversity

196 countries have signed up to the Kunming-Montreal Global Biodiversity Framework (Convention on Biological Diversity, 2022) that aims to halt and reverse biodiversity loss by 2030. The GBF includes a target to restore 30 per cent of all degraded ecosystems and conserve 30 per cent of land, waters and seas, by 2030.

Yet more than halfway through this UN Decade on Ecosystem Restoration, progress is far slower than it needs to be to meet these targets. Positive tipping points can play a key role in accelerating the restoration of nature, where pressures on land and sea use have been reduced (by initiatives like those described above). Here we highlight key actions to positively tip ecosystem restoration, resource recovery, and the spread of nature positive initiatives, and the potential for them to be combined to positively tip larger scale ecological recovery.



Figure 3.5.2. Location of examples of positive tipping points for nature discussed herein.

3.5.2.1. Positively tipping ecosystem restoration

Ecosystems that have been negatively tipped can be positively tipped back from a degraded state, by reversing anthropogenic drivers. It often takes a larger change in drivers to tip recovery than it did to trigger collapse, but numerous successes have been achieved (Figure 3.5.2). The secret is to work with the reinforcing feedback mechanisms that are already present in nature.

Reintroduce keystone species. Reintroducing a keystone species that was previously eliminated can positively tip ecosystem recovery. For example, reintroducing wolves to Yellowstone National Park in 1995-6 suppressed elk and deer populations triggering abrupt vegetation recovery and boosting populations of scavengers, songbirds, bison, and beaver (Ripple et al., 2025). The recovery and reintroduction of sea otter populations off the North Pacific coast of the US and Canada suppressed sea urchin populations and allowed kelp forests to abruptly recover (Selkoe et al., 2015). These cases increased carbon storage (in trees and kelp), biodiversity, recreation and tourism. There is huge potential for wider reintroduction of apex predators to positively tip vegetation recovery (Perino et al., 2019; Xu et al., 2023).

Reduce nutrient loading. Reducing nutrient loading of aquatic ecosystems can positively tip their recovery. Efforts starting in the Norfolk Broads and the Netherlands have shown that reducing phosphorus loading can reverse eutrophication of shallow lakes and positively tip them into a clear water state (Scheffer et al., 1993). This can be helped by introducing filter-feeding ecosystem engineers such as zebra mussels and piscivorous fish that suppress planktivorous and benthic fish allowing zooplankton and benthic filter feeders to recover (Jeppesen et al., 2007).

Clump reintroduction. Clumped reintroduction of salt marsh plants, mangroves, seagrasses, mussels and oysters can positively tip recovery of tidal ecosystems. This works by activating reinforcing feedback whereby these ecosystem engineers stabilise sediments and attenuate waves and currents, facilitating their persistence (Silliman et al., 2015). Positive tipping can be aided by introducing engineered structures like fencing for mussel beds or permeable dams for mangroves (Temmink et al., 2023). Excluding bioturbating animals that destabilise sediments (Suykerbuyk et al., 2012), or encouraging shorebirds that eat them can further help (C. Li et al., 2023). Clumped reintroduction can positively tip other stressed ecosystems including arid vegetation and peat bogs (Temmink et al., 2023).

Multiple actions for coral reefs. Reducing multiple local drivers can positively tip the recovery of tropical coral reefs, at least buying time from the increasing threats of global warming (see 4.3 Warm-water Coral Reefs Case Study) (Graham et al., 2013). Recovery depends on herbivorous fish being abundant enough and nutrient levels low enough to suppress macroalgae (Graham et al., 2015). Hence positive tipping can be enabled by controlling fishing and reducing anthropogenic nutrient loading (Holbrook et al., 2016). It is also aided by deliberately introducing juvenile corals, or artificial reef structures, supporting seabirds (Benkwitt et al., 2023), and taking advantage of natural variability that impairs macroalgal production, such as persistent cloudy conditions (Graham et al., 2013).

Box 3.5.3: Tipping recovery in the Baltic Sea

The Baltic Sea and its catchments have experienced multiple negative ecological tipping points (Reusch et al., 2018), but it has the potential for large-scale positive tipping of recovery. This shallow, brackish coastal shelf sea is effectively a giant estuarine system. Historically it has seen a trophic cascade tipping point in the 1950s-60s with the removal of seals as top predators. Then the 1980s saw a pelagic tipping point from overfishing, deterioration of spawning grounds, and climate change, with an abrupt switch from cod to sprat and herring. Numerous coastal tipping points have occurred involving the loss of macrophytes (seagrasses and perennial algae) through trophic cascades. There has also been a ten-fold increase in deoxygenated dead zones over the last century, driven by nutrient runoff and eutrophication and reinforced by phosphorus recycling from sediments.

Some nature positive change has already happened through the return of top predators, coordinated fisheries management, and reductions in nutrient loading. But the latter has suffered systematic delays and been thus far insufficient to positively tip away from eutrophication and dead zones (Varjopuro et al., 2014). Achieving a larger-scale positive tipping point for nature would benefit from positive tipping in diets (Box 3.5.1), reducing the demand for intensive agriculture on land and associated nutrient loading (as well as demand for fish). Already Denmark, for example, has revised dietary guidelines and is implementing new agricultural taxes. Reducing nutrient loading also requires institutional change in the Common Agricultural Policy (CAP) and its enforcement. This would benefit from coordination among multiple stakeholders including policymakers, farmers, environmental groups and consumers (Mennig, 2024).

3.5.2.2. Positively tipping resource recovery

The recovery of natural resources can be positively tipped either through triggering ecological tipping points or through social tipping points that transform resource stocks. The combination of some of these actions with some of those noted above (3.5.2.1) have the potential to positively tip recovery of larger scale systems – for example, the Baltic Sea (Box 3.5.3).

Reduce overfishing. The recovery of collapsed pelagic fish stocks can be positively tipped by enforcing a Maximum Sustainable Yield (MSY) – the highest yield that can be taken without significantly affecting reproduction. This typically requires short-term reduction in fishing effort, which in turn requires strong regulatory enforcement and punishment of those who do not comply. Enforcement of MSY has already positively tipped recovery of plaice and hake stocks in the North Sea (Blöcker et al., 2023), although recovering cod stocks will also require controlling sprat stocks (Sguotti et al., 2019).

Marine protected areas. For coastal fisheries, marine protected areas (MPAs) can positively tip fish stock recovery, by providing safe spawning areas and 'spillover' of fish into the surrounding waters (Di Lorenzo et al., 2020). MPAs can be particularly effective on coral reefs as these naturally support transient fish spawning aggregations (Russ et al., 2004). Successfully establishing MPAs requires careful engagement with fishing communities. (Russ et al., 2004).

Promote community governance of common pool resources. Societies can positively tip into cooperating to recover common pool resources (Castilla-Rho et al., 2017). For example, reinstating the traditional practice of maintaining artificial reservoirs that capture the monsoon rains has recovered depleted groundwater resources in drier parts of India (Everard, 2015). The rains infiltrate to recharge groundwater that in turn support natural vegetation, agriculture and the community. Cooperative village level governance of water resources was key to this.

3.5.2.3. Positively tipping the spread of nature positive initiatives

The spread of nature positive initiatives, including nature-positive farming (Box 3.5.4) and some conservation and regeneration initiatives can be positively tipped by reaching a critical mass at which one more person or group adopting can trigger a phase of self-propelling adoption in a population. Adoption can be further amplified by increasing returns whereby adoption becomes more attractive the more who adopt (e.g. because costs decline and benefits increase).

Ensure benefits to locals. Benefits to local people are critical to achieving positive tipping of diffusion for conservation and agroforestry initiatives (Mascia and Mills, 2018). For example, they determine the relative scaling up success of different community-based forest conservation initiatives in Tanzania. Benefits to smallholder farmers, including carbon payments, helping alleviate household credit constraints, economically empowering women, are key to the rapid spread of The International Small-Group and Tree Planting Program (TIST) in East Africa and India (Emenyu et al., 2023). It in turn greens the surrounding landscape (Buxton et al., 2021).

Promote community management. Community management is key to positively tipping the spread of sustainable resource management. It governs the spread of locally managed marine (protected) areas (LMMAs) across Pacific islands (Mascia and Mills, 2018). Community-based groundwater management has spread widely across Asia, improving productivity by up to 250 per cent. Modelling can forecast where there is greatest potential for further rapid scaling of adoption – for example, of LMMAs in the Solomon Islands (Clark et al., 2024).

Leverage moisture recycling. The spread of revegetation efforts can leverage natural moisture recycling (van der Ent et al., 2010). Evapotranspiration from regenerating vegetation supports precipitation and vegetation growth downwind. This is particularly important for precipitation in the western Amazon and La Plata basins (Zemp et al., 2014), the Congo basin (Worden et al., 2021), agricultural areas of sub-Saharan Africa (Nyasulu et al., 2024), and the Tibetan plateau (Y. Li et al., 2023) – suggesting regions where revegetation efforts would promote their own spread.

Together, reducing drivers of nature loss and activating positive tipping mechanisms of ecosystem restoration, resource recovery, and spread of nature positive initiatives, have the potential to positively tip the larger-scale recovery of degraded biomes, such as the Amazon rainforest (see Box 3.5.5 and 4.1 Amazon Case Study).

Box 3.5.4: Scaling nature positive farming

Nature positive farming methods prioritise efficient and effective use of natural resources for farming while providing benefits for society, the environment and biodiversity. Widespread adoption of such practices could reduce inputs, protect nature, and increase the health and resilience of ecosystem service provision in agro-ecosystems.

Diffusion and contagion can be observed for various models of nature positive farming across the world, from adoption of digital and smart farming technologies particularly in industrialised farming settings (Long, Blok and Coninx, 2016; Shang et al., 2021; Giua, Materia and Camanzi, 2022), to the spread of a suite of practices among smallholder farmers in the global South, including minimum-tillage, conservation agriculture, agroforestry, intercropping and natural pest control according to different farming contexts (Kassam, Friedrich and Derpsch, 2019, 2022; Emenyu et al., 2023; Olabanji and Chitakira, 2025; Spurk et al., 2025). More detail on factors that enable or slow adoption of these practices is given in Chapter 3.3.

Policy actions:

- Facilitate financial access, subsidy and incentives, including through strengthening and regulating markets for ecosystem service provision (Hilmi et al., 2024; Baker et al., 2025).
- Set clear, measurable targets through design of metrics and monitoring frameworks (HLPE, 2019; Baker et al., 2025).
- Engagement with farmers, respect for values and motivations, recognising them as crucial agents of change: ensure participatory approaches are adopted to facilitate collaboration and cooperation (Baker et al., 2025), and to develop targeted interventions that are sensitive to landscape and cultural context (Olabanji and Chitakira, 2025).
- Design and implement schemes at landscape (rather than farm) scale (HLPE, 2019; Baker et al., 2025).

Box 3.5.5: Tipping recovery in the Amazon Rainforest

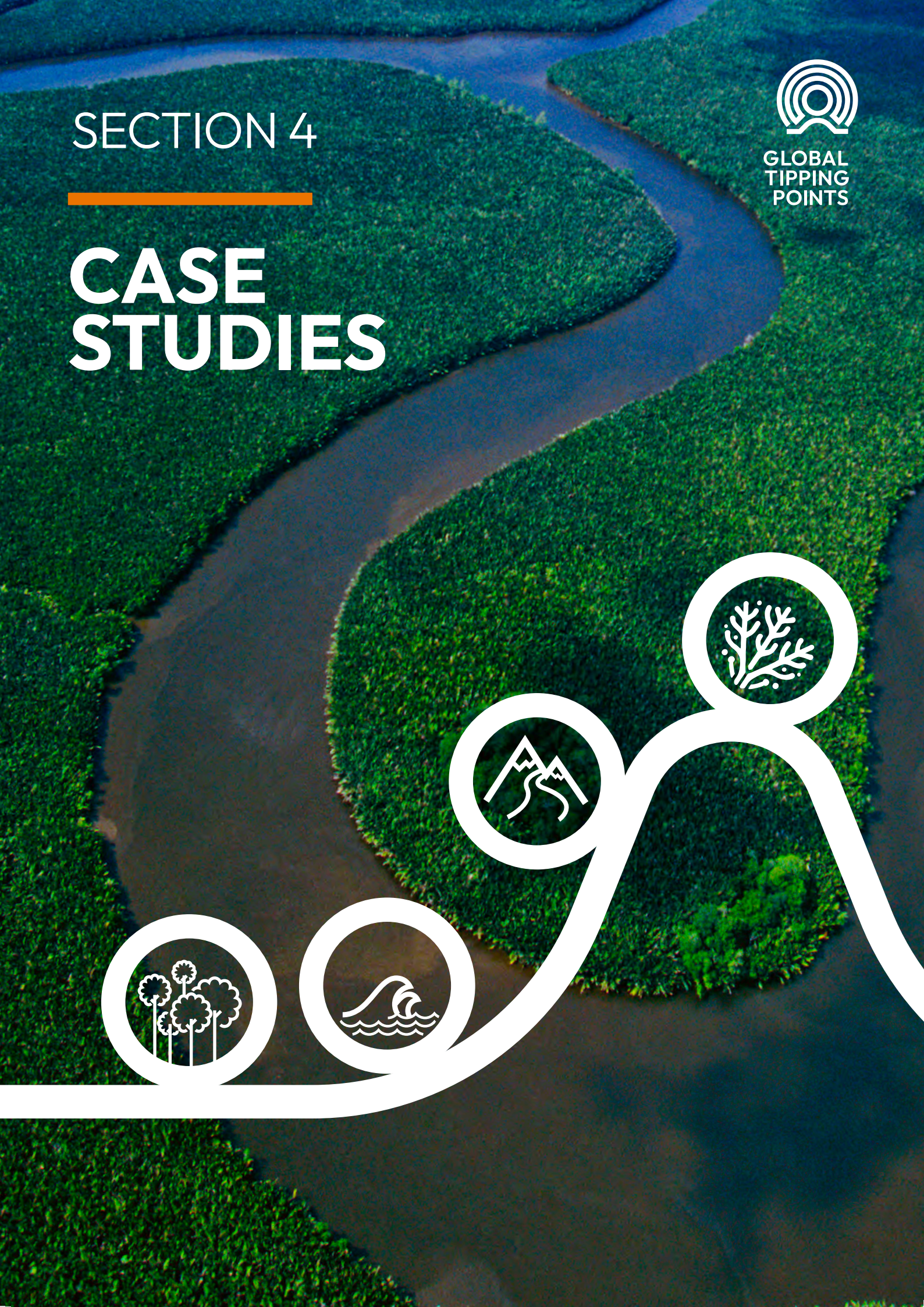
The Amazon rainforest is at risk of tipping to degraded forest or dry grassland states at large scales, through a combination of deforestation and other local pressures, climate change, and biophysical amplifying feedbacks (see 4.1 Amazon Case Study, Boulton, Lenton and Boers, 2022; Flores et al., 2024; Brando et al., 2025). The drivers of deforestation are complex and cross multiple scales; local, domestic, regional and international, but include cattle grazing, expansion of soy production, land speculation, mining and illegal land grabs. Yet the Amazon's resilience also offers pathways to self-propelling recovery.

Joined up action across scales to effectively protect forests and forest communities, and stop deforestation, could enable planting and natural regeneration to positively tip large-scale forest recovery. By understanding the ecological, biophysical and fire feedbacks that drive tipping between forested and dry grassland states, particularly in the southern Amazon (see 4.1 Amazon Case Study), interventions can be designed to maximise their potential to trigger positive tipping to restore forest cover (also see Chapter 1.2, Box 1.2.6). For example, reforestation efforts can consider localised geometry to maximise the resulting destabilisation of the grassland/pasture state (Wuyts and Sieber, 2023). Regions can be targeted for regeneration based on their contribution to moisture recycling and wind patterns to maximise longer range benefits (Boers et al., 2017; Wunderling et al., 2022).

Such spatially coordinated action would benefit from tipping cooperation among relevant actors, for example through inclusive governance approaches that ensure protections and opportunities for local communities, provide incentives for and ensure compliance by commercial actors, and align with national and international policy (Amazon case study 4. & 5.)

SECTION 4

CASE STUDIES



CASE STUDY 01

THE AMAZON RAINFOREST AT THE BRINK



4.1 The Amazon forest at the Brink: cascading risks of social-ecological tipping points and the opportunities to regeneration

Authors: Chris A. Boulton, Patricia Pinho, Avit Bhowmik, Sara Constantino, Bernardo M. Flores, Marina Hirota, Milena Holmgren, Isobel Parry, Tom Powell, José A. Sanabria-Fernández, Viktoria Spaiser, Sebastian Villasante, Nico Wunderling

Reviewers: Richard Betts, Lana Blaschke

Risk assessment

- **The Amazon is approaching ecological tipping points due to interacting climate and land-use feedbacks that threaten to trigger large-scale forest degradation and regime shifts in the range of 1.5-2 °C global warming.**
- **These changes risk transforming forested areas into altered ecosystems, weakening global climate regulation, altering regional climate, and accelerating biodiversity loss.**
- **Negative social tipping points, including displacement, health impacts, and cultural erosion are unfolding alongside ecological forest transitions, especially among Indigenous and traditional populations.**
- **These impacts and risks remain significantly under-addressed in climate policy and are intensified where governance fails to secure land rights, enforce protections, or support adaptation.**
- **Indigenous Territories and Protected Areas exhibit strong climate mitigation potential, underscoring their vital role in maintaining carbon stocks and resisting ecosystem collapse.**
- **In contrast, undesignated Public Forests account for the majority of carbon losses from degradation, reflecting the consequences of weak governance and land tenure insecurity.**
- **Without immediate action, cascading risks could result in irreversible losses to both ecosystems and communities, undermining regional and global sustainability.**

Recommendations

- **The Amazon forest holds global significance as a biocultural climatic-regulating system; safeguarding it requires urgent, justice-centered strategies that integrate understanding of ecological thresholds, social vulnerability, and climate adaptation.**
- **Positive social tipping points can be catalyzed by inclusive and polycentric governance, recognition of traditional knowledge systems, and targeted financial investments in forest conservation, restoration, and supporting Indigenous People and Communities Territories and their livelihoods.**
- **These interventions have the potential to reverse degradation feedbacks and ensure socio-ecological resilience across the Amazon.**



Executive Summary

This chapter explores tipping points in the Amazon as both a warning and a window of opportunity, revealing how the destabilization of forest and Earth systems is driving profound and often irreversible impacts on Indigenous Peoples traditional populations and local population in the region—their territories, rights, livelihoods, and cultures—while also accelerating the ecological and climate crisis. While the ecological tipping point of forest dieback has received global attention, the negative social tipping points unfolding across the region are overlooked despite their role in amplifying ecological risks and opportunities for transformative changes.

Failure to protect the remaining forested areas, Indigenous territories, cultural systems, and local governance structures is undermining forest resilience and climate stability, while also deepening health burdens, displacement, and social inequalities. Fire outbreaks now directly affect 24 million people in the Amazon, with severe health and economic consequences disproportionately borne by Indigenous Peoples, children, and the elderly who are up to 22 times more vulnerable to smoke and heat.

Yet the Amazon is also a place of resilience and innovation. Indigenous territories protected areas could prevent over 15 million respiratory and cardiovascular cases annually and save more than $2 billion USD in health-related costs. These territories also contribute an estimated $5 billion USD each year to the global economy through climate regulation, carbon storage, and food and energy production.

Protected areas are a vital investment for global climate and community stability because they protect forests from deforestation and fires. By preventing multiple threats such as deforestation, fire and land grabbing, they protect the communities living in these ecosystems.

Throughout the region, Indigenous Peoples and traditional communities are catalyzing positive social tipping points jointly articulated with multi-stakeholders both nationally and internationally through forest protection, sustainable livelihoods, and restoration-based economies. From agroforestry systems in the Brazilian Amazon such as Tomé-Açu to rubber-based "vegetable leather" industries in Acre, these efforts demonstrate that socially rooted and ecologically informed interventions can reverse destructive feedbacks and enable regenerative processes.

Governance plays a central role in tipping this balance. Brazil's legal frameworks and deforestation monitoring systems, including Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm), jurisdictional REDD+, sustainability programs like Mato Grosso's Produce, Conserve, and Include (PCI) strategy and Municípios Verdes (Green Municipalities) have helped reduce deforestation, but remain fragmented and often inequitable in terms of shared benefits with local communities, Indigenous and traditional populations. Scaling these initiatives can lead to positive tipping dynamics including polycentric governance models that secure land tenure, prioritize Indigenous and traditional knowledge, and promote inclusive benefit-sharing.

This case study provides key recommendations for catalyzing positive tipping points, including: establishing and strengthening protected areas, Indigenous and traditional populations territories, recognizing and supporting Indigenous and traditional knowledge systems; halting deforestation and forest degradation; and restoring degraded ecosystems. These interventions are not only essential to prevent irreversible changes in socio-ecological systems, but can catalyze a transformation toward climate justice, forest regeneration, and promoting earth stewardship.

Without a justice-centered approach, the Amazon's tipping points will not only spell disaster for the region but will also accelerate global climate instability, reinforcing patterns of historical inequities and deepening socio-economic divides. The time for action is now, to prevent a crisis, build resilience, and ensure that the Amazon remains a thriving ecosystem for both its people and the planet.



1. Introduction: The Amazon at the Crossroads of Climate and Social Tipping Points

The Amazon rainforest is a critical element of Earth's climate system (Malhi et al., 2021), the collapse of which has been highlighted as a tipping point which could be crossed under current climate projections (Armstong-McKay et al., 2022). Storing up to 200 Gt C shared between above- and below-ground biomass (Malhi et al., 2021), partial dieback of the rainforest in the most vulnerable 40% may cause emissions of ~30 Gt C, contributing to ~0.1°C of global warming and up to 2°C of regional warming (Armstong-McKay et al., 2022). While global climate changes that cause warming and drying in the region push the Amazon rainforest towards tipping (Armstong-McKay et al., 2022), this is further compounded by other concerns. Deforestation and forest degradation for example, can amplify regional water recycling feedbacks and fire feedbacks, which further push the system towards tipping (Salati et al. 1979, Brando et al. 2014, Betts et al. 2004, Pueyo et al. 2010, Zemp et al., 2017a,b).

The Amazon forest system is both a biodiversity hotspot and essential for regional and global climate stability, playing a central role in moisture recycling, cloud formation, and energy transport (Lovejoy & Nobre, 2018; Flores et al., 2024). The Amazon region is also culturally megadiverse, home to 1.7 million people from 375 Indigenous ethnic groups living across approximately 3,344 Indigenous territories, highlighting the profound and ancestral interdependence between cultural and ecological processes and resilience (Prist et al., 2023). It is where most staple crops were first domesticated and where the very disciplines of ecology and evolutionary biology took shape (Neves et al., 2021).

The risk of Amazon dieback has been predominantly documented in relation to climate change, deforestation and fire regimes (Lapola et al., 2018; Cox et al., 2004; Lapola et al., 2023; Wunderling et al., 2022; Hirota et al., 2011). The loss of resilience in the Amazon biome is increasingly evident, with local and regional-scale ecosystem transitions already occurring (Brando et al., 2025; Flores et al., 2024).

For instance, as climate change makes the Amazon rainforest hotter and drier, weak governance further amplifies fire risks, fueling uncontrolled burning that threatens ecosystems and the well-being of forest-dependent communities (Barlow et al., 2018). Some regions of the Amazon are now carbon sources rather than sinks, surpassing emissions from deforestation alone (Aragão et al., 2018; Gatti et al., 2021). Since the turn of the century, we have seen large amounts of deforestation within the basin, with an area ~3700km^2, mainly on the south-eastern edge, experiencing 50% or more deforestation (Fig. 1a; Hansen et al., 2013), increasing multiple natural and social risks.

While uncertainties remain regarding the precise Amazon tipping threshold and timeline, it is clear that the social consequences of the current environmental degradation are already profound and will only intensify, becoming far-reaching and irreversible (Lapola et al., 2023; Lapola et al., 2018; Pinho et al., 2015). Extreme events of droughts are leading to disasters in the region by blocking navigability, access to food, water, health, education, and energy, thus affecting all dimensions of livelihoods and wellbeing (Santos et al., 2024; Lapola et al., 2018). These impacts when reaching Indigenous and traditional Peoples are driving migration and increasing poverty and inequalities in larger urban centers in the Brazilian Amazon (Brondizio, 2025). Both extreme floods and droughts deemed one-in-a-century-events have affected the Amazon basin recently (Barichivich et al., 2018, Marengo et al., 2021). However, these do not have homogenous effects across the basin. Using the Standardised Precipitation-Evapotranspiration Index (SPEI; Beguería et al., 2010), we show the percentage of the Amazon basin that has experienced very wet (SPEI > 2) or very dry (SPEI < -2) conditions at some time each year between 2001-2022 (Fig. 1b,c). With red (blue) points denoting significantly reported droughts (floods) in the media, it is clear that these do not necessarily correlate when looking across the full basin, highlighting the importance of viewing the Amazon as a complex and diverse system.

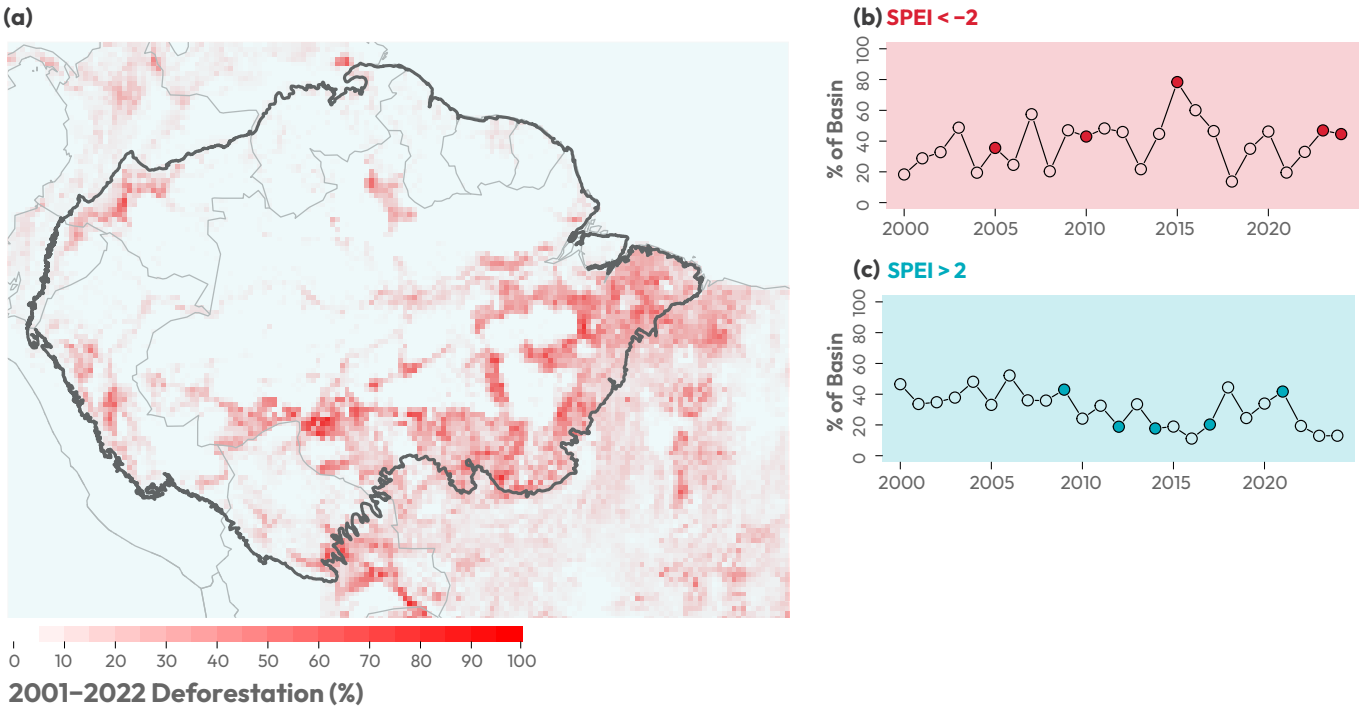


Figure 1: *(a) Percentage of deforestation observed in each grid cell for the period 2001-2022 according to the Global Forest Watch database (Hansen et al., 2013), with the Amazon basin shown in a black outline. (b,c) Percentage of Amazon basin (black line in (a)) that experiences Standardised Precipitation-Evapotranspiration Index (Beguería et al., 2010) values (b) <-2 and (c) >2 at some point in the year, suggesting very dry or very wet conditions respectively. Points are coloured if a drought (red) or flood (blue) was widely reported that year.*

In a scenario marked by deep social inequalities, violence, and accelerating forest degradation, what is at stake is not only the stability of the Amazon biome, but the future of its Indigenous and traditional Peoples—whose territories and ways of life are vital to global climate regulation, yet who face the risk of irreversible social collapse, deepening poverty, displacement, and the erosion of historical rights and cultural identities across the basin (Brondizio, 2025; Bowman et al., 2021). Nonetheless, Indigenous Protected Areas (IPAs) are critical buffers against escalating threats such as deforestation, fire, mining, and infrastructure development, which continue to undermine the ecological integrity of the Amazon Basin (Prist et al., 2023). Strengthening and expanding protected areas and Indigenous Peoples and traditional population territories not only safeguards biodiversity and Indigenous rights, but also reduces the risk of emerging zoonotic diseases and helps mitigate slow-onset climate impacts driven by forest degradation (Bowman et al., 2021).

The Overlooked Social Dimension of Tipping Points in the Amazon rainforest

Critical ecological transitions in the Amazon are already disrupting biodiversity, climate regulation services (Hirota et al., 2011; Flores et al., 2024; Brando et al., 2025), and livelihoods, health and cultural identities (Birkmann et al., 2023; Lapola et al., 2018; Pinho et al., 2015). Yet, despite the extensive research on biophysical tipping points, their social dimensions in terms of impacts, vulnerabilities, adaptation and limits to it, remain underexplored in the region (Brondizio et al., 2016; Spaiser et al., 2024; Birkmann et al., 2023). Despite their critical contributions to environmental stewardship and social resilience, the role of Indigenous, traditional, and community-based organizations remains largely invisible in dominant policy narratives and decision-making arenas (Brondizio et al., 2021).

Globally, the social dimension of impacts and vulnerabilities, adaptation, limits to adaptation and residual risks are disconnected from the discussion of ecological tipping points (Birkmann et al., 2023; Whyte, 2020), limiting full understanding of tipping points effects on livelihoods and culture (Parry et al., 2017; Brondizio et al., 2021; O'Neill et al., 2023).

This is an alarming oversight given that climate and ecological tipping points in the Amazon pose an existential threat to people, particularly Indigenous and traditional populations, as well as to economies, governance, and human rights. Associate loss and damage will disproportionately impact Indigenous and traditional Peoples whose livelihoods and cultural heritage are deeply intertwined with the forest, and may exceed their adaptive capacity (Birkmann et al., 2023; Lapola et al., 2023).

However, Indigenous Territories and Protected Natural Areas (PNAs) in the Amazon stored over 58% of the region's carbon stock in 2016 (41,991 MtC), yet accounted for only 10% (−130 MtC) of the net carbon loss, highlighting their critical role in climate stability (Walker et al., 2020). Despite this, nearly 434 MtC and 423 MtC of carbon were lost from Indigenous Territories and PNAs, respectively, due to forest degradation (Walker et al., 2020), pointing to the urgent need for increased political protection and financial support for Indigenous and local stewardship to meet the Paris Agreement targets. Although research is limited, growing evidence shows that Indigenous and traditional territories play a vital role in supporting human health and local economies, underscoring the need to fully recognize their ecological, social, and economic benefits in land tenure, conservation, and ecosystem service policies (Prist et al., 2023).

The Amazon's social tipping points present a major hurdle for achieving global sustainability in a socially just way under a rapidly changing climate. However, current global and public policies and governance mechanisms are shaped by historical inequalities and global legacies of exploitation (Birkmann et al., 2023, Box 8.5). They are failing to address the cascading socio-ecological impacts of Amazon degradation, particularly for Indigenous and traditional communities who are already suffering irreversible losses (Lapola et al., 2023). For instance, Indigenous territories are increasingly facing multiple pressures, including climate change and land-use change, while rising extremes such as severe droughts have intensified tree mortality and increased vulnerability to wildfires. These events have already been observed in Indigenous Territories like Xingu and Raposa Serra do Sol in the Brazilian Amazon, where climate-driven droughts are triggering cascading degradation and amplifying future risks (Walker et al., 2020; Brando et al. 2019). As these crises escalate, the window of opportunity for meaningful action is rapidly closing (Lenton et al., 2023). Without urgent and deliberate intervention, these communities will continue to face food and water insecurity, loss of health, displacement, and escalating violence, reinforcing cycles of vulnerability and exclusion in the context of global climate change. See chapter 1.4.8 of the report for more information on human rights and preventing regional tipping points.

We can, however, learn from some positive stories within the region. The local wellbeing benefits within the Amazon have been seen with the implementation of sustainable-use protected areas (Campos-Silva et al., 2021), and by reducing emissions (Walker et al., 2020).

Given the Amazon's essential role in global biodiversity and climate regulation, addressing its tipping points must be seen through a climate justice lens—locally, nationally and internationally. The Amazon is not only a regional concern but a critical solution providing climate regulation and an ecosystem where the societal costs of inaction will extend far beyond its borders. Safeguarding the Amazon requires a fundamental shift toward the adoption of policies that prioritize Indigenous and traditional Peoples' land rights, recognize traditional knowledge systems, and ensure equitable access to adaptation and resilience-building resources. The Indigenous territories have a large potential to mitigate climate change and deforestation in these areas, avoiding the Amazon tipping points from being reached (Brondizio 2025). Hence, international cooperation and financial mechanisms must acknowledge the Amazon's planetary significance, providing adequate support for conservation, restoration, regeneration and climate adaptation efforts as to reduce the risks of crossing irreversible tipping points.

This case study examines the Amazon's negative tipping points, analyzing the critical transitions already underway and the cascading socio-ecological risks they trigger. We explore how these processes can lead to impacts on food, water, and health security, promoting forced displacement, conflicts, governance breakdowns, and livelihood collapses, amplifying existing inequities and systemic vulnerabilities. The case study will then assess pathways for building Amazon resilience, highlighting opportunities for positive social tipping dynamics that can reduce socio-ecological risks, advance climate justice, and foster transformative change.

As COP 30 unfolds in Belém, within the Amazon rainforest, this topic takes on unprecedented global relevance. The Amazon's fate is a defining issue for climate stability, biodiversity conservation, and global equity. Preventing its tipping points from becoming cascading crises is not just an environmental imperative, it must become a human rights and climate justice priority.

2. Climate and Ecological Feedback Loops in the Amazon Rainforest System

The Amazon rainforest system is under increasing pressure from interacting climate and ecological feedbacks that push it closer to a tipping point (Flores et al., 2024). These feedbacks, driven by both climate-driven stressors and human-induced disturbances, threaten to destabilize the rainforest's ability to sustain its natural equilibrium. Understanding these processes is critical to assessing the conditions that accelerate degradation and determining how their effects are distributed across the basin.

The interplay of climate change, deforestation, and forest degradation is reshaping the Amazon through both short- and long-term stressors. Extreme droughts have become more frequent and severe over the last 20 years with record droughts in the years 2005, 2010, 2014-2015 and 2023-2024 (Marengo et al., 2021). Many of them were triggered by anomalous warming of sea surface temperatures (SSTs) in the tropical Atlantic and Pacific, often intensified by El Niño events (Marengo et al., 2008; Jiménez-Muñoz et al., 2016). Meanwhile, the dry season has lengthened significantly over southern Amazonia since 1979 (Fu et al., 2013; Marengo et al., 2021), exposing large forest areas to prolonged water deficits. These shifts disrupt key biophysical feedback loops, such as the forest-rainfall feedback, which regulates Amazonian precipitation patterns.

Amazon forest ecosystems play a major role in moisture recycling, with up to an estimated 30% of rainfall in South American cities originating from evapotranspiration (Beveridge et al., 2024). As moisture moves westward across the basin, it becomes almost entirely recycled by the forest itself. The release of latent heat when this moisture condenses in the atmosphere also helps drive the monsoon circulation that draws more moisture into the Amazon basin (Boers et al. 2017). However, deforestation, particularly along the eastern Amazon, can disrupt both processes, reducing rainfall further into the basin (Staal et al., 2018). This positive feedback loop of drying and tree loss contributes to widespread forest dieback, further intensifying regional water deficits and leading to a degraded state.

At smaller scales, fire-vegetation feedback loops drive local forest mortality. As droughts become more severe, forests become drier and increasingly prone to wildfires (Brando et al., 2014). Fire frequency has surged in recent years (Aragão et al., 2018; Gatti et al., 2021), often leading to the replacement of burned areas with highly flammable grasses, which further desiccate the landscape, dry the atmosphere above, and increase future fire risks (Higgins et al., 2000). These dynamics create self-reinforcing degradation cycles, making it difficult for forests to naturally recover over time.

Beyond regional climate feedback, the Amazon is also influenced by large-scale atmospheric and oceanic circulation shifts. The Atlantic Meridional Overturning Circulation (AMOC) has weakened since the 1950s, likely due to anthropogenic emissions (Caesar et al., 2018), which could alter Amazon rainfall patterns; a southward shift in the Intertropical Convergence Zone (ITCZ) can increase precipitation in the southern Amazon while intensifying drying trends in the north (Akabane et al., 2024; Nian et al., 2023). These divergent patterns could stabilize forests in some regions while pushing others toward a degraded or savanna-like state (Ciemer et al., 2021).

Currently, up to 47% of Amazonian ecosystems are exposed to compounding stressors that increase the likelihood of reaching localized or basin-wide tipping points (Flores et al., 2024). Locally, tippings could result in three possible future states across different regions, depending on the location: degraded forest, degraded open-canopy ecosystems, or savanna type of ecosystems. Each has different levels of irreversibility, depending on the persistence and intensity of disturbances.

Recent modeling results, in agreement with earlier expert assessments (Lovejoy & Nobre, 2018), suggest that if deforestation reaches more than 20% of the current forest extent, combined with 1.5–2°C of global warming, over two-thirds of the Amazon could cross a tipping point (Wunderling et al., 2025), changing state within decades (Cooper et al. 2020). However, other modelling studies suggest a smaller change in rainfall response to deforestation than previously thought (Yoon & Hohenegger, 2025). Flores et al. (2024) suggest precautionary limits of 1.5°C and 10% deforestation (requiring restoration of 5% of the biome) to avoid broad-scale ecosystem transitions. These findings underscore the urgent need for strong, effective governance, climate action, and conservation policies to safeguard the Amazon forest system from irreversible transformations.

3. Societal impacts in the Amazon Rainforest System

The Amazon rainforest is facing profound social and economic vulnerabilities due to ecological and climate tipping points. Historically, Indigenous and traditional populations were well-adapted to natural seasonal patterns (Harris 1998), but increasingly frequent and severe extreme climate events, such as droughts and floods are overwhelming these communities' ability to cope (Maru et al. 2014; Lapola et al. 2018; Kreibich et al., 2022; Pinho et al., 2025 in review). Losses in food production, infrastructure, and health services are becoming commonplace, with extreme flooding now occurring every four years instead of once every two decades (Marengo et al. 2024). These disruptions are directly tied to shifts in the hydrological cycle and climate feedback loops (Zemp et al. 2017a,b; Garcia et al. 2018), which are not only degrading ecosystems but also undermining basic human needs like food and water security (Nobre et al. 2025, Padilha et al. 2025).

Applying the risk framework, adapted from the IPCC AR6 and discussed in Section 2.1, highlights the interconnected nature of climate-related hazards, exposure, and vulnerabilities in the Amazon. Should the Amazon rainforest reach its bio-physical tipping point, immediate hazards, including extreme climate events and wildfires, will severely affect health, livelihoods, infrastructure, and culture particularly among rural and Indigenous communities. The combination of extreme droughts, degradation of forests and aquatic ecosystems is likely to lead to a collapse in biodiversity and commercial fish stocks (Birkmann et al., 2023; Lapola et al., 2023), while water shortages would further destabilize hydropower and river transport (Lapola et al., 2018; Lenton et al., 2023; Costa & Marengo, 2023). These cascading ecological failures are leading to increased food prices and reduced access to essential resources , creating acute risks for marginalized populations who lack the resources and infrastructure to adapt effectively (Monteverde et al., 2024; Begazo-Curie & Vranken, 2025). Already the Brazilian government is bringing in food and water to the Amazon during droughts (Kelly & Grattan 2023), and under a tipping scenario such a crisis situation would become chronic.

Fire outbreaks in the Amazon Basin directly affect Indigenous Peoples, traditional communities, and among these, children, and the elderly are up to 22 times more vulnerable to smoke and heat exposure (Machado-Silva et al. 2020; Campanharo et al. 2019, Urrutia-Pereira et al. 2021). Burning a single hectare of Amazon forest can release 760.5 kg of PM2.5 (fine particulate matter in the air with a diameter of 2.5 micrometres or less), resulting in public health costs exceeding $2.1 million USD, and up to $7.5 million in severe cases, highlighting the profound societal and economic toll of fires in the region (Prist et al. 2023).

Vulnerabilities in the Amazon forest are heterogeneous; they are shaped by deep-rooted inequalities and historical injustices such as land dispossession and marginalization of Indigenous Peoples and traditional communities (Birkmann et al., 2023; Pinho et al. 2015, Sultana, 2021, Parry et al., 2017). Unequal access to capital, healthcare, education, and basic infrastructure compounds the impact of climate shocks, particularly if the Amazon region suffers from ecological tipping points. As these stressors intensify under a tipping scenario, so too would the risks of economic decline, social unrest and forced migration (Pinho et al., 2015; Lapola et al., 2018; Birkmann et al., 2023). The Amazon's social tipping points such as migration and conflict, would be increasingly triggered not only by actual environmental degradation but also by perceived climate risks (De Longueville et al., 2020), undermining community stability and deepening socio-economic disparities (Spaiser et al. 2024). However, the further into the cascading chain of socioeconomic impacts we move in anticipating scenarios under Amazon systemic tipping, the more uncertainty we face. Still, the transition from sporadic climate shocks to permanent large-scale ecological regime change, will likely result at least temporarily in large-scale impoverishment and loss of social cohesion that would further erode adaptive capacity and accelerate displacement and systemic instability (Lenton et al., 2023).

Self-reinforcing cycles of decline can emerge, involving food insecurity, displacement, violence, and physical and mental health deterioration (Spaiser et al. 2024). Cascading risks, which cannot be mitigated through adaptation strategies (Thompson et al. 2024, de Carvalho 2025), represent irreversible losses in biodiversity, livelihoods and cultural identity. The erosion of traditional knowledge and social cohesion would further accelerate these declines (Birkmann et al., 2022, Pearson et al. 2023).

The societal impacts of climate and land-use change in the Amazon, ranging from escalating health crises and economic losses to the erosion of traditional knowledge, rights and cultural identities, are already deeply felt, particularly among Indigenous and traditional communities. Overcoming these interconnected risks requires confronting historical asymmetries in power, capacity, and voice. Moving forward, effective responses must be rooted in inclusive governance arrangements that bridge public and private sectors, science and policy, and, most critically, the lived knowledge and leadership of Indigenous Peoples and local communities (Garnett et al., 2018).

4. Governance to Avoid Socio-ecological Tipping Points in the Amazon

As highlighted in the previous section, the Amazon faces imminent socio-ecological tipping points driven by land-use change, environmental degradation, and deep-rooted inequalities. Avoiding collapse and fostering resilience requires strengthening governance systems that are inclusive, territorially grounded, and capable of integrating Indigenous knowledge and science into policies for conservation, climate adaptation, and sustainable livelihoods (see Prevention Chapter 1.2 of the report).

In the absence of robust governance, crises can escalate, straining state capacity, undermining democratic institutions, and increasing the risk of climate-induced social unrest and authoritarian backsliding (Spaiser et al., 2024; Urzedo & Chatterjee, 2022). Just responses must center the rights and agency of Indigenous Peoples and Local Communities, prioritizing land tenure security, participation in decision-making, and access to sustainable finance (Pereira et al., 2024; Human Rights Chapter 1.4).

Brazil and other Pan-Amazonian countries have developed legal frameworks, monitoring systems, and institutional arrangements to curb deforestation and safeguard ecosystems. Brazil's Action Plan for the Prevention and Control of Deforestation in the Legal Amazon PPCDAm, reinstated in 2023, combines enforcement tools such as DETER and PRODES with territorial strategies like the demarcation of Indigenous Lands and Protected Areas, which remain among the most effective barriers to deforestation (Nolte et al., 2013; Walker et al., 2020). Recent reductions in deforestation alerts by 50% in 2023, compared to the previous year, and the lowest since 2018, show the impact of renewed governance efforts (Reuters, 2024).

Regional governance for protected areas in the Amazon has also evolved beyond extractivist models, increasingly embracing participatory approaches that recognize the interdependence between forest conservation and social equity (Brondizio 2025). For instance, extractivist and Sustainable Development Reserves, supported by grassroots mobilization and international cooperation (e.g., UN Rio 92, PPG-7), have helped link biodiversity protection to poverty reduction and local empowerment (Pinho et al., 2014). Programs such as Bolsa Floresta, SDR Mamirauá, and Proambiente are incentive-based policies, e.g., payment for ecosystem services (PES), that promote capacity building, local participation and generate socio-ecological co-benefits in the Brazilian Amazon. The co-management of pirarucu fisheries -one of the largest freshwater fisheries in the world- in Mamirauá at the Juruá River exemplifies how community-led governance can improve well-being while protecting biodiversity (Campos-Silva et al., 2021).

Hybrid governance arrangements, blending national policy, international partners and funding, and strong local institutions have enabled innovations such as in freshwater management agreements and sustainable practices for fisheries (Brondizio 2025). For instance, along a 2,000-km stretch of the Amazon, co-managed protected areas involving over 100 communities have delivered improved health, education, and livelihoods while restoring wildlife populations (Campos-Silva et al., 2021). The 2006 Soy Moratorium (also summarised in Box 3.5.2 of the report), catalyzed by civil society pressure and corporate accountability, became a landmark governance intervention, proving that market-driven agreements can effectively curb deforestation by making environmental compliance a condition for market access (Nepstad et al., 2014). The Amazon Fund and state-led REDD (Reduction Emissions from Deforestation and Forest Degradation) programs exemplify how performance-based partnerships, combining international donor funding, national and subnational strengthening and local implementation can align incentives across scales to reduce deforestation and strengthen forest governance in the Amazon (Nepstad et al., 2014; Garret et al., 2021).

A range of innovative governance instruments has gained force recently to curb deforestation in the Brazilian Amazon. Jurisdictional REDD+ programs in states like Acre, Amazonas, Amapá, Pará, and Mato Grosso offer performance-based incentives for reducing emissions while promoting sustainable development associated with the carbon market (Gueiros, 2023). Locally driven initiatives such as Mato Grosso's Produce, Conserve, and Include (PCI) strategy and Pará's Municípios Verdes Program link land-use planning, environmental licensing, and inclusive rural development, demonstrating how subnational and municipal leadership can drive effective forest governance (Garret et al., 2021). Yet, these market-based instruments still face implementation challenges, including insecure land tenure and unstable funding that must be addressed to ensure sustainability and justice. The finance subchapter (1.2.3) of the prevention chapter of the report delves into more detail about this.

Despite advances, governance of the Amazon remains fragmented. Policies have largely focused on Indigenous and traditional territories, often neglecting smallholders, colonists, and urban populations leaving structural vulnerabilities unaddressed (Pinho et al., 2014; Birkmann et al., 2022). Unequal representation, combined with ongoing development pressures, contributes to rural-urban migration and the emergence of new social risks (Brondizio, 2025).

To enable positive social tipping dynamics, governance must be polycentric and inclusive and nested across scales and sectors (Lenton et al. 2022). This includes reinforcing territorial governance, financing community-led solutions, integrating biodiversity and ecosystem services into social policy, and protecting biocultural heritage.

The Amazon forest holds many opportunities for transformation. Mobilizing its governance innovations can shift the region's trajectory away from collapse and toward building resilience, offering promising pathways towards global climate justice and sustainability. Halting deforestation and forest degradation, while securing sustainable, equitable livelihoods for Indigenous Peoples, is central to this shift. Building on this section, the next section outlines concrete pathways to activate positive social tipping points—recommendations that harness local agency, institutional innovation, and territorial integrity to drive transformative change across the Amazon.

5. Positive Tipping Points for Conservation and Restoration

Feedback mechanisms that risk triggering irreversible ecological tipping points in the Amazon also offer opportunities to catalyze positive social tipping points, transformative shifts in behaviors, institutions, and land use that reinforce forest regeneration, climate stability, and community resilience (see also the Prevention Chapter 1.2 of the report). Nowhere is this synergy more striking than in the Amazon, whose unmatched ecological and cultural wealth makes its protection central to planetary climate stability and human wellbeing (Barlow et al., 2018).

By investing in locally rooted solutions, restoring forest health, and advancing inclusive governance, it is possible to reverse negative trajectories and activate regenerative cascades across the region.

While the cascading social impacts of forest degradation may be difficult to reverse, positive social-ecological feedback, rooted in local agency and institutional transformation can slow, halt, or even shift these dynamics toward resilience. For instance, the development of vegetable leather in Acre exemplifies how accumulated social capital, collaborative networks, and place-based innovation—driven by rubber-tapping communities, women's groups, governments, and national/international donors can trigger lasting socio-economic transformation and diversified micro-industries such as art-crafts and medicinal oils (Brondizio et al., 2021). Similarly, the agroforestry systems led by local communities in Tomé-Açu provide a compelling alternative to widespread forest-to-pasture conversion, enhancing carbon sequestration, sustaining livelihoods, and redirecting land-use trajectories toward climate-resilient futures (Batistella et al., 2013).

Despite these contributions, Indigenous Peoples, traditional populations, and smallholders often receive only a fraction of the benefits. This has prompted initiatives focused on value aggregation, bioprospecting, and certification to increase equity within forest-based economies (Brondizio et al., 2023). State-led programs in Amapá, Acre, and Pará have also promoted inclusive forest economies, while the emerging bioeconomy paradigm seeks to reframe development through the diversification of production methods, the enhancement and protection of biodiversity, and the recognition of traditional knowledge and equitable benefit-sharing (Bergamo et al., 2022). Interventions that reinforce mutually beneficial relationships between restoring forest health and improving livelihoods can trigger locally positive cascades, generating both ecological protection and socio-economic well-being. These dynamics are central to activating the kinds of positive tipping points needed to shift the Amazon away from collapse and toward a just, climate-resilient future.

To shift from risk to building resilience, we propose five pathways to prevention, interventions capable of fostering positive tipping dynamics and transforming the Amazon into a global model of socio-ecological sustainability. Figure 2 shows where these pathways can prevent tipping and its cascading effects from occurring.

1. Commitment to Halt Deforestation and Biodiversity Loss

Building on Brazil's pledge to end deforestation by 2030 and its NDC under the Paris Agreement, transparent enforcement mechanisms must ensure real implementation. These actions align with global goals, including the Convention on Biological Diversity (CBD)'s 30×30 target. Multi-stakeholder platforms—like MapBiomas, the Climate Observatory, and the Amazon Trade and Environment Observatory, enhance accountability, are present among higher levels of governments such as public ministry and offer public pressure (Moutinho & de Azevedo, 2023). If all deforestation in the Amazon is curbed, emissions from land-use change could fall by 96%, reducing Brazil's total GHG emissions by 44% (Zimbres et al., 2024).

2. Strengthen Protection for Forest Conservation

Protecting intact forests, Indigenous Territories and Protected Areas is critical to tenure rights, culture, biodiversity and climate stability. These areas show the lowest deforestation and degradation rates and consistently safeguard carbon stocks (Walker et al., 2020; Josse et al., 2024). Protected areas in the Amazon reduce fire occurrence by up to 12% per year, with subnational reserves showing the strongest protective effect, underscoring their critical role in curbing fire-related environmental damage and the urgent need to expand and enforce these territories (Pêssoa et al., 2023). In contrast, Undesignated Public Forests account for 82% of degradation-driven emissions, and 44% of total forest carbon losses between 2003 and 2019 within the Brazilian Amazon (Bullock et al., 2020; Kruid et al., 2021). Prioritizing the protection of centuries-old forests and transferring non-designed public forests to Indigenous and traditional communities is vital for safeguarding ecological services and cultural integrity (Almada et al., 2024; Moutinho & Azevedo, 2023).

3. Territorial Protection and Empowerment of Indigenous Peoples and Local communities

Indigenous Peoples and Local Communities (IPLCs) manage over 58% of Brazil's protected lands and 59% of its forest carbon stocks (Walker et al., 2020). Their stewardship is essential for climate mitigation, biodiversity conservation, and health protection. Indigenous Territories in the Brazilian Amazon contribute to over US $5 billion annually to the global economy through food, energy, and vital climate regulation services (Siqueira-Gay et al. 2020). Protecting Indigenous Territories could prevent more than 15 million pollution-related illnesses annually and save $2 billion in health costs of population to fire (and particulate matter) exposure (Prist et al. 2023). Securing land rights, enhancing forest monitoring capacity, and recognizing ancestral knowledge are key to enabling IPLCs' continued role in safeguarding the Amazon and promoting intercultural and transdisciplinary solutions (Levis et al., 2024).

4. Restoration of Forest Ecosystems

Restoring degraded and abandoned lands can stabilize rainfall patterns and recover forest resilience. The Science Panel for the Amazon estimates restoration could help sequester 15–30 billion tonnes of CO_2 by 2050 (Gatti et al., 2023). Programs like Restaura Amazônia and the National Plan for the Recovery of Native Vegetation (PLANAVEG) aim to restore 12 million hectares by 2030 in the region and country. However, priorities must align across actors and sectors to avoid undermining restoration goals that need to be attentive to biodiversity (Barlow et al., 2021a,b). Restoration strategies should protect secondary forests (Jakovac et al., 2024), enhance connectivity, support seed and seedling supply chains, and engage Indigenous and local knowledge (Jakovac et al., 2024; Levis et al., 2024; Heinrich et al., 2021). Agroforestry systems rooted in Indigenous practices offer a scalable solution for restoration, food security, and livelihood income generation (Brondizio et al., 2021;. See also the Prevention chapter of the report (Chapter 1.2)

5. Cross-Sector Collaboration for Polycentric Governance

Transversal to all these initiatives is the imperative of cross-sector collaboration. Effective transformation requires coordination across governance levels: international, national, regional, and local. It needs collaboration between science and policy, and with Indigenous Peoples and Local Communities. Brazil's history of polycentric models, such as co-managed protected areas and sustainable-use reserves (Campos-Silva et al., 2021), and landmark international governance innovations like the Soy Moratorium, illustrate how the integration of science, monitoring, local participation, economic incentives, and secure tenure can generate lasting socio-ecological co-benefits. Multi-stakeholder coalitions must go beyond isolated projects and actively integrate biodiversity, climate, and social equity goals to enable resilient and just territorial governance.

Equitable climate and biodiversity finance, particularly through Payment for Ecosystem Services (PES) and jurisdictional REDD+ mechanisms, must directly reach Indigenous Peoples and Local Communities, and be backed by safeguards that ensure social inclusion, accountability, and long-term sustainability (Brondizio, 2025). Beyond financial flows, this demands institutional support for IPLC-led monitoring, territorial management, and innovation systems.

Despite the Amazon's extraordinary socio-biodiversity crucial to global ecosystem services, cultural diversity, and scientific innovation, at least in Brazil it remains one of the most under-researched and underfunded regions (Barlow et al., 2018). Unlocking its full potential for resilience and sustainability demands urgent, equitable, and cross-sectoral investment in knowledge, innovation, and local capacity.

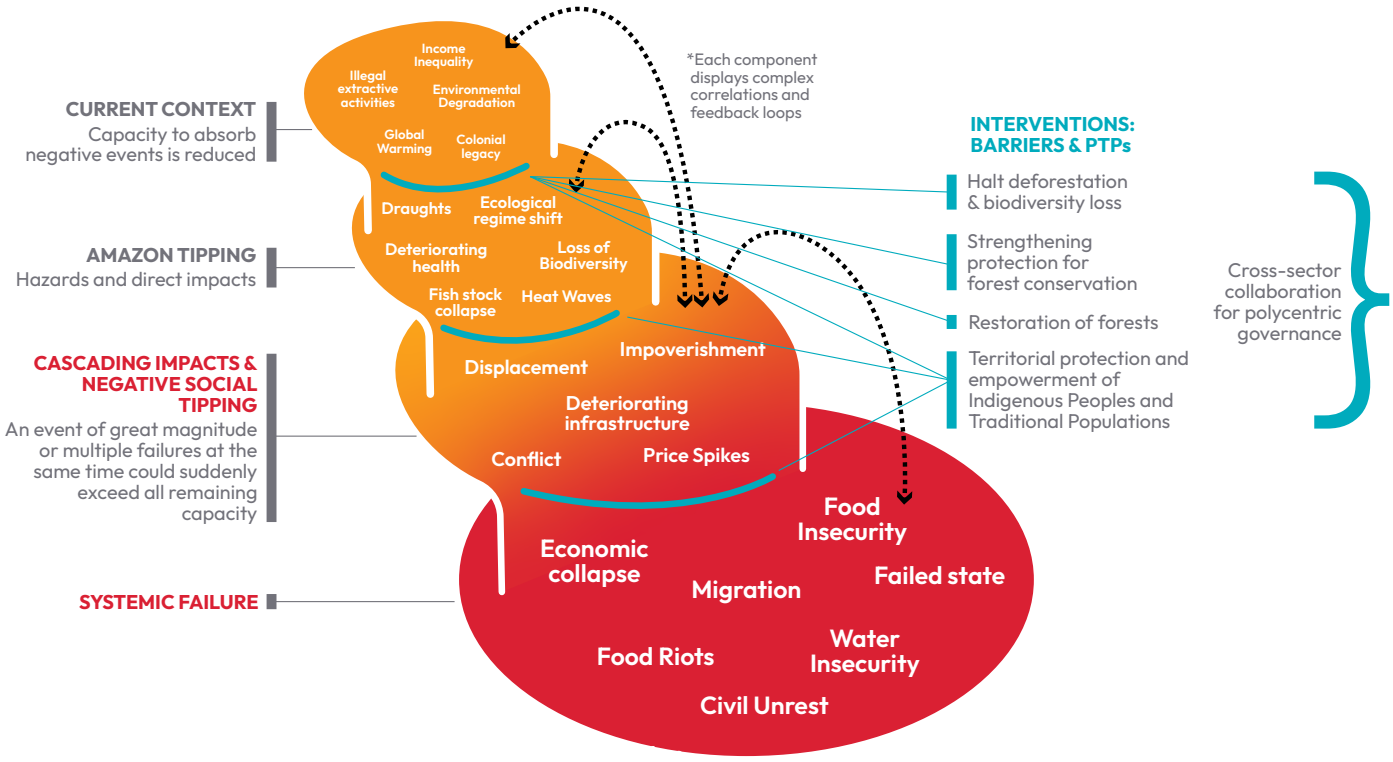


Figure 2: *The cascading impacts of the Amazon rainforest tipping point, flowing from current context through the effects of tipping, and the social tipping points that could also be crossed, culminating in systemic failure. The 5 pathways recommended here act as barriers and offer potential for positive tipping against this cascade. Figure adapted from Laybourn et al., 2024.*

CASE STUDY 02

ATLANTIC OCEAN CIRCULATION



4.2 Atlantic Ocean Circulation Case Study

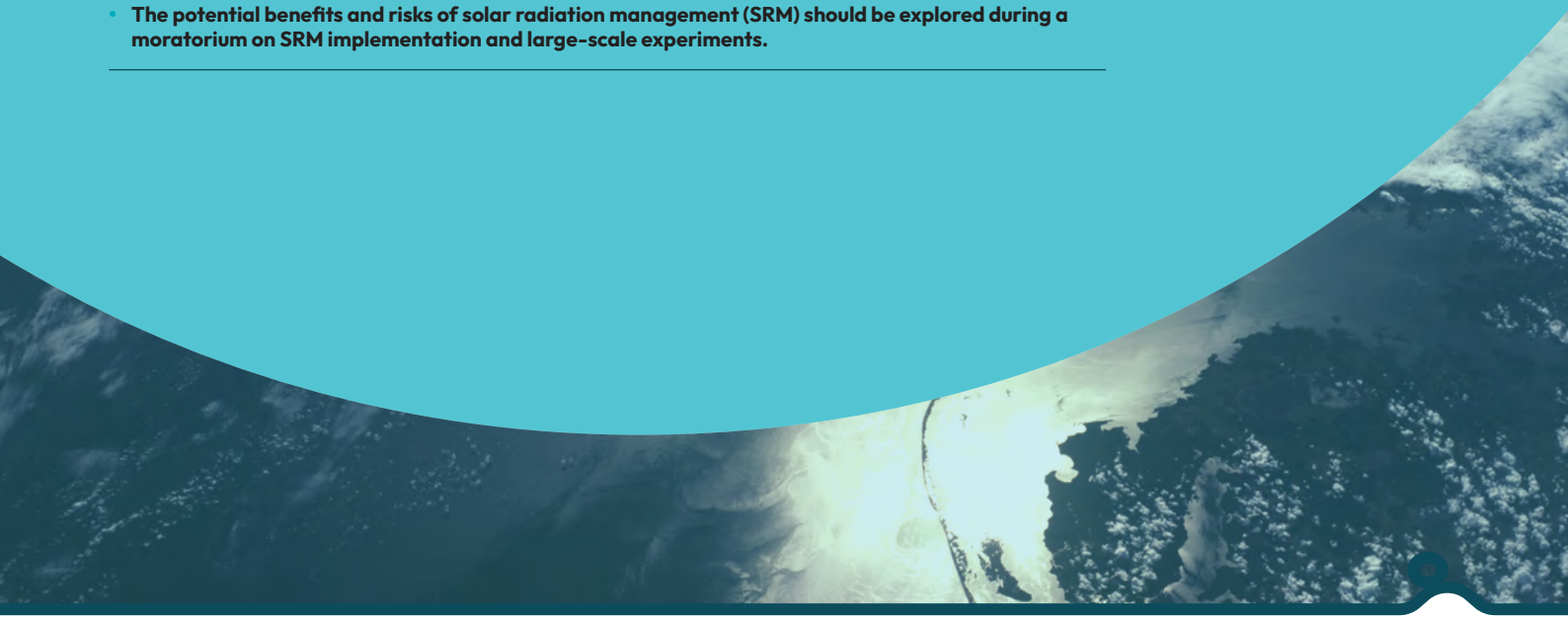
Authors: Henk Dijkstra, Didier Swingedouw, Caroline Katsman, Sybren Drijfhout, Amber Boot, Viktoria Spaiser, Yevgeny Aksenov, Manjana Milkoreit, Jesse F. Abrams, Marius Årthun, Andreas Born, Sara Constantino, Matthew England, Timothy M. Lenton, Valentin Portmann, Paul Ritchie, Stefanie Rynders, Bablu Sinha, Sebastian Villasante, René van Westen, Claudia Wieners

Risk assessment

- **The Atlantic Meridional Overturning Circulation (AMOC) and Subpolar Gyre (SPG) have different tipping points and timescales of transition but are strongly coupled via influencing stratification of the northern North Atlantic Ocean.**
- **Crossing either tipping point has numerous impacts, including much harsher northwestern European winters, disruption of the West African Monsoon, decreased agricultural yield and marine ecosystem shifts.**
- **The conditions under which SPG and AMOC can tip remain uncertain, due to a limited observational record and biases in climate models, but we cannot exclude that an AMOC tipping point may already have been passed.**
- **Deep winter mixing in the Labrador, Irminger and Nordic Seas is projected to collapse before 2050 in many CMIP6 models causing the AMOC to decline to a weak and shallow state beyond 2100.**
- **The likelihood of tipping for both SPG and AMOC systems increases with global temperature.**

Recommendations

- **Current observational arrays in the Atlantic Ocean should be maintained and Earth system model bias should be reduced as both are crucial for the science and future early warning systems of AMOC or SPG tipping.**
- **Continuous monitoring of SPG and AMOC risks, rapid communication of early warning signals and nation-specific complex risk-assessments of the impacts of AMOC or SPG tipping should be made for European countries to inform prevention and adaptation policies.**
- **Preventing the crossing of AMOC or SPG tipping points should be a primary governance target.**
- **The potential proximity of SPG collapse demands that European governments and the EU revisit and update national and European climate adaptation and preparedness plans, policies and institutions to account for the expected impacts of this tipping process.**
- **To minimize the risk of SPG or AMOC tipping, overshoot of 1.5°C global warming needs to be avoided.**
- **Net-zero timelines need to be shortened and immediate investment in the development and scaling of sustainable carbon removal technologies is required.**
- **The potential benefits and risks of solar radiation management (SRM) should be explored during a moratorium on SRM implementation and large-scale experiments.**



Executive Summary

The Atlantic Ocean Circulation is dominated by several large-scale currents, one prominent example being the Gulf Stream. The depth-dependent northward and southward volume transport of these currents is the Atlantic Meridional Overturning Circulation (AMOC). The AMOC is responsible for the northward heat transport which affects climate around the Atlantic basin (Rahmstorf, 2024). In the northern regions of the Atlantic, warm surface water from the upper branch of the AMOC is cooled and transformed into water of the deep AMOC branch. One of the regions where this water mass transformation occurs is the Subpolar Gyre (SPG) region (Straneo, 2006). Key components of the SPG region are currents in the Labrador and Irminger Seas, generating an overall counterclockwise flow (Fig. 1) and the transformation of large volumes of lighter surface waters to denser deep waters in the interior of these seas.

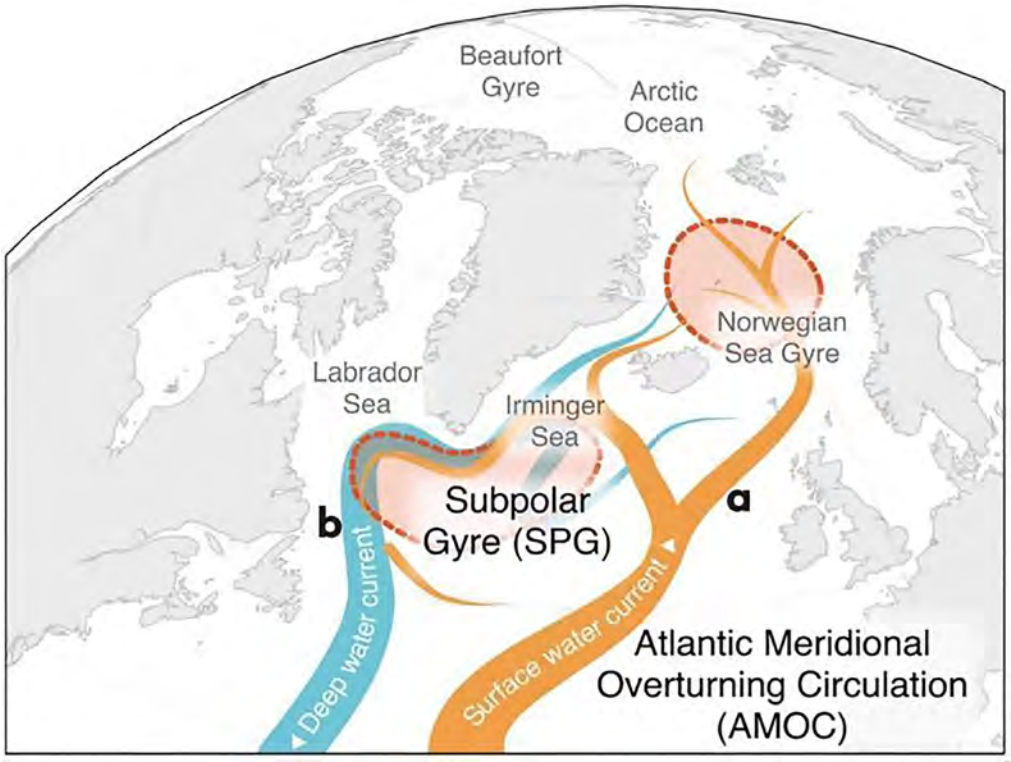


Figure 1: *Sketch of the AMOC-SPG current systems in the North Atlantic, depicting (orange) lighter surface currents, (blue) dense deep currents and (shading) regions of pronounced water mass transformation. Source: Lenton et al. (2023), Figure 1.4.2; Credit: Sina Loriani.*

Although the AMOC and the SPG are strongly coupled, it is useful to consider their behaviour separately regarding tipping (Loriani et al., 2025). First because different time scales are involved and second because the physical processes causing the tipping behaviour are different. Both SPG and AMOC are sensitive to freshwater input such as additional rainfall or inflow of meltwater from the Greenland Ice Sheet, and to changes in heat exchange between ocean and atmosphere. The AMOC can tip to a very weak state because critical conditions involving the salt advection feedback are crossed. The SPG can tip to a state with a strongly reduced formation of dense water when surface water becomes too buoyant, taking place on shorter time scales than the AMOC tipping.

We provide an overview of all aspects associated with the tipping of the Atlantic Meridional Overturning Circulation (AMOC) and Subpolar Gyre (SPG), including the physics of the tipping behaviour, the climate and ecosystem impacts and the possible role of governance in preventing and mitigating the effects.

1. Tipping of the AMOC and SPG

1.1 AMOC tipping

The AMOC has strongly varied in the past, notably during the last glacial period, where most paleodata are available. It has contributed to the large cooling and warming events that are recorded in Greenland ice cores, indicative of large instabilities in the ocean-cryosphere-atmosphere system in the North Atlantic (Sadatzki et al. 2023). In particular a large weakening of the AMOC might explain the cold Younger Dryas (~12,900–11,700 years ago) that interrupted the warming trend during last deglaciation (Velay-Vitow 2024).

Over the historical era, there is still a debate concerning the status of the AMOC trend. While some papers have proposed that the AMOC might have weakened over the historical period (Dima and Lohmann 2010, Drijfhout et al., 2012, Rahmstorf et al., 2015, Caesar et al. 2021, Zhu et al., 2023, Li and Liu 2025) with a potential amplitude of 15% (Caesar et al. 2018), other studies, using different proxies of the AMOC, question those conclusions (Fraser and Cummingham 2021, Worthington et al. 2021, Latif et al. 2022, Rossby et al. 2022, Terhaar et al. 2024). There remains an ongoing search for an optimal AMOC fingerprint which is sensitive to the forced anthropogenic signal, whilst minimizing noise resulting from multi-decadal variability. Given that the AMOC has only been directly observed since 2004, more observational evidence is required before any strong confidence will arise concerning the evolution of the AMOC over the historical era. Since 2004, the RAPID observations do show a downward linear trend (Volkov et al., 2024), consistent with model simulations that feature a collapse of the AMOC in the northern North Atlantic beyond 2100 (Drijfhout et al., 2025). However, this observed trend is only marginally significant (Volkov et al. 2024) and may not be only an 'anthropogenically forced' weakening signal, but also be 'blurred' by natural variability. A similar picture arises from an evaluation of deep convective mixing in the northern North Atlantic (Drijfhout et al., 2025). That observational trends are not (yet) being significant could possibly be explained by a 'tug of war' between natural and anthropogenic influence on AMOC (Bonnet et al. 2021). The latter may include remote teleconnections as well as local forcing (Liu et al., 2020).

The impact from anthropogenic forcing of the AMOC over the historical period in CMIP6 models is a weakening trend, but which is only starting in the late 1990s (Menary et al. 2021). Recent studies also evaluated the potential impact of Greenland melting which is usually poorly represented in those models. While Devilliers et al. (2024) found almost no impact of observed Greenland meltwater fluxes on the AMOC in the EC-Earth model, in line with results from IPSL-CM6A-LR (Devilliers et al. 2021), Pontes and Menviel (2024) did find a strong impact within the ACCESS-ESM1.5 model. However, the amount of freshwater is largely overestimated in the latter study as compared to Greenland meltwater reconstruction, casting doubt on the results of the latter study. Another study by Wei and Zhang (2024) reports the results of freshwater hosing restricted to the southern Greenland Sea and finds some impact (order a few Sv) on subpolar gyre overturning. However, the magnitude of the freshwater forcing perturbation is again rather large and the rationale behind the choice of the geographical region is unclear. Note that in CMIP6, already quite a few models do show a collapse or are en route to a collapse of the northern branch of the AMOC without including Greenland meltwater forcing. In line with the study of Bakker et al. (2016) who found that the effect of meltwater did enhance the weakening and probability of a collapse, but was of secondary importance compared with the effect of global warming. To conclude, based on recent results and projections available, the impact of anthropogenic forcing on the AMOC is a slight weakening trend of the AMOC since the 1990s, possibly due to internal variability (Latif et al. 2022).

In addition to changes in meltwater input, the oceanic freshwater transport from the Arctic to the Atlantic is expected to increase in the future due to the projected accumulation of freshwater in the Arctic caused by changing wind patterns and decreasing sea ice concentration (Lin et al,. 2023). The dynamical mechanisms, timing, magnitude and impacts of such a release are still very uncertain (Bellomo and Mehling, 2024), but in present-day climate models, it seems most likely to impact AMOC variability rather than to cause a collapse of the AMOC before the year 2100.

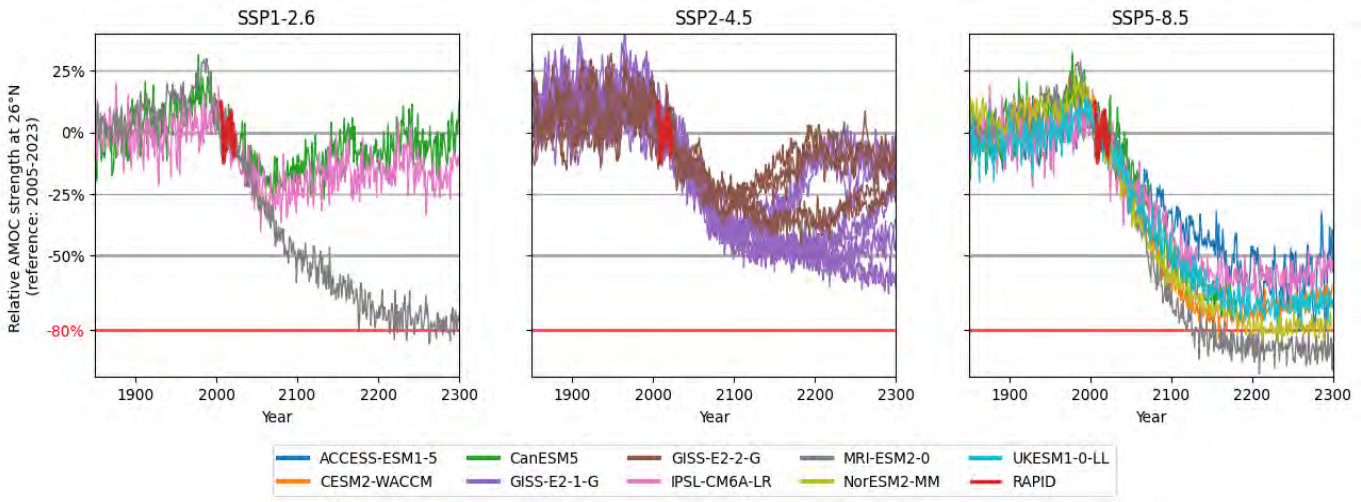


Figure 2: *AMOC strength at 26°N (in Sv, 1 Sv = 10^6 m^3/s) for climate models that run projections beyond 2100. The historical simulations and various emission scenarios are shown, with SSP1-2.6 scenario on the left, SSP2-4.5 scenario in the middle and SSP5-8.5 scenario on the right. The different colors correspond to the different models presented in the legend. Some of them are providing different members. The RAPID observations are shown in red.*

According to climate models, the AMOC will actually weaken within this century (Weijer et al. 2020), which might not necessarily indicate a coming collapse. Thus, direct observations might inform us in the coming years to decades of a significant negative trend in the AMOC. However, a key question remains what the amplitude of such a weakening would be, also going beyond 2100. As shown in Fig. 2, the AMOC response is very dependent on the model analysed. For instance, at the end of this century, CMIP6 models project a weakening that goes from 3 to 72%. Beyond 2100, the few simulations that exist can show a strong AMOC reduction even for the low emission scenario SSP1-2.6 (Fig. 2). The scenario SSP5-8.5 highlights a very strong weakening in all models, but while some seem to have almost collapsed, others do show early signs of recovery by 2300 (Fig. 2) which can be related to stabilising effects of the increased Southern Ocean upwelling (Baker et al. 2025) in such models, although it should be stressed that this might be an artifact of non-eddy-resolving models that do not show the effect of eddy-compensation and saturation seen in eddy-permitting and resolving models (Munday et al., 2013, Bishop et al., 2016). This spread among models illustrates the urgent need for knowledge concerning the proximity of the AMOC to a tipping point, which might strongly influence the AMOC response among the models (Van Westen and Dijkstra 2024). However, Fig. 2c is not implying necessarily that when the AMOC is collapsing it has crossed a tipping point since this is still a transient response to a very strong forcing in most cases. This, however, is not true for the SSP1-2.6 and SSP2-4.5 simulations where the forcing after 2100, or even earlier (SSP1-2.6), no longer increases and in SSP1-2.6 even weakens after 2050 (Riahi et al., 2017). As such, a number of studies highlights that the AMOC might recover after anthropogenic forcing in some models when greenhouse gas forcing is stabillised (Jackson et al. 2013, Bonan et al. 2022) although not true in all models (e.g. Romanou et al. 2024). Indeed, it should also be noted that the likely tendency of the current generation of models to be over stable with respect to the AMOC remains a concern. This too strong stability might be related to biases in South Atlantic salinity, which need concerted effort on the part of model developers to correct them (Van Westen and Dijkstra, 2024).

1.2 SPG tipping

The SPG is a crucial area, as the AMOC's upper branch and lower branches connect here. The SPG circulation is partly driven by the surface winds, and partly by temperature and salinity differences in the subpolar ocean. In the current climate, wintertime atmospheric cooling drives strong water mass transformation in the interiors of the Labrador Sea and Irminger Seas. The heat loss to the atmosphere makes the surface waters denser, causing them to mix vertically with the waters below. This process, known as deep ocean convection, may reach depths of more than 2.5 km (Marshall and Schott, 1999), thus creating vast volumes of dense waters. The anti-clockwise currents along the SPG boundaries (Fig. 1) are more buoyant, and their strength is partly governed by this cross-shore density gradient with the interior (Straneo 2006). On an annual timescale, the net buoyancy loss of the Labrador and Irminger Seas to the atmosphere is balanced by lateral advection of buoyancy. In particular, mesoscale eddies (vortices of ± 25-100 km) that are shed from the unstable SPG boundary currents transport lighter waters towards the interior, yielding a seasonal cycle of convection and restratification (Spall 2004, Gelderloos et al. 2011, Georgiou et al. 2019, Yashayaev 2024, Sterl and De Jong 2022).

SPG tipping refers to a longer-term (decadal or longer) shutdown of deep ocean convection and a drastic weakening of the part of the SPG circulation driven by the above-mentioned cross-shore density gradient (Born and Stocker 2014, Born et al. 2016). The tipping mechanism is linked to the properties of the waters transported to the interior by the eddies: compared to the basin interior, these are warmer and saltier. An increase in salinity in the SPG boundary current therefore results in a stronger lateral eddy salt transport and (as saltier waters are denser) facilitates and deepens convection. This densifies the water column at mid-depth, which strengthens the cross-shore density gradient and hence speeds up the boundary current. This in turn makes this current more unstable, enhances the shedding of eddies, and thus constitutes a positive feedback mechanism as more salt is transported towards the interior. Although such an increase in eddy shedding also yields a larger lateral heat transport (i.e., a negative feedback on convection), a heat anomaly can be efficiently removed by the atmosphere, in contrast to a salt anomaly. Reversely, a freshening of the boundary current suppresses convection. This poses a substantial tipping risk: as this fresh anomaly is not easily eroded by atmospheric interaction it can induce longer-lasting suppression of convection (Yashayaev (2024), Fedorov et al. (2023)) and even multiple years of shutdown (Born and Mignot 2012, Born et al. 2016, Swingedouw et al. 2021). In this respect, the tipping mechanism shares similarities with the salt advection feedback of the AMOC: the difference in persistence of temperature versus salinity anomalies is an essential ingredient.

Support for SPG tipping occurring in the past can be found in paleoclimate reconstructions and modeling. For example, two episodes of a shutdown of SPG convection prior to the Little Ice Age have been identified in high resolution bivalve data from the North Icelandic shelf (Arellano-Nava et al., 2022), corroborating earlier studies with similar findings (Lehner et al., 2013; Moffa-Sanchez et al., 2014, Moreno-Chamarro et al., 2015). Both episodes appear to be driven by freshening of the surface waters in the region, either by anomalously high amounts of Arctic sea ice or by anomalously strong melting of the Greenland Ice Sheet during the preceding Medieval climate optimum. SPG tipping events are also found in the warmer-than-present last interglacial period (Steinsland et al., 2023), and in a simulation of the mostly colder-than-present past 21,000 years (Mandal et al., 2024). However, the paleo records cannot answer if the SPG tipping is attributable to an expansion of the sea ice cover that creates freshwater anomalies that in turn trigger a response in the ocean circulation involving lateral exchange between boundary currents and interior as described above. An alternative explanation is that the sea ice expanded so far that it shielded the ocean from the atmosphere and thus shut down deep convection in the SPG region directly (Kleppin et al. 2015, Li and Born 2019).

For future climate conditions, the latter direct sea ice effect is not very plausible, and thus is freshwater transport into the interior of the SPG considered the key ingredient in the mechanism of SPG tipping (Born et al. 2016). This process thus needs to be represented properly in models to assess the tipping risk (Jackson et al. 2025). Model resolution is known to have a strong impact on the simulated susceptibility of the SPG to tipping, in line with the expected susceptibility to the representation of the freshwater transport. At the resolution typical for present-day climate models, the eddy field is too weak to generate sufficient lateral transport (Martin and Biastoch, 2023). Climate models typically produce ocean currents that are unrealistically sluggish and wide, and hence the boundary current and convection region are not sufficiently separated. As a result, freshwater anomalies in the boundary current may spread directly into the interior and shut down convection too fast and too drastically (Shan et al. 2024).

Falkena et al. (2025) investigated if the current generation of climate models comprises the feedback mechanisms that may lead to SPG tipping. They found that nearly all CMIP6 models display the expected response in mixed layer depth to changes in sea surface salinity. However, the feedback on the SPG strength via subsurface temperature and density changes could be identified only in a subset of the models, and appeared sometimes positive and sometimes negative. Consistent with the tipping mechanism described above, the models characterised by a negative feedback on SPG strength appeared prone to abrupt shifts in SPG circulation under climate warming.

In addition to a realistic representation of the freshwater transport in the SPG region, the properties of dense overflow waters from the Nordic Seas also need to be adequately simulated (Wei and Zhang 2024, Årthun et al. 2023). Since these overflow water properties affect the density properties at depth in the SPG region, they affect the ability of a model to correctly simulate convection depths and their response to freshwater input. The representation of overflows is another aspect in which climate models are known to have poor skills (Danabasoglu et al. 2014).

1.3 Early warning

Early detection of an impending tipping event is highly relevant for society. This information will guide current policies and long-term adaptation measures to climate change and a tipping event. On the specific topic of early-warning signals (Boers, 2021) and the proximity to an AMOC tipping point, a number of key publications have appeared since the last report. The study of Ditlevsen and Ditlevsen (2023) is warning of the risk of a collapse of the AMOC for this mid-century. Here, the time of the onset of the collapse was estimated using a proxy of the AMOC in the past based only on sea surface temperature. Ben Yami et al. (2024a) highlight the high sensitivity of this result to a number of factors, including the proxy of the AMOC used, so that the uncertainty concerning the date of the collapse is large. Note that it will take another 100 years from onset of the collapse to the realization of the associated very weak AMOC state.

Other studies based on climate models and analysis of the dynamics of the AMOC have also progressed our understanding of the risk of the AMOC to cross a critical threshold. Van Westen and Dijkstra (2023) showed that the overturning transport of fresh water at 34°S is a very useful indicator of AMOC multistability as illustrated in the CESM model. Van Westen et al. (2024a) also showed that the time evolution of this indicator might be an interesting early-warning signal of a potential collapse. However, the latter study was not analysing the potential change in surface forcing of the AMOC due to global warming, which is able to strongly modify the AMOC stability (van Westen et al. 2025c). Furthermore, it has also been shown that the AMOC might have a more complex behaviour than anticipated from the Stommel (1961) simple model, with many additional multiple equilibria (Lohman et al. 2024). Machine learning is an alternative approach to locating the proximity to tipping and its potential has begun to be explored (Zhai et al. 2024). These methods still rely on training data in the form of direct or proxy observations or model output. However, one can envision them using a much richer variety of data, potentially enhancing their effectiveness.

Meanwhile there has been further study of noise- and rate-induced tipping, underlining its possible role in causing tipping even before a bifurcation point is reached (Ritchie et al. 2023). Thus far, the studies have been largely for idealised systems (Alkhayuon et al. 2019, Castellana et al. 2019, Chapman et al. 2024) and the implications for the real world AMOC remains unclear. A promising new approach, applicable for more realistic models is that of Cini et al. (2024) where a rare event algorithm is used to find trajectories in an intermediate complexity climate model. Here the AMOC collapses due to internal noise without the need for changes to external forcing such as artificial oceanic freshwater input. Lohmann et al. (2025) explore a data-driven method for identifying optimal observables for early warning based on operator-theoretic arguments.

Another approach to determine proximity to tipping is by developing physics-based early-warning indicators. The freshwater transport at the southern boundary of the Atlantic Ocean is such an indicator which is currently being monitored (Arumí-Planas et al. 2024). Although this indicator suggests that the present-day AMOC is on route to tipping, the time series is too short to make a reliable tipping time estimate (van Westen et al. 2024). Another physics-based indicator which has been recently developed is the northern North Atlantic surface buoyancy flux (van Westen et al. 2025c) which also suggests a mid-century onset of an AMOC collapse (van Westen et al. 2025c, Drijfhout et al. 2025). For early warning, it is of great societal interest to maintain current observational arrays in the Atlantic Ocean, which are very useful for monitoring the AMOC strength. An important future challenge is to develop both statistical and physics-based early-warning signals for SPG tipping.

2. Potential impacts

2.1 Climate impacts

While the horizontal circulation in the SPG may possess bistability (Born and Stocker, 2014), this type of tipping has not been identified in climate models as occurring in isolation, and the more general and impactful tipping is the collapse of deep convection or mixing in the SPG, sometimes accompanied by an abrupt shift in circulation (Sgubin et al., 2017). Such an SPG collapse is a necessary but not sufficient precursor for an AMOC collapse, as an SPG collapse may be accompanied by an intensification of deep convection in the Nordic Seas. This leads to a dipole pattern in SST with a cold anomaly in the centre of the SPG, but intensified warming and sea-ice retreat in the Nordic and Barents Seas (Sgubin et al. 2017; Swingedouw et al. 2021). Due to the limited extent of the area of cooling over the North Atlantic and concurrent warming over the Nordic Seas and Arctic Ocean, temperature effects over Europe are much smaller than in case of an AMOC collapse.

They do have in common, however, a southward shift of a main precipitation region, the Intertropical Convergence Zone, and an enhancement and northward shift of the North Atlantic jet stream through a basic state shifting towards a more positive North Atlantic Oscillation (Jackson et al. 2015). There is, as in case of an AMOC collapse, drying in Boreal summer over the Sahel and in Austral summer over the Amazon region, associated with a weakened monsoon system (Dunstone et al. 2011). Furthermore, summers get dryer in North and Central Europe and winters a bit wetter. Apart from the wetter winters, all these precipitation changes are also present in case of an AMOC collapse, but there the amplitude is a few times larger (Swingedouw et al. 2021, Bellomo et al. 2023). The different impacts between an SPG collapse and an AMOC collapse result from the former evolving much faster and abruptly, within one or two decades due to local convective feedbacks (Rahmstorf, 2001) that interrupt the vertical heat transfer from the deep ocean to the surface (Brodeau and Koenigk, 2016), while an AMOC collapse evolves more gradual and evolves over typically over five to ten decades (Sgubin et al. 2015, Drijfhout et al. 2025) involving large scale advective feedbacks, freshening and cooling the SPG and the Nordic Seas and Arctic Ocean, and invoking a much stronger sea-ice response by increasing sea-ice cover over the North Atlantic.

An AMOC collapse would have widespread global impacts, with relatively large climate impacts over Europe (Jackson et al. 2015, Orihuela-Pinto et al. 2022, Bellomo et al. 2023, Ben-Yami et al. 2024b; Saini et al. 2025). The European impact is first and foremost dependent on the mean global temperature at the time of tipping (van Westen et al. 2025b). In general, the European impact is larger for a cooler climate than for a warmer climate (van Westen and Baatsen, 2025). The effects of changes in ocean heat transport between the Northern and Southern Hemispheres are much more pronounced in the Northern Hemisphere, which is the net receiver of heat. This is because heat loss in the north happens over a smaller area compared to heat spread in the south. When this heat transport diminishes, cooling occurs in regions that are already cold in the north, leading to significant growth in sea ice (van Westen et al. 2024). This sea-ice expansion plays a major role in amplifying the cooling effect, by capping off heat release to the atmosphere and returning otherwise absorbed solar radiation back to space. And the expansion of sea-ice is larger in a colder climate. Increased sea-ice cover also inhibits evaporation, drying and cooling the Northern Hemisphere by reducing water vapour in the atmosphere, a strong greenhouse gas (Vellinga and Wood, 2008, Drijfhout, 2015a, Jackson et al. 2015, Liu et al. 2020). This process can result in a noticeable drop in global mean temperatures, even though the root cause is a shift in how heat moves through the oceans.

These effects are ultimately determined by large-scale changes in the AMOC itself, determining the regional freshening and cooling in the North Atlantic. The evolution of the freshening and cooling patterns and sea-ice expansion is strongly time-dependent and much less instantaneous than the response to an SPG collapse (Drijfhout 2015b). Initially, the cooling is concentrated in a key region of the North Atlantic, but over time, it spreads and intensifies as sea ice expands southward during winter (Vellinga and Wood, 2008, Jackson et al. 2015). In today's climate, this cooling pattern would emerge in the northeast Atlantic, and as the climate warms or cools, the location of these effects would shift slightly. When the climate is warmer, the impacts are confined further north; when it is colder, they extend further south (Drijfhout 2015a, van Westen and Baatsen, 2025). The zone where the globe is maximally heated shifts southward, implying southward shifting tropical rain belts and drying in e.g., the Sahel and northeast Brazil (Ben-Yami et al. 2024b). With increased warming in the Southern Hemisphere subtropics, southern westerlies increase and the Benguela upwelling system strongly weakens.

The climate in Northwest European winter becomes harsher with stronger winds, more often snow and less often rain and especially stronger (and colder) extremes (Meccia et al. 2024), implying more and more often stormy weather (Woollings et al. 2012, Orbe et al. 2023, Jackson et al. 2015). Summer weather is getting sunnier and less cloudy often due to more frequent blocking high pressure systems east of the British Isles (Haarsma et al. 2015, Bellomo et al. 2021, Orihulea-Pinto et al. 2022). These blockings change the frequency of heatwaves across Europe, where Eastern Europe sees more heatwaves (Meccia et al. 2025). The warm extremes are not much affected under an AMOC collapse and are expected to increase in combination with climate change (van Westen and Baatsen 2025). While an AMOC collapse in general counteracts the effect of warming on the hydrological cycle, diminishing the "wet gets wetter" and "dry gets drier" pattern, it invigorates the drying (especially in summer) in Europe (van Westen et al. 2025c) leading to strong reductions in arable farming in the UK (Ritchie et al. 2021), water supply and agricultural output (Jackson et al. 2015; Bellomo et al. 2021). With increased temperature gradients in the Northern Hemisphere, zonal winds and the jet stream intensify with maximum winds moving to the north. Storm tracks do not show such poleward movement, but strongly increase and extend eastward, especially over the northern half of west and central Europe (Woollings et al. 2012, Orbe et al. 2023). Consequently, storm surges would become higher and more frequent, enhancing the risk of flooding (Volkov et al. 2023, Howard et al. 2024), in particular in combination with North Atlantic dynamic sea-level rise due to an AMOC collapse (Levermann et al. 2005, van Westen et al. 2024, van Westen et al. 2025a).

In the Pacific, warming south and cooling north of the Equator leads to a modification of the El Niño-Southern Oscillation (ENSO). While the upwelling off the coast of Peru decreases and the surface waters get warmer, also ENSO shifts eastward with the warming signal becoming more confined to the east (Williamson et al. 2018). The ENSO period was also found to increase and become more regular. An AMOC shutdown also influences the Australasian region, with overall drier conditions over the southeastern portion of this region (Saini et al. 2025). The West African, Indian Summer and East Asian Monsoons will be disrupted with shorter wet and longer dry seasons and less overall rainfall. The opposite seems to occur with the South American monsoon, with especially rainfall increasing over the southern Amazon (Ben Yami et al. 2024b). In general, the Southern Hemisphere becomes wetter and the Northern Hemisphere drier after an AMOC collapse.

2.2 Ecosystems impacts

An AMOC and SPG collapse would influence both marine and terrestrial ecosystems. An AMOC collapse can have global consequences, directly affecting the ocean's horizontal and vertical transport of heat and nutrients, and indirectly altering the climate system, such as through changes in temperature, precipitation, and wind patterns. In contrast, an SPG collapse would lead to more localised effects, including reduced nutrient concentrations in the euphotic zone and regional cooling. These ecosystem changes also influence the capacity of marine and terrestrial systems to sequester carbon, potentially contributing to elevated atmospheric CO_2 levels (Boot et al. 2023, Boot et al. 2024).

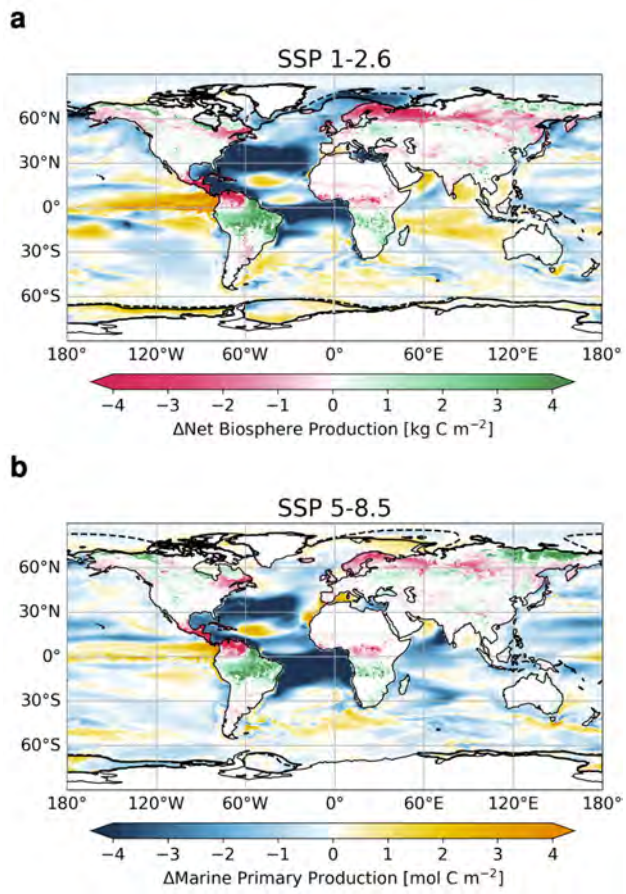


Figure 3: *The effect of an AMOC weakening on Net Biosphere Production on the land integrated over the period 2015 – 2100, and the change in Marine Primary Production over the period 2096 – 2100 compared to the period 2016-2020. The figures show the difference between a simulation with a strongly weakened AMOC, and a slightly weakened AMOC. Black dashed lines represent the average sea ice cover over the period 2081-2100 in the simulations with a slightly weakened AMOC, and solid lines represent the strongly weakened AMOC simulations. (a) For SSP1-2.6. (b) For SSP5-8.5. Source: Boot et al. (2024), with permission from Copernicus Publications.*

Marine ecosystems in the North Atlantic are particularly sensitive to changes in the AMOC and the SPG. Over the past 75 years, some regions in the North Atlantic have undergone shifts in ecosystems already which are tightly coupled to temperature (Beaugrand et al. 2008, Greene et al. 2013, Osman et al. 2019, Bode 2024). Whether this is due to variability in the AMOC or the SPG is not clear, however, it shows the clear potential of effects of an AMOC or SPG collapse on marine ecosystems through its effects on temperature. Changes in the AMOC and the SPG have the potential to affect the North Atlantic bloom. Reduced deep convection decreases nutrient entrainment which decreases (Fig. 3) productivity of phytoplankton (Yool et al. 2015, Boot et al. 2023, Boot et al. 2024, Kelly et al. 2025) and temperature changes can result in biogeographical shifts (Barton et al. 2016). These changes have the potential to cascade through the food web with potentially amplifying effects on higher trophic levels (Boot et al. 2025). Also, the timing of the North Atlantic bloom can shift. If species higher up the food web cannot adapt to this shift, this might lead to a strong change in functioning of ecosystems (Asch et al. 2019, Cyr et al. 2024).

A recent study (Boot et al. 2025) analyses impacts on marine ecosystems in simulations with an SPG collapse and simulations with an AMOC weakening. An SPG collapse leads to a shift in dominant phytoplankton type from large phytoplankton to small phytoplankton. However, the net effect is a decrease of total phytoplankton biomass in the SPG region of around 50% in 2100 compared to the beginning of the 21st century. Higher trophic levels show a much smaller decrease in SSP5-8.5 (12%), whereas in SSP1-2.6 there is even an increase (13%). Whether this is a sustainable response is uncertain. When accompanied with a strong AMOC weakening, a similar net response is found in total phytoplankton biomass. However, higher trophic level biomass in the SPG region decreases by 20% in SSP1-2.6 and 43% in SSP5-8.5 over the 21st century as a response to the strong AMOC weakening. Species important for fisheries decrease up to 17%, meaning that both the functioning of the ecosystems and the services these ecosystems provide, will be negatively impacted by an AMOC weakening.

Terrestrial ecosystems are mostly impacted through changes in precipitation and temperature following an AMOC collapse. Strong cooling in the Northern Hemisphere can, for example, negatively impact the productivity of boreal forests but also prevent permafrost melt. Shifts in the ITCZ also shift the locations of prime productivity in the equatorial rainforests (Fig. 3). Models using dynamic vegetation also suggest there is a significant relation between vegetation type and AMOC strength (Armstrong et al. 2019), and a collapse of the AMOC can show large changes in vegetation type locally (Woillez et al. 2013).

Besides vegetation also animals can be affected. An AMOC weakening can enhance the effects of warming globally and lead to a decline in amphibians (Velasco et al. 2021) and reduce the geographic range of both plants and animals, suggesting that an AMOC weakening can enhance the biodiversity crisis (Ureta et al. 2022).

More research is necessary that directly investigates the impact of AMOC and SPG tipping on marine ecosystems. Based on physical princples, and the few available studies, both the AMOC and the SPG tipping can strongly impact the functioning of ecosystems and consequently the services they provide.

2.3 Societal impacts

There are great uncertainties around societal impacts, whether direct or systemic/cascading and more research needs to happen to model and where possible quantify possible societal impacts. However, using the risk framework from Chapter 2.1 we can try to map out possible pathways of societal impacts while translating them into risk currencies for policy makers. The AMOC/SPG hazards were outlined above. It is important to emphasise that, while the collapse of SPG (one to two decades) and AMOC (one to five decades) unfolds over decade(s), some impacts of these unfolding collapses would materialise immediately and continuously intensify over time. For instance, the weakening of AMOC has already impacts such as the North Atlantic Warming Hole (Li and Liu, 2025). The change in temperature and precipitation patterns described above would first of all have direct impacts, such as decreasing agricultural yield or even recurring crop failure (medium confidence) particularly in European countries in the North-West, such as UK, Norway or Finland (OECD 2022, Merikanto et al. 2024), furthermore intensifying water shortage in the same region (medium confidence) (Haustein and Rayer 2023), which further complicate agricultural production. While a SPG collapse would affect mainly North-West Europe and North-East US, an AMOC collapse would have more global and more severe repercussions with possibly catastrophic implications for global food production (Ritchie et al. 2020, Ben-Yami et al. 2024b, see Fig. 4). Furthermore, given that infrastructure in some of these areas have not been built for this drastically ecological regime shift and the intensifying, recurring storms, direct impacts would likely include frequent and at times severe infrastructure damage or even infrastructure loss (Shakou et al. 2019). The increased likelihood of storms and flooding would moreover likely result in the direct impacts of property loss or in the long-term even settlement loss (e.g. on US east coast) and more generally accumulating asset loss as well as life los (Lenton et al. 2023).

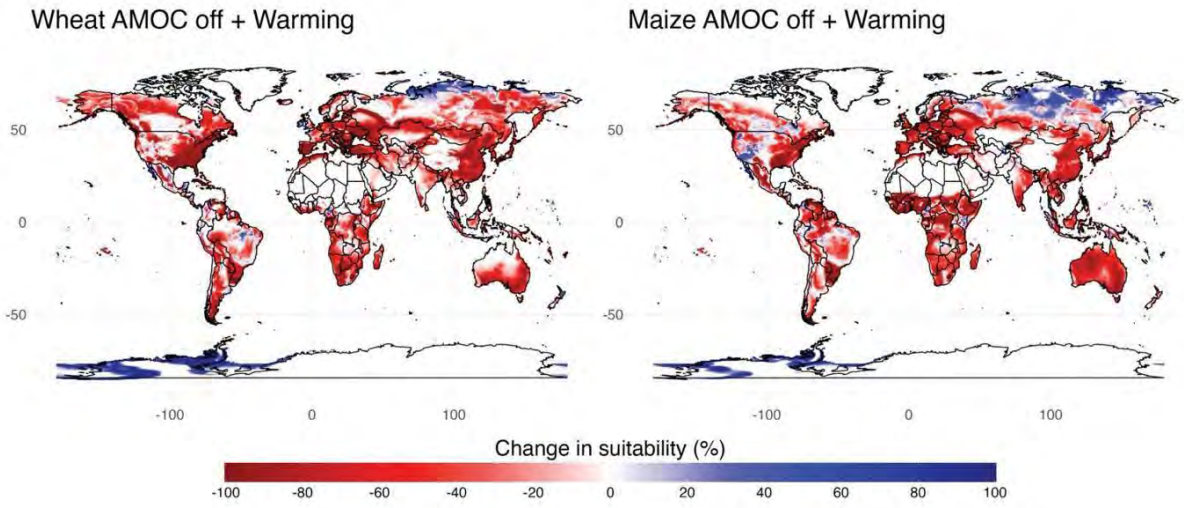


Figure 4: AMOC effects on food production (wheat and maize), Percentage difference in crop suitability between no AMOC collapse (present day) and the effects of AMOC collapse plus 2.5°C of global warming. Decreases in suitability are represented with red shading, increases with blue. Source: Laybourn et al. (2024), Figure 2.4, with permission from the IPPR. For discernment of the AMOC effects vs. warming effects, see OECD (2021).

These are the most likely direct impacts, however as outlined in the Chapter 2.1 risk framework, societal impacts tend to be systemic, with cascading effects, as direct impacts accumulate and interact, resulting in systemic risks that can reinforce each other (Simpson et al. 2021, Schweizer and Juhola, 2024) and even exhibit secondary tipping dynamics (Spaiser et al. 2024). It is more difficult to establish likelihoods for systemic and cascading risks as further factors (such as state capacity, economic resources, structural resilience, international cooperation, people's response to interventions etc.) play a huge role and our confidence here can only be low. Considering worst case scenarios (e.g., when adaptation largely fails due to insufficient state capacity or compounding crises), possible systemic risks from AMOC/SPG collapse include displacement from lost settlements (e.g. US East coast, West Africa), rising poverty linked to displacement (e.g. US East coast, West Africa) and loss of property and loss of assets (e.g. US East coast, North Europe). Furthermore, these may give increased food insecurity (incl. spiraling food prices, globally, e.g. see Jackson 2025) due to decreasing agricultural yield and/or crop failure, which further drives poverty, both also resulting in poor health (Lenton et al. 2023).

The disruptions from direct impact and the cascading impacts just described will strain social cohesion and social stability, likely leading to increased disorder and social fragmentation (Spaiser et al. 2024). Poor health as well as the more direct impacts, e.g. on infrastructure, will also cascade into economic productivity loss, which will in turn drive further impoverishment. The accumulating loss of assets could also trigger a financial crisis, which itself could display tipping dynamics (Gajewski et al. 2025) and result in further impoverishment as well as weakening of national states and their capacity to respond to multiplying crises. In this explosive situation, political destabilisation may escalate, resulting in social unrest (Jones et al. 2023), potentially aided by external intervention of some form.

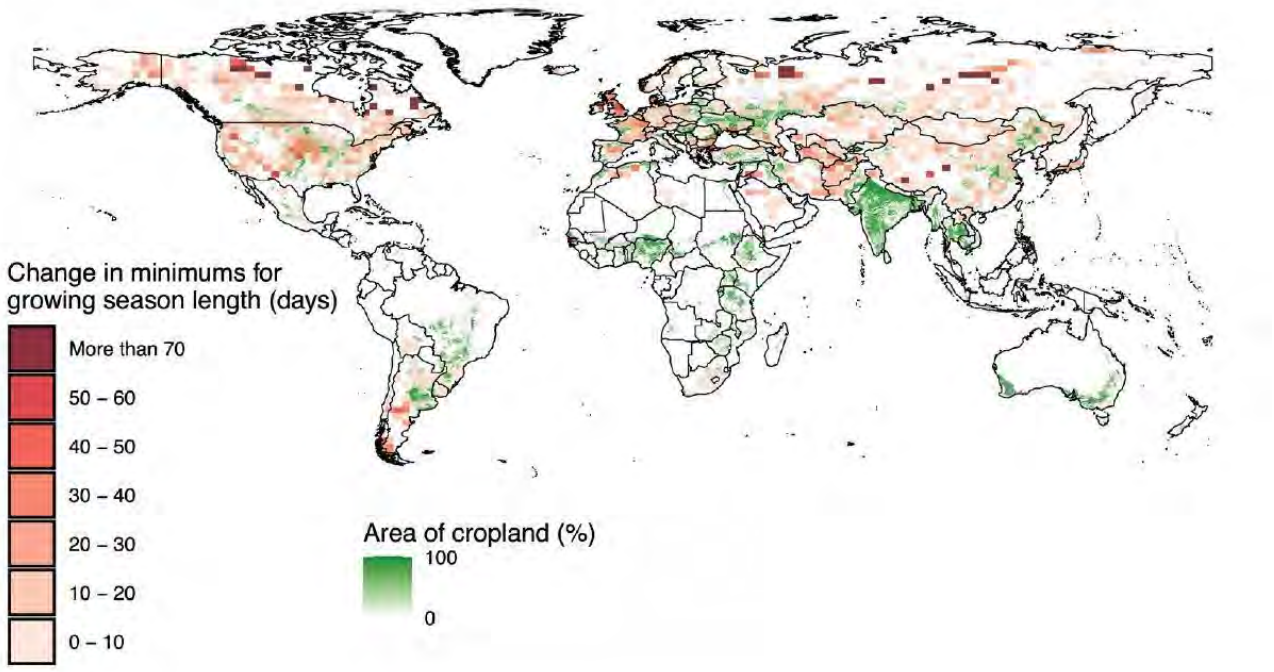


Figure 5: *Modelling results comparing minimum growing season length (GSL) in pre- and post-collapse in an SPG collapse scenario, mapped over crop growing locations (in green), with darker shading representing larger reductions in GSL. Source: Laybourn et al. (2024), Figure 2.6, with permission from the IPPR.*

Given the increasing geo-political destabilisation and fragmentation, some nation states may seek to exploit the weakening of certain countries (in particular North Europe, incl. UK) hit by the AMOC/SPG collapse hazards, contributing to political destabilisation for instance through hybrid forms of warfare, such as spreading misinformation to generate rage and social unrest, strengthening radical groups and undisclosed attacks on infrastructure (Lawrence et al. 2024, Bosch et al. 2025). There is a danger of the state increasingly failing to respond to multiple crises and helping its citizens with adaptation, and if state failure becomes increasingly endemic, social order may further break down and social unrest could turn into violence (e.g. gang violence) (White et al. 2025). For a detailed exemplary exploration of security implications for the UK from an AMOC/SPG collapse, see Laybourn et al. (2024) or for Finland, see Merikanto et al. (2024). Nation-specific complex risk-assessments are needed for many more countries and regions (e.g. EU) too, as every nation would be affected by an AMOC collapse in some way (e.g. at the very least through increasing food prices).

We note that the described cascading impacts could unfold similarly over one or several decades, alongside the unfolding of AMOC/SPG collapse, depending on the speed with which impacts from the unfolding AMOC/SPG collapse materialise and interact with social, political and economic factors. And this is why governance strategies are vital. Furthermore, we note that direct impacts of an SPG collapse are likely to be less severe and more regionally contained, compared to an AMOC collapse (Fig. 5). We thus expect also less severe systemic risks; still for counties such as the UK or Canada the risks are severe enough to lead to significant consequences, including increasing poverty due to increased food prices due to decreasing agricultural productivity and property loss due to severe weather events, economic productivity loss as well as the danger of some social unrest and political destabilisation as people are likely to turn against established political elites (Laybourn et al. 2024).

3. Governance

Current governance frameworks do not adequately address the potential risks of SPG and AMOC tipping, making it essential to prioritise these high-stakes climate threats on the global governance agenda. We address two complementary governance tasks: prevention of AMOC and SPG tipping and management of potential impacts. Both tasks require continuous monitoring, learning, systemic risk assessments, and early warning systems. Governance approaches should be polycentric, linking institutions across global, regional and national scales, and embedded within existing climate and ocean governance frameworks.

At present, responsibility for addressing AMOC and SPG tipping risks is diffuse, and relevant actors and institutions need to recognise and adopt clear roles. Given the high uncertainty regarding timing, magnitude, and affected regions, the precautionary principle is essential in guiding decision-making. Plurilateral and regional initiatives—particularly among states likely to experience the earliest or most severe impacts—could complement broader international cooperation by facilitating knowledge exchange, joint planning, and coordinated risk management.

3.1 Prevention strategies

Given the severity of potential impacts of an AMOC and SPG collapse on relevant timescales, preventing the crossing of these tipping points should be the primary governance objective. Both systems are primarily driven by global temperature change, and prevention strategies must focus on curbing global warming. This places a critical responsibility on the United Nations Framework Convention on Climate Change (UNFCCC), the success of the Paris Agreement in driving global mitigation ambition, and national policies, particularly from major emitters and fossil fuel producers. The objective of preventing these tipping points provides new impetus for the 1.5°C global temperature goal of the Paris Agreement.

There is significant uncertainty regarding the threshold temperature for AMOC collapse (1.5°C - 8°C) and a more narrow range for the SPG (1.0°C – 3.8°C). Both systems might be destabilised by increasing meltwater inflow from the Greenland Ice Sheet, creating potentially reinforcing risks between cryosphere and ocean circulation systems. However, the meltwater effect is likely to play out over long time horizons without a significant effect on AMOC stability this century (Klose et al. 2024). Given these uncertainties and the possibility of near-term tipping-point transgression for both systems, prevention strategies for AMOC and SPG collapse should prioritise as:

- Rapidly returning global average temperatures to below 1.5°C,
- Minimizing peak warming, and
- Minimizing the duration of any overshoot above 1.5°C.

This reframes the policy focus from solely end-of-century temperature targets to the shape and speed of near-term emissions pathways. Only pathways that achieve front-loaded emissions reductions and limit reliance on Carbon Dioxide Removal (CDR) meaningfully reduce SPG and AMOC tipping risks. Delivering these trajectories requires immediate acceleration of fossil fuel phase-out and scaling up of sustainable CDR technologies to enable net-negative emissions. At the same time, rapid drawdown of atmospheric CO_2 following any temperature overshoot could trigger AMOC oscillations on centennial timescales (Schwinger 2022), introducing additional risks and uncertainty, and therefore must be implemented cautiously and in conjunction with continuous monitoring and adaptive management.

Fostering international agreement on mitigation pathways that minimise tipping risks could occur within the Paris Agreement, e.g., in the Mitigation Ambition and Implementation Work Programme or in a new ad-hoc working group under the UNFCCC. The Global Stocktake should assess to what extent collective mitigation efforts minimise tipping risks and prepare for their potential impacts. Future NDCs should explicitly address to what extent a country is exposed to AMOC/SPG tipping risks, how national mitigation efforts contribute to reducing tipping risks based on explicit emission/temperature pathway assumptions.

Model-based assessments have examined a range of prevention strategies, from well-established to speculative:

- Rapid GHG emissions phase-out – the most reliable and safest approach, directly addressing the root cause.
- Negative emission/carbon removal technologies – essential to achieve future reductions in global temperature and return to 1.5° C, though scalability and permanence remain concerns.
- Solar Radiation Modification (SRM) – such as Stratospheric Aerosol Injection (SAI) and Marine Cloud Brightening (MCB), which may help slow or prevent AMOC weakening, but come with significant risks and uncertainties.
- Greenland Ice Sheet preservation through geoengineering approaches such as undersea membranes to limit warm water intrusion into fjords (Wolovick et al. 2020, Hunt et al. 2019, Keefer et al. 2023). While potentially reducing basal meltwater flows, these methods do not prevent surface runoff and have limited impact if marine glaciers retreat inland.

The effect of the prevention options has been studied in climate models but not exhaustively, especially for SRM. While SRM may reduce near-term AMOC weakening, it should only be considered as a temporary, emergency measure to buy time for emissions reductions and CDR to take effect. SAI must not be deployed on a permanent basis. Instead, its design and governance must include from the outset a clear, feasible exit strategy aligned with steep reductions in greenhouse gas emissions and the buildup of sustainable carbon removal capacity. Without this, SRM risks creating long-term dependency and exposure to termination shock, undermining rather than supporting climate stabilization efforts.

Some models suggest that mitigation alone may have limited short-term (next 30–50 years) influence on AMOC weakening (Weijer et al. 2020), though it substantially reduces post-2100 tipping risks (Drijfhout et al., 2025). SAI (Futerman et al. 2023) and MCB (Hirasawa et al. 2023) may exert stronger short-term effects. One study using a single climate model showed that SAI from 2080 onwards prevents further AMOC weakening but cannot restore it to earlier levels while earlier SAI deployment (from 2020) preserves more of the AMOC's strength (Pflüger et al. 2024). For SPG, results are mixed and uncertain: Kelly et al. (2025) show SPG collapse before 2100 regardless of mitigation, while Pflüger et al. (2024) show partial preservation of Irminger Sea deep convection with early SAI. Overall, SRM remains understudied, especially for SPG dynamics, and should not be considered a silver bullet.

Model uncertainty remains high, particularly in single-model studies, and results should be interpreted with caution. Nonetheless, available evidence tentatively supports the conclusion that if reducing AMOC and SPG tipping risks were the only goal, the most effective strategy would involve a combination of rapid and deep emission reductions, strategic use of carbon dioxide removal, and timely, temporary SRM deployment if ever deemed acceptable through robust governance. However, SRM introduces significant physical, ethical, and geopolitical risks. Its potential benefits for the ocean circulation must be weighed against potential harms elsewhere—such as triggering a tipping point in the Amazon or undermining global cooperation on mitigation. Any deployment must be evaluated through a comprehensive, risk-risk framework, which weighs different kinds of risk against each other, identifying trade-offs (Sovacool et al. 2023, McLaren 2023). However, even a risk-risk approach has shortcomings, and novel risk assessment approaches might be needed (McLaren 2025). Such an assessment would also have to consider that the deployment of SAI for the prevention of SPG or AMOC collapse could increase the risks of a tipping point in the Amazon Rainforest.

3.2 Impact governance

The potential impacts of SPG collapse and/or AMOC changes present significant threats to human security, especially in European countries, but also in tropical countries and in the Amazon region. Currently these impacts are understudied, poorly understood and to the extent they are known, they are not considered in adaptation planning and preparedness efforts of affected countries (Roman Cuesta et al. 2025). More broadly, there is an immediate need to assess and respond to the impacts of potential tipping dynamics in the North Atlantic Ocean. This is particularly important for the SPG, which has a tipping threshold close to 1.5°C, could be triggered within a few years, and would unfold in less than a decade, i.e., before 2040.

Here, we discuss two specific domains of impact governance, with two distinct action horizons: 3-5 years for adaptation and 5-10 years for food security. Other national and international policy domains would also be affected, including disaster preparedness, trade, infrastructure, and energy production.

Adaptation (3-5 years): SPG and AMOC tipping impacts present major challenges to current adaptation planning, especially in Northern Europe. Considering tipping impacts should not impede urgently needed and ongoing climate adaptation efforts, but adaptive planning needs to consider a larger range of possible futures, including the passing of tipping points (Biesbroek et al. 2025). AMOC and SPG tipping could have three types of effects: amplifying well-known climate change impacts (especially sea-level rise, coastal erosion, flooding, increased storm frequency), reversing the direction of currently expected climate change impacts (e.g., cooling rather than warming temperatures and wetting rather than drying), and changes to the timing and spatial distribution of these impacts (i.e., creating different vulnerabilities).

We recommend that all countries potentially affected by SPG tipping initiate a review of their national adaptation strategy or plans in light of this (and other) tipping risk within the next three years. This requires:

- Incorporating climate tipping elements into risks and adaptation scenarios.
- Preparing for a broader spectrum of possible futures with uncertain timing.
- Updating regional models and vulnerability assessments.
- Coordinating cross-border adaptation initiatives, especially in Europe and the North Atlantic basin.

Food Security (5-10 years): A weakening or collapse of the AMOC/SPG taking place over one (SPG) or multiple decades (AMOC) could significantly disrupt agricultural productivity, fisheries, and food trade across Europe, Africa and South America (see sections 2.2 and 2.3). Over the coming 5-10 years, governments should invest in early-warning systems for agricultural impacts, diversify trade relationships, increase food storage and distribution resilience, and support research into climate-resilient and regionally adaptive crop systems.

3.3. Other governance considerations

Preparing for and responding to AMOC and SPG tipping impacts requires novel science–policy engagement mechanisms that enable iterative, timely, action-oriented learning and capacity building related to AMOC and SPG in Europe and around the North Atlantic. This could include:

- Rapid response risk panels to conduct iterative, policy-relevant assessments under deep uncertainty. These could support regional political bodies (e.g., EU, Arctic Council, Nordic Council of Ministers) and connect/align with international scientific assessments in the IPCC and IPBES.
- A permanent North Atlantic tipping element monitoring facility, equipped to detect and communicate early-warning signals, and rapidly respond to observed change.

3.4 Policy priorities for AMOC and SPG risk governance

Immediate Actions (1–5 years)

Objective: Lay the foundation for tipping risk prevention through urgent mitigation and foster preparedness for possible emergency responses.

PREVENTION

- Accelerate fossil fuel phase-out: Legislate phase-out schedules, redirect subsidies.
- Strengthen global mitigation: Update NDCs with early reductions to avoid overshoot.
- Invest in CDR: Launch large-scale pilots with verified accounting.
- Initiate SRM governance frameworks: Start multilateral dialogues and research into impacts, design temporary-only frameworks.

IMPACT GOVERNANCE

- Foster research on impacts of SPG/AMOC tipping scenarios with a focus on social and economic impact categories.
- Integrate into national planning: Include SPG/AMOC in climate risk and contingency strategies.
- Adaptation Planning: Initiate national reviews of adaptation strategies in potentially affected regions, especially Europe and West Africa; include SPG/AMOC tipping scenarios in adaptation planning.
- Food Security and Infrastructure: Begin climate stress-testing of food supply chains, storage, and trade exposure.

RESEARCH, MONITORING AND EARLY WARNING

- Enhance observation systems: Fund AMOC/SPG monitoring, including Greenland Ice Sheet meltwater tracking.
- Launch a North Atlantic tipping element monitoring initiative.
- Begin scenario planning and foresight exercises on tipping-related uncertainties, including rapid response expert panels for dynamic tipping risk assessment.

Near-term Actions (5-10 years)

Objective: operationalise risk minimisation pathways and revise climate adaptation and preparedness measures.

PREVENTION

- Assess progress towards minimizing tipping risks in the Third Global Stocktake.
- Scale sustainable carbon removal to support net-negative emissions post-overshoot.
- Refine early-warning systems: Operationalise risk dashboards.
- Continue developing SRM governance aligned with precautionary and ethical frameworks: Define legal limits, triggers, and exit strategy.
- Mainstream into global policy: Make tipping prevention a criterion in finance and adaptation priorities.

IMPACT GOVERNANCE

- Food Security: Strengthen global and regional food reserves and diversify agricultural systems with region-specific adaptation R&D.
- Infrastructure: Prioritise resilient critical systems (e.g., power, communications) in high-risk zones.
- Integrate tipping-related scenarios into the Loss and Damage Fund and national adaptation planning.
- Expand access to climate finance for tipping-relevant monitoring, preparedness, and adaptation, especially for vulnerable countries.

RESEARCH, MONITORING & EARLY WARNING

- Fully operationalise a dedicated North Atlantic Tipping Observatory, integrating oceanic, cryospheric, and atmospheric data.
- Formalise transdisciplinary science–policy interfaces to enable policy-relevant, iterative risk updates and response capacity development.
- Build capacity in national and subnational institutions to interpret and respond to early warnings.

CASE STUDY 03

WARM-WATER CORAL REEFS



4.3 Warm-water coral reefs

Authors: Paul Pearce-Kelly, Chris Yesson, Melanie McField, Aarón Israel Muñiz-Castillo, Melina Soto, Jesus Ernesto Arias-Gonzalez, Kyle Morgan, Alina Bill-Weilandt, Björn Kjerfve, Christopher E. Cornwall, Lorenzo Alvarez-Filip, Manjana Milkoreit, Tim E. Lenton, Rosa M. Roman-Cuesta.

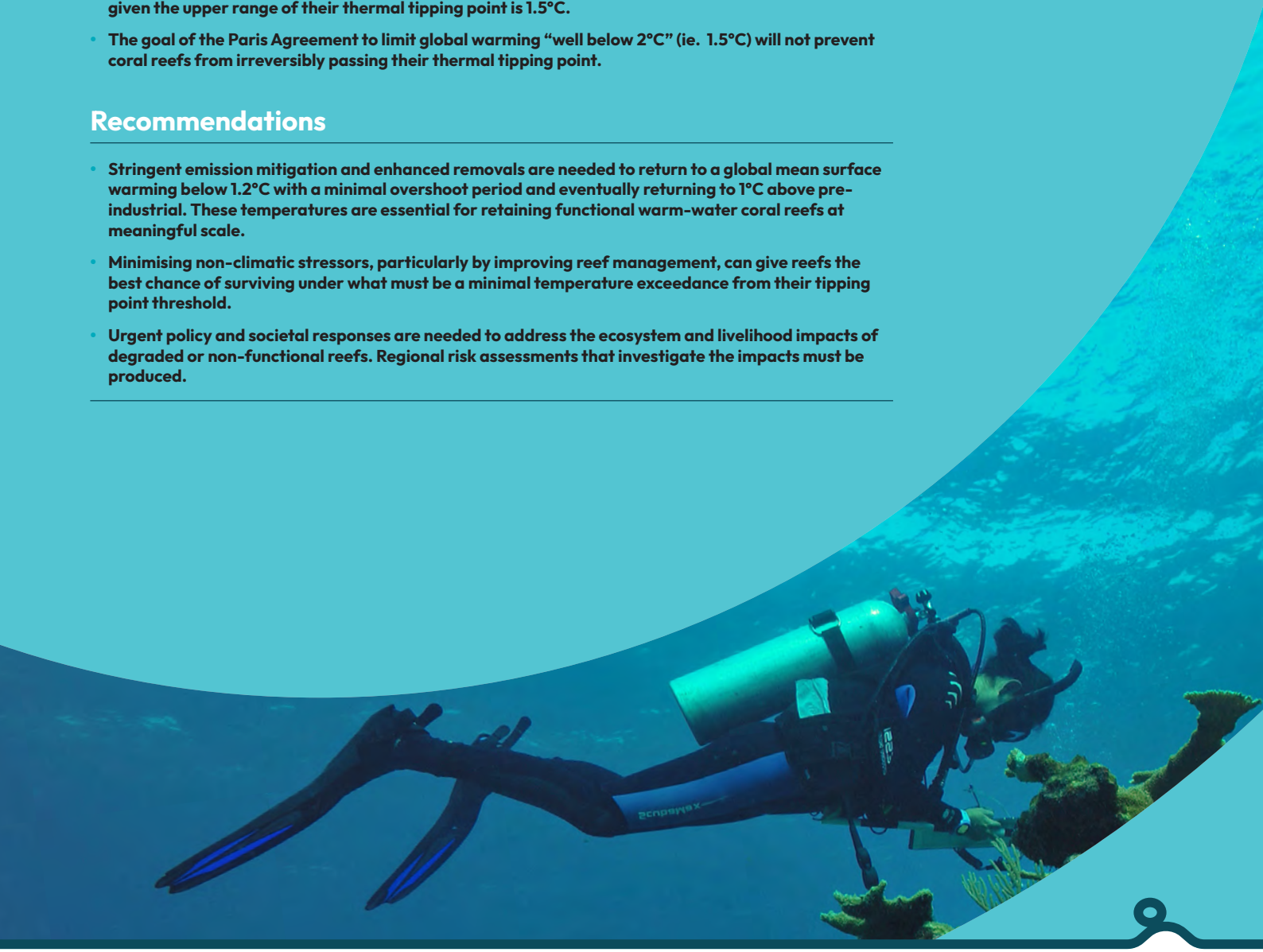
Reviewers: David O. Obura, Chris T. Perry

Risk assessment

- **Warm-water coral reefs are vital to the wellbeing of up to a billion people and almost a million species.**
- **Globally, coral reefs are experiencing unprecedented mortality under repeated mass bleaching events, highlighting the impact that global warming (interacting with other, predominantly human-driven environmental stressors) is already having.**
- **The central estimate of the thermal tipping point for warm-water coral reefs of 1.2°C global surface warming above pre-industrial is already exceeded and without stringent climate mitigation their upper thermal threshold of 1.5°C may be reached within the next 10 years, degrading reef functioning and provision of ecosystem services to millions of people.**
- **Even under the most optimistic current emission scenarios of stabilising warming at 1.5°C without any overshoot, it is considered that warm-water coral reefs are virtually certain (>99% probability) to tip, given the upper range of their thermal tipping point is 1.5°C.**
- **The goal of the Paris Agreement to limit global warming "well below 2°C" (ie. 1.5°C) will not prevent coral reefs from irreversibly passing their thermal tipping point.**

Recommendations

- **Stringent emission mitigation and enhanced removals are needed to return to a global mean surface warming below 1.2°C with a minimal overshoot period and eventually returning to 1°C above pre-industrial. These temperatures are essential for retaining functional warm-water coral reefs at meaningful scale.**
- **Minimising non-climatic stressors, particularly by improving reef management, can give reefs the best chance of surviving under what must be a minimal temperature exceedance from their tipping point threshold.**
- **Urgent policy and societal responses are needed to address the ecosystem and livelihood impacts of degraded or non-functional reefs. Regional risk assessments that investigate the impacts must be produced.**



Executive summary

Warm-water coral reefs are among the most biodiverse and valuable ecosystems on Earth, sustaining nearly a billion people and contributing trillions of dollars annually in goods and services. They provide food, coastal protection, cultural value, and livelihoods. Yet, these reefs are now facing an unprecedented crisis, as the first Earth System to cross its central estimated thermal tipping point of 1.2 °C of global warming above pre-industrial levels. This is triggering widespread reef degradation. Under current emission trends, the upper tipping point threshold of 1.5°C for coral reefs could be crossed within the next decade. Even under the most currently optimistic scenario of stabilising warming at 1.5 °C, all coral reefs are virtually certain to globally tip, making this one of the most pressing ecological losses humanity confronts.

The risks and impacts associated with crossing thermal tipping points are severe. Coral reefs are undergoing the 4th Global Coral Mass Bleaching Event which is the most extensive and intense ever recorded with over 80 percent of reefs worldwide being impacted . Marine heatwaves are increasing in frequency and intensity, which is increasingly pushing corals beyond their recovery limits. Heat stress is exacerbated by local to regional scale stressors such as overfishing, nutrient pollution, disease outbreaks, predator and competitor species imbalance, and destructive coastal development, reducing resilience, hindering recovery, and accelerating coral reef degradation and loss with major implications for the structural and ecological functions that sustain biodiversity, food security and protect shorelines, upon which millions of people are reliant.

The Caribbean illustrates the severity of these impacts, with reefs there already experiencing quasi-annual bleaching compounded by chronic, largely human-caused stressors, at multiple scales. The combination of climate-driven stress, low species diversity, and frequent disease outbreaks is pushing Caribbean reefs toward collapse. Their decline threatens fisheries, tourism, and coastal protection, heightening the vulnerability of small island states and coastal nations to storms and flooding. Globally, the effective loss of functional coral reefs will disrupt food systems, trade, and geopolitical stability, highlighting their significance as a systemic risk far beyond reef regions.

Societies and Governments remain unprepared for this reality, with no regional risk assessments investigating the consequences of these impacts on societies, economies and ecosystems. Urgent discussions on resilience and societal adaptation are needed. Addressing these risks requires coordinated action at multiple scales. At the global level, rapid and stringent greenhouse gas mitigation is fundamental to return coral reefs back from the brink. Unless we return to global mean surface temperatures of 1.2°C (and eventually to at least 1°C) as fast as possible, we will not retain warm-water reefs on our planet at any meaningful scale. To address non-climate drivers of reef tipping, coordinated efforts to eliminate local and regional human stressors on reefs are crucial to retaining these invaluable ecosystems. This includes “strategically” expanding marine protected areas, acting on overfishing, curbing agricultural runoff, and regulating coastal development. Restoration and innovation, such as coral nurseries, assisted evolution, and breeding of heat-tolerant genotypes, may support local resilience, though their effectiveness will remain limited without decisive climate action.



1. Introduction

Warm-water coral reefs (tropical and subtropical) occur in over 100 countries and territories and cover up to 900,000 km2 (Carlson et al 2021). They are the world's most biodiverse ecosystem, supporting up to a third of all known marine biodiversity (Plaisance et al., 2011), including over 25% of marine fish species (Laffoley and Baxter, 2016), and provide essential habitat for over 800,000 species (Fisher et al 2022). These reefs contribute up to USD 9.9 trillion annually in goods and services, including $109 billion in GDP worldwide, from which up to a billion people benefit (Costanza et al 2014). The degradation of reefs and reef-dependent species threatens the livelihoods of these people, most of whom are living in lesser developed countries and face severe consequences of reef demise (Wilson et al., 2006; Cinner et al., 2016; Pendleton et al., 2016).

In addition to the ongoing increase in average ocean temperatures, coral reefs face an urgent threat from marine heatwaves. These are distinct, prolonged periods during which ocean waters become significantly hotter than normal (i.e. 5 or more days above the 90th percentile for the last 30 years) (Smith et al., 2023; Capotondi et al. 2024; Marcos et al., 2025;). Since 1940, comparisons between real ocean temperatures and a world without global warming reveal that human activity is driving nearly half of all marine heatwaves. This influence has already tripled the number of days each year that the oceans experience extreme heat conditions with an increase of 1°C higher in the maximum intensity of these events.(Marcos et al. 2025). Unlike the gradual increase in average temperatures, marine heatwaves hit abruptly and intensely, pushing corals beyond their limits and causing mass bleaching, subsequent mortality, and major disruptions in reef ecosystem states (Smith et al 2023).

The central thermal tipping point for warm-water coral reefs has been estimated to be of 1.2°C global warming (range 1–1.5°C) (Lenton et al 2023, Pearce-Kelly et al 2025). With 2025 reaching global mean surface temperatures ~1.3-1.4°C above the pre-industrial level (Copernicus 2025), this central thermal tipping point has already been passed. This situation is causing severe global mass bleaching events (NOAA 2025), and in combination with other stressors, is leading to unacceptably high risk of widespread reduction of coral cover, mortality of major reef-building taxa, loss of critical geo-ecological functions including reef growth potential, and thus degradation of the ecosystem services reefs sustain (IPCC 2022, Lenton et al. 2023, Henley et al. 2024; Byrne et al. 2025; Pearce-Kelly et al. 2025).

Unprecedented ocean heating over the latest global mass bleaching period 2023–2025, highlights the severe functional degradation risk warm-water coral reefs are facing at a global scale. Societal and policy responses are urgently needed to minimize the magnitude and duration of this tipping point temperature exceedance, to avoid the functional loss of reefs at any meaningful scale (Lenton et al. 2023, Pearce-Kelly et al. 2025). Accelerated climate change mitigation and large-scale ocean conservation actions are needed to attempt to rescue coral reefs. The precautionary principle must be followed when considering uncertainty regarding thermal tipping points and the feasibility of the duration of their temperature exceedance for such critically important systems (Wunderling et al 2022; Meyer et al 2022; Schleussner et al 2024).

In the following sections, we provide an update on the global status of warm-water coral reefs in 2025 and consider the escalating threats they face in the near future. We consider their resilience and adaptation potential and conclude with a deeper dive into Caribbean coral reefs, as witnesses of the risk of irreversibly crossing ecological tipping points. We consider policy and societal conservation and sustainable ocean management responses to minimise human-driven stressors impacting reefs and maximise reef resilience under what must be a minimal period of temperature exceedance of their tipping threshold.

2. Global status of reefs in 2025

Coral reefs are one of the most sensitive ecosystems to direct and indirect human activities, with an estimated 50% of global live coral cover lost over the last 50 years (Eddy et al. 2021, Souter et al. 2021) and accelerated decline over the last 30 years (IPBES, 2019, Eakin et al 2019; Heron et al. 2016). Over 80% of the world's coral reefs are severely overfished or have degraded habitats (IPBES, 2019). Local, regional and even larger scale stressors such as unsustainable fishing, water pollution, disease, nutrient enrichment, and predator imbalance remain major issues. However, climate change, especially ocean heating, has now become the dominant global-scale threat to the functional viability of these ecosystems (IPBES, 2019; IPCC, 2022).

Since the 2023 Global Tipping Points Report (Lenton et al. 2023), warm-water coral reefs have experienced a 4th global bleaching event (GBE4), declared on 15 April 2024 by the National Oceanic and Atmospheric Administration (NOAA) and the International Coral Reef Initiative (ICRI). Beginning in January 2023, bleaching-level heat stress has impacted 83.8% of the world's coral reefs as of 20 May 2025, with mass coral bleaching documented in at least 83 countries and territories. (NOAA update 21 May 2025). This 2023-2025 Global Bleaching Event is the second global bleaching event in less than a decade and is both the warmest and most widespread bleaching event ever recorded (See Fig. 1).

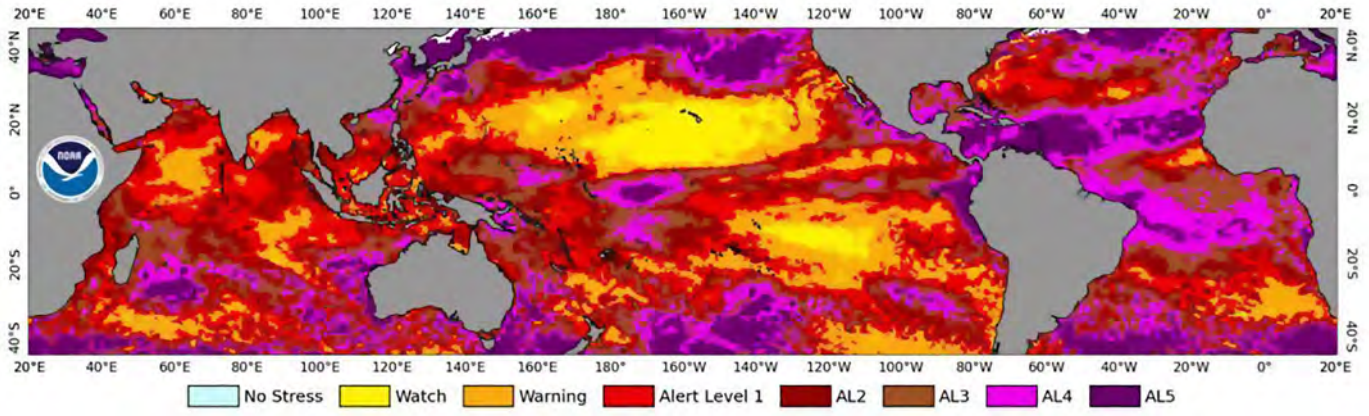


Figure 1. NOAA Coral Reef Watch 5km Bleaching Alert Area Maximum (V3.1) 1 January 2023-20 May 2025 (NOAA update 21 May 2025). Three new highest alert levels had to be added in December 2023.

In the Caribbean and wider regions, global ocean circulation changes are heightening and prolonging heat stress episodes including GBE4 (2023-2025) (Goreau and Hayes, 2024). Several authors highlight that background ocean warming is now so severe in this region that bleaching events are occurring quasi-annually and becoming desynchronized from El Niño events. Bleaching in normal and even La Niña years is now common (Muñiz-Castillo et al. 2019, Reimer et al. 2024). This region is considered in more detail in Section 6, below.

In the Great Barrier Reef (GBR) region, the ocean reached unprecedented warming levels, duration and depth in GBE4 (AIMS 2025), leading to rapid bleaching, disease onset, and mortality in diverse corals and depths, including genera that were formerly considered resilient. Catastrophic bleaching has occurred in protected reefs of the Southern GBR (Byrne et al., 2025) and Coral Sea (Henley et al 2024, AIMS 2025). A reef to rubble phenomenon (Image 1) is occurring, whereby colonies fragment and transition to rubble (Hoegh-Guldberg et al 2023; Kenyon et al 2022; Kopecky et al 2023) as part of a transformation towards lower complexity ecosystems that are difficult to recover from (Byrne et al., 2025). Drone imagery at Lizard Island confirmed one of the highest rates of bleaching mortality ever recorded, despite cumulative heat stress exposure being lower than many other parts of the GBR (Raoult et al 2025).



Image 1: reef to rubble trajectory in the Caribbean. @Kieth Ellenbogen/iLCP (left) Healthy Reefs for Healthy People (right)

As in the Caribbean, bleaching on the GBR, is now becoming a biennial event. Researchers conclude that the GBR ecosystem is under existential threat from climate change (Byrne et al. 2025) and, globally here are increasing risks of regime shifts from coral dominated systems towards non-coral dominated systems (IPCC 2022).

3. Reefs have crossed a dangerous tipping point

"Catastrophic conditions and dire reef ecosystem changes are no longer a threat on a distant horizon: It's happening now." Michael Kingsford. Marine Biologist. James Cook University (2025).

The central estimate of the thermal tipping point for warm-water coral reefs of 1.2°C global warming above pre-industrial (Lenton et al 2023, Pearce-Kelly et al 2025) is already exceeded and without stringent climate mitigation their upper thermal threshold of 1.5C may be exceeded within the next 10 years (Bevacqua et al 2025). The resultant severe impacts on reef functioning and provision of ecosystem services to millions of people will be compounded by a range of co-occurring and interacting coral reef stressors, including ocean acidification, pollution, unsustainable fishing, invasive species, and disease outbreaks.

Even under the most optimistic current emission scenarios of stabilising warming at 1.5C without any overshoot, it is considered that warm-water coral reefs are virtually certain (>99% probability) to tip, given the upper range of their thermal tipping point is 1.5°C, Richie et al (2025) Chapter 2.3., High peak warming levels and prolonged exposure due to temperature exceedance of their tipping thresholds (Reisinger et al 2025) imply irreversible damage to coral reefs (Tachiiri et al 2019; IPCC 2022; Santana-Falcón et al 2023). Therefore, except for relatively few isolated refuge areas, functional warm-water coral reef ecosystems are expected to be severely degraded unless global mean atmospheric temperature returns below their central thermal tipping point threshold of 1.2°C with a minimal exceedance period and eventually returns to their lower thermal threshold of 1.0°C (Lenton et al. 2023). There is thus an urgent need for rapid greenhouse gas emissions phase out and atmospheric CO2 draw down at the speed and scale necessary to realise these temperature reduction imperatives.

The oceans are warming at unprecedented rates, particularly in the upper mixed layer (Cheng et al. 2024; von Schuckmann et al. 2024; Cheng et al. 2025). Surface warming has quadrupled since the late 1980s (Merchant et al. 2025), with marine heatwave persistence and intensity also rising (Marcos et al. 2025). Depending on emission scenario, by 2100, projected ocean temperature in the top 2000m is 2-6 times that observed so far (Cheng et al. 2022) and currently, ocean temperature is rising at 0.27 °C per decade (Merchant et al 2025). These increases are already driving severe global bleaching (NOAA 2025; Smith et al. 2025) and, if not reduced, will overwhelm coral resilience and adaptation potential, especially in combination with other human-driven stressors (Lenton et al. 2023; Pearce-Kelly et al. 2025). Ocean circulation changes are exacerbating the problem, warming currents are slowing vertical mixing with cold deep water, increasing ocean stratification (Goreau and Hayes 2024). This amplifies surface warming and reduces CO_2 mixing with the deep ocean compounding coral stress.

Delayed warming of the ocean in response to the Earth's energy imbalance takes approximately 25–50 years, for the majority of committed warming to be realised with upper layers responding fastest (Hansen et al. 2005; Abraham et al. 2023). This lag factor masks the full impact that any given global mean surface temperature and atmospheric CO2 concentration will have on reefs. Increasing Earth's energy imbalance (Allan and Merchant 2025, Forster et al 2025, Mauritsen et al. 2025) has the potential to increase onset, magnitude and duration of heat stress events and severity of exceedance of the thermal tipping point for coral reefs. The possibility that equilibrium climate sensitivity (the warming expected for a doubling of CO2) is greater than 3°C (Witkowski et al. 2024, Hansen et al. 2025;Kaufhold et al 2025; Myhre et al. 2025) could also increase rate and magnitude of thermal stress (and other temperature driven stressors such as extreme weather events) that coral reefs are exposed to, whilst reducing the time available for corals to adapt to and recover from mass bleaching events and their compounding stressors.

Other interacting Earth system dynamics have the potential to further compromise coral reef futures, predominately by increasing the rate and magnitude of global warming. These include the weakening of land and possibly ocean carbon sinks (Ke et al. 2024; Oziel et al 2025; Virkkala et al. 2025) and the possibility that major cryosphere and ocean circulation systems are more sensitive to global warming than previously thought (Möller et al. 2024, Stokes et al. 2025). Such cascading impact risks, combined with inadequate greenhouse gas emissions reductions (World Metrological Organisation 2025, Forster et al 2025) may significantly increase coral reef threat severity, challenge adaptation and restoration potential and the scale of global warming mitigation required. Therefore these factors need to be considered when evaluating coral reef tipping point sensitivity and mitigation response requirements.

4. Reef resilience, adaptation and restoration potential

Mass bleaching events, due to climate change driven marine heat wave severity, and other mortality drivers such as disease and predation, more than twice per decade are generally considered to give insufficient time for the recovery of impacted populations and their ecological functions, due to compromised reproduction, dispersal, recruitment, and growth of corals (Hughes et al.,2018; Sheppard et al. 2020; Lenton et al. 2023; Venegas et al.2023). Other local and regional scale stressors reduce the ability of corals to resist thermal stress, further lowering their thermal tipping thresholds (Setter at al 2022, Lenton et al 2023; Pearce-Kelly et al 2025). In addition to population and species level impacts, key geo-ecological functionality characteristics of healthy coral reefs, such as the production of complex calcium carbonate structures, that sustain reef growth and habitat complexity, are increasingly being impaired as thermal and other stressor impacts increase (Hoegh-Guldberg et al 2018; Perry and Alvarez-Filip 2019, IPBES, 2019; Souter et al 2021).

There is a large and often conflicting literature regarding the potential for coral reefs to resist, and adapt to increasingly challenging environmental conditions, especially marine heatwaves and compounding stressors. The largest consensus projections foresee 70 –90 % coral loss at 1.5°C (Hoegh-Guldberg et al. 2018; IPBES, 2019; Souter et al 2021), whereas finer-scale modelling projects a 95 –98 % loss (Kalmus et al 2022) and a 99 % loss (Dixon et al 2022). Existing evidence (mainly from the Indo-Pacific) shows that coral communities can come back after severe periods of thermal stress, but these novel coral communities do not necessarily have the same life-story traits and physical functionality as the previous communities. Furthermore, the existing evidence does not ensure that coral and reef communities will be able to resist the probable future levels of stress occurring at more frequent time periods (Lorenzo Alvarez-Filip pers com 12 August 2025).

There is some evidence of the persistence of heat-adapted genotypes in some species (eg. Lachs et al 2023, Lachs et al 2024) but also that heat stress is increasingly overwhelming this resilience (Logan et al.2021; Venegas et al., 2023; Cornwall et al 2022, Byrne et al. 2025). Some laboratory-based analyses have shown better than expected results for a broad range of Indo-Pacific coral species, suggesting these species have sufficient heritability to allow for adaptation to both warming and acidification levels (Jury and Toonen, 2024). However, these analyses do not explicitly account for wider climatic and non-climatic stressors, nor for out-of-the lab survival conditions.

The potential for significant thermal refugia for corals under future scenarios is looking increasingly doubtful (Dixon et al., 2022; Setter et al.,2022; Lenton et al. 2023). Bleaching is reaching ever greater depths, and very few reef areas are predicted to remain below tipping thresholds for temperature and other stressors. The existence of putative refuges at greater depths or higher latitudes is increasingly questioned (Hoegh-Guldberg et al., 2017, Rocha et al 2018; Setter et al. 2022; Fuchs et al 2024; Muñiz-Castillo et al 2024; Vogt-Vincent et al 2025). Hence, although we may see some resilience of coral to future ocean heating through acclimatization, and adaptation, this potential is likely to be overwhelmed by increasing rate and magnitude of thermal stress and compounding stressors (Dixon et al. 2022; Setter et al. 2022; IPCC 2022; Lenton et al. 2023; Hoegh-Guldberg et al 2023; Henley et al., 2024; Muñiz-Castillo et al 2024; Byrne et al. 2025; Vogt-Vincent et al 2025; Raoult et al 2025; Wang et al 2025).

If reefs manage to persist in the future, they are likely to be very different to those we benefit from today (Figure 2), with much less diversity in coral species (Hughes et al 2018, Henley et al. 2024), and lower structural complexity (Perry and Alvarez-Flip 2019). Mass bleaching events have differential impact on different coral species, with fast-growing branching and tabulate corals being more affected than slower-growing massive species (Hughes et al 2018), although latest mass bleaching observations suggest increasing vulnerability of all types. Ocean acidification is also expected to increasingly negatively impact coral communities around the world, selecting species that have an inherent resistance to elevated pCO2 (Agostini et al 2021), which are not necessarily the same taxa most resistant to thermal stress (Cornwall et al 2024, Pearce-Kelly et al 2025).

The changing geo-ecological functions of reefs (Perry and Alvarez-Flip 2019) will have increasingly severe impacts on the thousands of species that rely on the complex three-dimensional structure of reefs and also on the ecosystem services reefs provide, including coastal protection, food security and livelihoods (Laffoley and Baxter, 2016; Perry et al 2018; Resource Watch 2022, Henley et al. 2024; Smith et al 2024).

Restoration efforts are ongoing and have been shown to be effective at small scales in the absence of thermal stress and with intensive maintenance effort (Boström-Einarsson et al 2020; Lange et al. 2024). Multiple scientific initiatives are looking for coral genotypes that can stand increasing thermal stress. Coral restoration is likely to continue to be compromised unless climate change and other anthropogenic drivers are urgently reduced (Hughes et al.,2023). Scale remains the biggest hurdle (Mulà et al 2025) with fewer than 4% of restoration initiatives being more than a hectare in extent. Large scale restoration is greatly limited by funding constraints and increasing stress severity (Boström-Einarsson et al 2020; Hughes et al.,2023; Mulà et al 2025).

While innovations like assisted evolution or heat-tolerant corals can offer coral reefs a temporary lifeline, they cannot replace decisive and immediate climate action—without it, such efforts will be powerless to prevent the degradation and effective loss of these reefs through long-term tipping point thermal exceedance. This underscores the urgent need for phase out of greenhouse gas emissions and carbon drawdown mitigation.

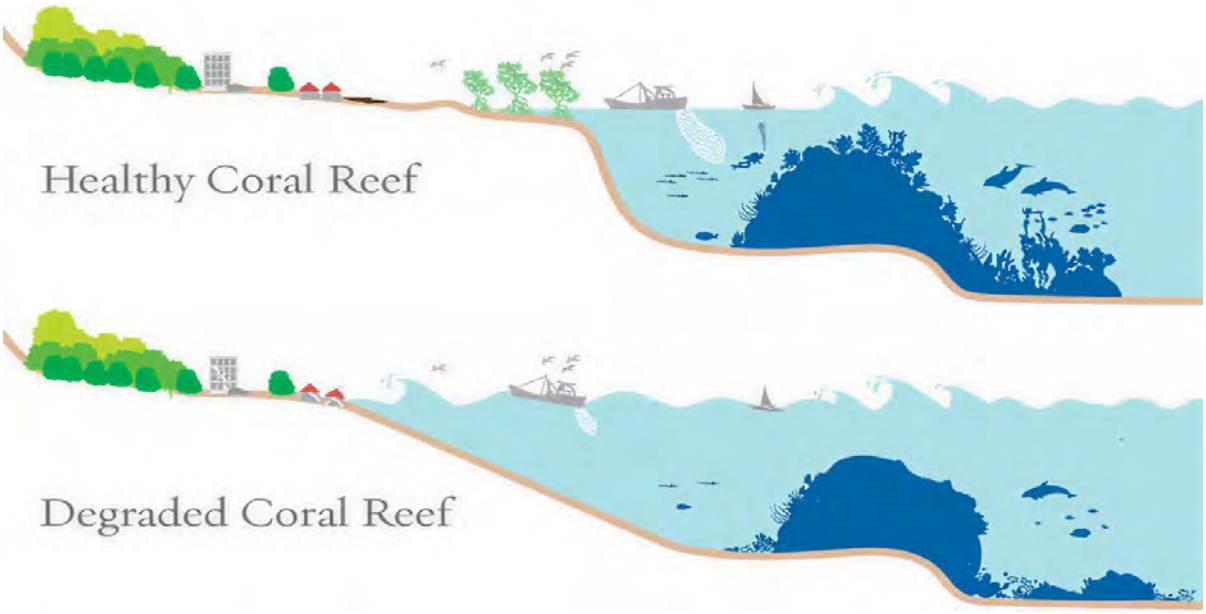


Figure 2. Severely degraded reefs lose much of their ecosystem services, such as coastal protection and food provision (Adapted from: Germanwatch 2023)

5. Caribbean reefs: a miners' canary of the tipping and degradation of warm-water coral reefs

The 2023–2025 mass bleaching event has left a stark and widespread imprint on global coral reef ecosystems, which were already weakened by a diversity of co-stressors. This global crisis underscores the urgent need for targeted conservation strategies, and the Caribbean offers a compelling case study. While reefs across the globe suffered, the Caribbean's unique ecological, economic, and cultural reliance on coral reefs makes it particularly significant.

The Caribbean is home to the largest concentration of Small Island Developing States and overseas territories and comprises five coral reef subregions, representing 10% of the global coral reef extent.

The region ranks among the most vulnerable globally for coral reef degradation due to several factors: first, unlike other regions, the Caribbean is a semi-enclosed oceanic basin (Miloslavich et al. 2010). This geography influences water circulation, thermal stress, pollution retention, hurricane landing, and larvae dispersal. Second, the Caribbean hosts far fewer coral species (65-75) than more diverse regions like the Indo-Pacific (McWilliam et al. 2018). This lower functional redundancy means less backup species to perform similar ecological roles, making these reefs more vulnerable to disturbances. Third, as a highly inhabited region, the Caribbean has long suffered from chronic human stresses including overfishing, poor wastewater management, coastal development, and pollution from nutrient runoff and sedimentation. Fourth, the Caribbean has experienced region-wide coral disease outbreaks rare or absent elsewhere, with white-band diseases decimating Acropora species since the 1980s and Stony Coral Tissue Loss Diseases (SCTLD) rapidly spreading since 2014 (Aronson and Precht 2006; Precht et al. 2016; Precht et al. 2020; Cramer et al. 2021; Alvarez-Filip et al. 2022).

These conditions are now adding to a warmer Caribbean Sea, with the ocean being 0.7-1 °C warmer than in pre-industrial times. Past heat stress events (e.g., 1998, 2005, 2010, 2015–2017) produced widespread bleaching but variable mortality across the Caribbean (Eakin et al. 2010; 2022; Muñiz-Castillo et al. 2019, 2024). By contrast, the 2023–2024 marine heatwave was unprecedented, with mass bleaching and mortality documented at multiple sites (Neely et al. 2024; (Bon et al. 2025; Doherty et al. 2025; Goreau & Hayes 2024). Climatic and human compounding impacts have been pushing Caribbean reefs towards their ecological collapse, with already reported regime shifts that are adversely affecting ecosystem functions and services (Goreau & Hayes 2024; Rodrigues et al., 2025a). Aligned with the recent passing of the central estimate for the thermal tipping point of warm-water coral reefs (1.2 °C) (Lenton et al. 2023, IPCC 2022), researchers fear that Caribbean corals may already be trapped in an extinction vortex, being vulnerable to the interplay of climate change, habitat degradation, small coral population size, low genetic diversity and reduced coral dispersal (Goreau & Hayes 2024; Richards Z.T. 2024).

Degrading reefs are not merely an environmental issue, they are a socioeconomic and geopolitical concern. Coral reefs are foundational to the livelihoods, nutrition, and safety of millions across the Caribbean. They provide critical habitat for over 25% of all marine species and support regional fisheries that supply both subsistence and commercial markets (Pearce-Kelly et al., 2025; IPBES, 2019). In many Caribbean nations, where alternative food sources and economic opportunities are limited, the collapse of reef ecosystems would seriously impact food security and increase economic instability. In hurricane-prone regions, reefs act as natural breakwaters, though their protective role depends on reef structure. In the Caribbean, for example, reefs in Mexico reduced hurricane damage by 43% during Hurricane Dean and now prevent an estimated 42 million USD in building losses and 20.8 million USD in hotel damage annually (Reguero et al. 2019). Reefs therefore significantly mitigate the impacts of storm surges and hurricanes on coastal communities (Pearce-Kelly et al., 2025; Guannel et al., 2016). The Caribbean is one of the most hurricane-exposed regions globally, and reef degradation is increasing flood and storm-related damages in a region with intensifying hurricane seasons (e.g. loss of coral reefs in Florida and Puerto Rico could raise flood risk to over 7,300 people, with $824 million/year in additional damage) (Storlazzi et al. 2021). Losses and displacement are growing in the Caribbean due to the impacts of a diversity of extreme weather events (Mycoo et al. 2022; Henley et al., 2024).

Economically, coral reefs generate approximately USD 8–10 billion annually through fisheries, tourism, and shoreline protection in the Caribbean alone (Pearce-Kelly et al., 2025). The tourism sector contributes over 11% to the regional GDP (year 2023) (World Bank 2025), and between 25-90% GDP in ten island nations (Statista 2022). Tourism is tied to the health and visual appeal of its sea, beaches and coral reefs, for snorkeling, diving, and recreational fishing. Their degradation threatens, therefore, vital pillars of regional economic stability (Pearce-Kelly et al., 2025; IPCC, 2022; Mycoo et al. 2022), which currently suffer from the high levels of exposure and vulnerability associated with small island economies.

5.1. Evidence for coral reef degradation in the Caribbean and its multiple drivers

Over the past six decades, the percent of living coral coverage has declined by c. 71.7% (relative percent change) in the Caribbean, from c. 60 to 17 percent from 1970 to 2023 (GCRMN - Caribbean, 2025) (43% absolute percent change) (Figure 3). These values are aligned with other authors' regional declines in living coral coverage of up to 83% (relative percent change), from c. 60 to 10 percent in an earlier time period (70s-2001) (Gardner et al. 2003, Precht et al. 2020; Jackson et al. 2014) (50% absolute percent change).

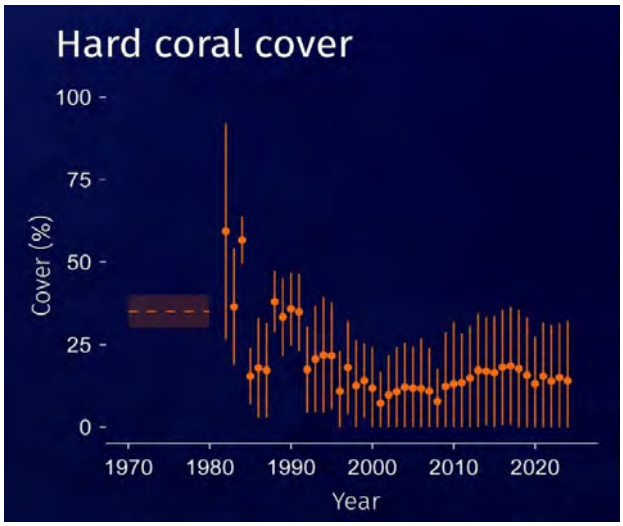


Figure 3: taken from the Global Coral Reef Monitoring Network (GCRMN-Caribbean (2025), this graph shows the estimated regional decline of living coral cover on Caribbean reefs for the period 1980-2024, expressed as annual percent of coral cover. Points and error-bars represent yearly average and standard deviation calculated on raw data from 12,000 sites across the region, respectively.

The decline of Caribbean coral reefs has been driven primarily by human pressures over decades, with recent ocean warming and climate disturbances further weakening reef resilience. Among these drivers, coral diseases stand out as a particularly important cause of mortality. Since the 1980s, white band disease has decimated populations of Acropora palmata and A. cervicornis, leading to subregional losses of 50–90% of reef-building corals (Cramer et al. 2020, Precht et al. 2020). More recently, the emergence of Stony Coral Tissue Loss Disease (SCTLD) since 2014 has caused unprecedented mortality across multiple coral species, accelerating reef decline throughout the region (Alvarez-Filip et al. 2022; Dobbelaere et al. 2024). These disease outbreaks, though influenced and exacerbated by human-induced stressors such as poor water quality and habitat degradation, represent ecological crises of their own rather than simply consequences of local human activity.

Nutrient pollution and coastal development have also been central drivers of reef degradation. Sewage, urban runoff, and agricultural inputs increase nitrogen and phosphorus loads, promoting phytoplankton and macroalgal growth (Fabricius 2005). Research by the World Resources Institute (Burke & Sugg 2006) highlighted the contribution of large watersheds in the Mesoamerican Reef region, where fertilizer use, soil erosion, and poor land management elevate nutrient and sediment loads reaching coastal reefs. These bottom-up processes fuel algal proliferation, with regional and local analyses documenting widespread increases in macroalgae that in many cases surpass the declines in live coral cover (e.g., Jackson et al. 2014; Suchley et al. 2016; Arias-González et al. 2017).

The expansion of macroalgae is one of the clearest ecological shifts on Caribbean reefs. Macroalgae outcompete corals for space and resources, inhibit coral recruitment, and reduce the potential for reef recovery. Their increase is driven both by nutrient enrichment and by the depletion of herbivores. Overfishing of parrotfish and surgeonfish reduces grazing pressure, allowing algae to proliferate unchecked (Martinez-Rendis et al. 2015; Suchley et al. 2016; Arias-González et al. 2017; Randazzo-Eisemann et al. 2021). However, while herbivory is critical for maintaining coral–algal balance, nutrient enrichment often plays the more pervasive role in promoting rapid algal growth across the region (Lapointe et al. 2004; Szmant 2002; Jackson et al. 2014). Both processes interact, reinforcing a trajectory of phase shifts from coral-dominated to algal-dominated systems.

Additionally, increased frequency and intensity of hurricanes, which are projected to rise with climate change, physically damage reef structures through wave action and sediment displacement, reducing coral cover and disrupting reef ecosystems, complicating recovery efforts (Mumby & Harborne, 2020).

Building on these chronic stressors, marine heatwaves have become the most acute and rapidly increasing threat in recent years (Muñiz-Castillo et al. 2019, Goreau & Hayes 2024), stressing already damaged reefs (Cramer et al. 2020). The record-breaking ocean heat stress during the El Niño 2023–2024 (highest ever recorded ocean temperatures in the region) (Goreau & Hayes, 2024), has led to unprecedented levels of coral bleaching and mortality across the Caribbean (Birkart & Alvarez-Filip 2025; Neely et al. 2025; Thompson et al. 2025). Unprecedented values of > 19 DHW for 2023 and 2024, suggest this latest ocean heat wave is ~ three times stronger than the prior heat waves, entering a new climate dynamic. As examples, during the 2023 bleaching event, Caribbean reefs reported SST anomalies of 1.5–2.5°C above the climatological mean, generalized DHW values exceeding 16°C-weeks, and widespread coral bleaching (>80% of the reefs) (Goreau & Hayes 2024). In Florida Keys, monitoring of over 4,200 coral colonies revealed near-100 % bleaching, with site-level mortality peaking at 43 % and 24 %, while other sites experienced minimal losses (Neely et al. 2024). Reports from Little Cayman and Martinique also confirmed widespread bleaching and mass mortality (Bon et al. 2025; Doherty et al. 2025). These events underscore spatial heterogeneity in outcomes.Extreme thermal events and associated bleaching responses are now occurring in a rapid succession regionally (1998, 2015-2017, 2023-2025) and quasi-annually subregionally (2003, 2005, 2010-2011) (Muñiz-Castillo et al. 2019). Such short return intervals alter local environmental conditions and leave not enough time for reef recovery, damaging reef recruitment, and pushing many reefs beyond their resilience thresholds (Pratchett et al. 2018; Stuart-Smith et al. 2018; Hughes et al. 2019). Combined, these drivers have created a cumulative impact resulting in long-term declines in coral cover, loss of reef diversity and complexity, and diminished ecosystem services (Rodrigues et al. 2025b, Smith et al. 2025). Under current heat trends, Caribbean reefs are under imminent risk of long-term regime shifts to algal-dominated or degraded states.

Figure 4 shows the evolution of human-driven stressors since the 70s and later combination with heat driven impacts (year 1998) on reef physical functionality trajectories in the Caribbean (Alvarez-Filip et al. 2022).

Human-stressors such as water-vector diseases have long diminished the region's reef health, before heat stress overtook these ecosystems (Cramer et al. 2020, 2021, Precht et al. 2020, Alvarez-Filip et al. 2022).

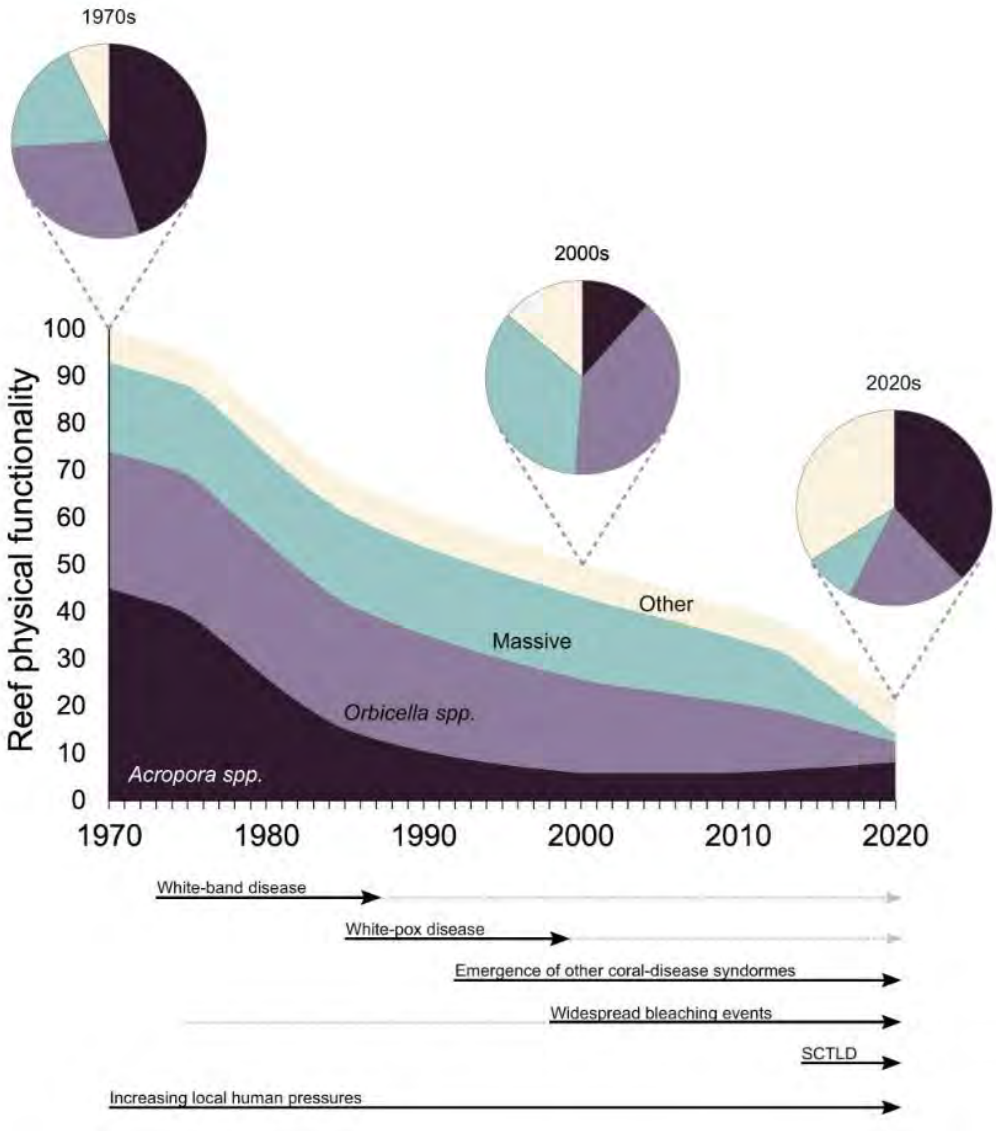


Figure 4: Taken from (Alvarez-Filip et al. 2022) this is a conceptual diagram of the long-term trajectory of the physical functionality of Caribbean reefs from 1970-2020 showing the occurrence of human-driven stressors, particularly white-band disease, white-pox disease and Stony Coral Tissue Loss Diease. The physical functionality of reefs depends on the abundance (or cover), capacity to accumulate CaCO3, and structural complexity of each species present in the system. The stacked plot represents the functional contributions of four coral groups. The pie charts illustrate the proportional contributions of each coral group during three different periods. Acropora spp. and Orbicella spp. contain all the species for each of these genera and are illustrated as a single group, as they are the main reef-building corals in the Caribbean. The group of massive corals includes reef framework builders from the Diploria, Pseudodiploria, Colpophyllia, Montastraea, and Dendrogyra genera (many of which were severely affected by SCTLD). The other group includes all other coral species, which are largely classified as weedy, submassive, or foliose-digitate corals for which little evidence of declines exists. The black arrows indicate major sources of coral decline widely recognized in the literature. White-band disease resulted in severe population declines of acroporids. The white-pox epidemic has infected many of the remaining colonies of this genus since the 1990s. Other coral-disease syndromes (e.g., white plague and Caribbean yellow band) that mainly affect Orbicella and other massive species have increased in frequency and virulence over the last three decades. Coral mortality has also continued to increase in the Caribbean and is associated with warm-water bleaching events and other local-scale anthropogenic impacts. The grey-dashed arrows indicate that the source of stress remains, although the effects on widespread coral mortality are unclear.

5.2. Monitoring systems and indicators in the Caribbean

Effective monitoring of coral reef health in the Caribbean relies on both in situ observations and remote sensing. While not regionally nor temporally complete (Cramer et al. 2021), the region counts on one of the largest and longest in-situ datasets of reef health in the world, collected under diverse initiatives and methodologies (e.g. CARICOM, CoRIS, AGRRA), including fossil records (Reverter et al. 2022). We here focus on data from the Healthy Reefs for Healthy People, which runs biennial regional data collection with the standardized AGRRA (Atlantic and Gulf Rapid Reef Assessment) methodology (Kramer et al. 2003). Their Healthy Reefs Initiative provides reef health indicators to reef managers and policy-makers in the Mesoamerican Reef region, aiming for policy responses. We also rely here on NOAA's Coral Reef Watch program, which provides real time Degree Heating Weeks (DHW) data and bleaching alerts. DHW is a metric used to quantify cumulative thermal stress, and the principal remote sensing tool to measure heat stress relevant for coral bleaching employed worldwide. Caribbean reefs now frequently experience Degrees Heating Weeks (DHW) values exceeding 8°C-weeks, a threshold associated with high mortality risk (Skirving et al., 2019; Goreau & Hayes, 2024). Onsite data collection both in the Mesoamerican Reef (MAR) (Healthy Reefs database) and in the wider Caribbean (AGRRA database) have long supported NOAA's early warning system, largely validating their model. The region counts on a unique regional long-term database (since 2006) that covers classical indicators of reef health: coral cover, fish biomass (herbivores and commercial carnivores), macroalgae cover, and macrobenthos presence (urchins, seastars, etc), among others. This allows general tracking of the reef health that supports policy responses.

A widely recognized ecological threshold for coral reef degradation occurs when live coral cover drops below ~10% (Vercelloni et al. 2020).While reefs may have already seen their functionality collapse above this threshold, below 10% of living coral cover, fish community structure deteriorates significantly (with noticeable declines in fish diversity and abundance), and eventually ecosystem functions and services collapse as reefs lose structural complexity, habitat provision, and resilience (Darling et al. 2019; Sheppard et al. 2020; Vercelloni et al. 2020). An analysis of 12,000 reef sites across 44 countries and territories and 22,000 surveys reported a regional mean live coral cover of c. 17% in 2023 for the Caribbean (GCRMN-Caribbean 2025) (Figure 3). These values differ subregionally and the latest statistics for the MAR countries (Mexico, Belize, Guatemala, Honduras) show coral cover percent that range from national averages of 13% (Mexico) to 26% (Guatemala) in 2022-2023 (HRI Report Card, 2024). However, these recent studies do not include the regional mortality of the 2023-2024 bleaching event. Local post-bleaching mortality statistics are already showing a gloom view of the Caribbean reefs' health status in 2025 (Birkart & Alvarez-Filip 2025; Neely et al. 2025; Thompson et al. 2025).

Live coral cover is a commonly used indicator of reef health but it hides relevant information on reef diversity and structure, offering an overoptimistic view of their status. Because data on diversity and structure are not typically included in standardized monitoring programs (they require taxonomic training), a frequently used indicator to complement the evolution of reef health beyond live coral cover is the evolution of live coral cover vs algae cover. These indicators show clear declines for the Caribbean, as presented in Figure 5a below, where Precht et al. (2020) display the absolute difference between coral cover and algae cover for 1983-2001. In a similar line, but for a longer period, 1980s-2023, data from the Global Coral Reef Monitoring Network- GCRMN-Caribbean (2025) (https:/gcrmn.net/) captures regional mean increases of up to 60% for algae cover since the 90s and the already mentioned decreases in coral cover from c. 60% to c. 17% (Figure 5b).

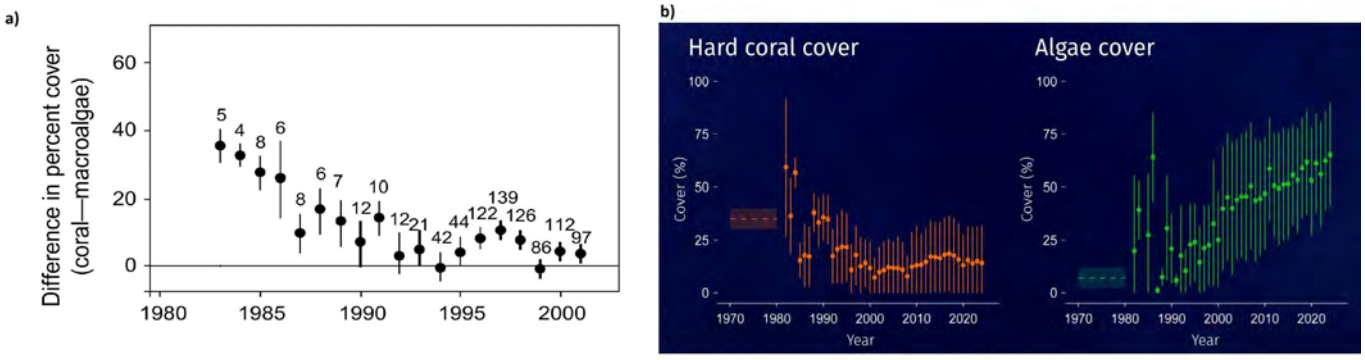


Figure 5: Reef degradation observed as declining trends of live hard coral cover and increasing trends of macroalgae on Caribbean reefs in different time periods, from different datasets. a) figure modified from Precht et al. (2020), this series represents regional annual differences between live coral cover and macroalgae on Caribbean reefs between 1977 and 2001 (black dots). Positive values indicate that the cover of coral was higher than that of macroalgae. Numbers above the error bars show the sites contributing to each mean, with higher uncertainties in earlier data. And b) annual trends of living hard coral and algae cover in reefs of the Caribbean from 1970 to 2024. Points and error-bars represent yearly average and standard deviation calculated on raw data from 12,000 sites across the region, respectively. Dashed lines from 1970 to 1980 indicate the likely benthic cover in this decade, and taken from Jackson et al. (2014). This figure has been obtained from GCRMN-Caribbean (2025) with permission for use.

5.3. Call for action: strategic responses for the Caribbean region

The Caribbean is affected by unprecedented climate hazards (e.g. hurricanes, sea level rise, extreme ocean heat, drought), where urgent societal and policy responses are needed. While global GHG mitigation and carbon removal remain key to reducing the impacts of those climate hazards, in the meantime, improved reef governance is a matter of survival for coastal ecosystems and the livelihoods of coastal communities in the Caribbean. Climate combines with human-driven stresses such as overfishing, water pollution, sedimentation or coastal development. Given the multi-faceted nature of reef degradation, an integrated approach that combines local conservation with global climate action is essential. Actions will need to be site-specific but will cover activities that reduce human impacts, such as:

Control Overfishing and Establish and Enforce Marine Protected Areas (MPAs) to prevent habitat destruction.

- Expand no-take (fishing prohibition) zones and enforce patrols to reduce fishing pressure and protect reef biodiversity.
- Enforce bans on herbivorous fish capture (e.g., parrotfish and surgeonfish).
- Shift toward rights-based fisheries and co-management with local communities.
- Integrate ecological connectivity and reef health indicators into MPA zoning plans.
- Support alternative livelihoods (e.g., ecotourism, aquaculture) for small-scale fishers.

Regulate Coastal Development and Reduce Sediment Runoff to limit land-based pollution and habitat destruction.

- Implement coastal zone management laws that regulate hotel, marina, and port construction.
- Strengthen mangrove protection and watershed reforestation programs to reduce erosion and sedimentation.
- Introduce setback policies and sustainable land-use zoning near sensitive reef areas.

Regulate Agricultural Pollution and Watershed Inputs to limit nutrient-run off, algae blooming and turbidity through soil erosion

- Ban and regulate agrochemical (e.g. phosphorous, nitrogen) runoff through watershed-based agreements and farming best practices (e.g., buffer zones, cover crops).
- Support cleaner practices in upstream agriculture, including fertilizer reduction and wetland restoration.
- Regulate perverse subsidies in agriculture that result in reef degradation.

Respond to Coral Disease and Heat Stress

- Establish rapid coral disease surveillance and treatment protocols (e.g., antibiotic application, coral rescue nurseries).
- Expand bleaching early warning systems and coral restoration for resilient genotypes.
- Limit anthropogenic stressors (e.g., all the above) to improve coral immune response.

Support Regional Monitoring and Science-Policy Integration to target data gaps and lack of enforcement.

- Fund and extend regional reef monitoring efforts under standardized protocols (e.g., AGRRA, GCRMN-Caribbean, HRI).
- Operationalize surveillance and law enforcement in MPA.
- Use citizen science and national reef report cards to inform policymakers and the public.
- Embed reef data into marine spatial planning (MSP), coastal development review, and tourism regulations.

Scale Up Reef Restoration Through Coral Nurseries and Outplanting in selected areas where reefs have the capacity to deliver the most significant functional gains, and in areas where the other stressors are already attended.

- Establish in situ and ex situ coral nurseries focusing on thermally tolerant and disease-resistant genotypes.
- Promote large-scale outplanting of nursery-grown corals to degraded reefs using micro-fragmentation or larval seeding.
- Integrate coral gardening into national restoration plans and tourism partnerships.

Implement Blue Bonds and Debt-for-Nature Swaps to tackle underfunded conservation, economic dependence on reef-degrading industries

- Launch Blue Bonds to refinance national debt in exchange for marine conservation commitments (e.g., protected areas, enforcement, tourism taxes).
- Use debt-for-nature swaps to direct debt relief toward reef management and monitoring.
- Develop sustainable tourism fees or coral conservation trust funds to finance long-term.reef protection.

Use Reef Insurance and Risk-Based Financial Instruments to protect reefs and communities against storm damage, bleaching, and loss of tourism value.

- Adopt parametric reef insurance policies, triggered by storm or heat events, to fund rapid coral restoration and post-disaster response.
- Establish reef protection as critical infrastructure, eligible for climate resilience and disaster recovery funding.

Active participation in regional Policy and International Advocacy to elevate coral reef conservation as a priority global issue.

- Actively participate in UNFCCC negotiations to advocate for ambitious global climate mitigation, particularly to limit warming below 1.5°C —a threshold critical to reef survival (IPCC, 2022).
- Integrate coral reef protection into the SIDS Accelerated Modalities of Action (SAMOA Pathway) and the Blue Economy agendas, ensuring reef health supports economic resilience.
- Leverage participation in regional agreements like the Cartagena Convention and its Protocol on Specially Protected Areas and Wildlife (SPAW) to harmonize reef governance.

6. From prevention to adaptation: Governing coral reef tipping points

Governance of warm-water coral reefs requires returning global mean warming below 1.2°C with a minimal overshoot period, and eventually returning to 1°C above preindustrial, as essential targets for retaining functional warm-water coral reefs at meaningful scale, beyond a relatively few isolated refuge areas.

Policy makers and societies remain fully unprepared for the imminence of reefs' functional collapse. While urgent global and local action can still reduce drivers of decline, the irreversible loss (in the absence of effective mitigation outcomes) of many reef functions requires governance systems that also prepare societies for profound ecological, social, and economic transitions.

Effective governance of coral reef tipping points requires action at multiple, interconnected scales, because the drivers of reef decline are simultaneously global, regional, and local. At the global level, the persistence of functional reefs depends overwhelmingly on rapid decarbonization, carbon dioxide removal, and speedy return to a global temperature well below 1.5°C. This means coral reef governance cannot be siloed into marine or biodiversity policy alone, but must be integrated into climate governance under the UNFCCC and linked financial, trade, and energy regimes. Equally, prevention requires coordinated action at national and local scales to reduce non-climatic drivers of tipping dynamics, including pollution from agriculture and industry, overfishing, unsustainable tourism, and coastal development. Marine protected area networks, improved fisheries management, and stricter land-use and water-quality regulation can help alleviate these stressors, buying reefs precious time during what is expected to be a protracted period of global temperature overshoot above coral reefs upper tipping point threshold of 1.5°C.

At the same time, recognition that the central thermal tipping point for warm-water coral reefs has already been exceeded and with near-term exceedance of the upper 1.5°C tipping point threshold, implies that even the most ambitious, current mitigation pathways will not prevent large-scale, irreversible loss of reef functions. This presents an urgent challenge to improve mitigation pathways to their fullest potential to align with temperature reduction needs for functional coral reef persistence. Failure to sufficiently mitigate will require governance frameworks to shift emphasis from "saving" reefs to managing the consequences of their decline, including supporting transitions in livelihoods, securing food security, and ensuring just adaptation for the most affected communities. Globally, impact governance for coral reef tipping includes the Paris Agreement goals and mechanisms. Adaptation governance will need to be anticipatory and transformative, with dedicated governance bodies (e.g., a strengthened International Coral Reef Initiative [ICRI]) or regional platforms (e.g., in the Caribbean or Southeast Asia) facilitating exchange of experiences, coordination of responses, and integration of science with policy. Such polycentric arrangements can help societies prepare for futures in which current reef-based subsistence and economic activities may no longer be viable. Inclusive governance processes that integrate Indigenous and local knowledge alongside global trade and development policy are essential for designing equitable adaptation pathways. Importantly, the decline of coral reef-based fisheries will reverberate well beyond reef regions, affecting international food trade, nutrition, and global security.

The governance of coral reef tipping points must be elevated onto global governance agendas, as no existing international framework directly addresses the risk of widespread and irreversible reef collapse. Strongly affected states, together with intergovernmental organizations such as UNEP, will be essential in championing this issue, mobilizing political attention, and creating the institutional space for both preventive and adaptive responses.



CASE STUDY 04

MOUNTAIN GLACIERS: ÁAK'W T'ÁAK SÍT' (MENDENHALL GLACIER)

4.4 Mountain glaciers: Áak'w T'áak Sít' (Mendenhall Glacier)

Authors: Donovan P. Dennis, Bethan Joan Davies, Shivani Ehrenfeucht, Jeremy C. Ely, Lindsey Nicholson, Annika Ord, Judith Daxoots̲ú Ramos, Ricarda Winkelmann

Reviewed by: Jason Fellman, Eran Hood, Sonia A. Nagorski, Allen Pope, and Helen Werner

Risk Assement:

- **Mountain glacier tipping behaviour depends on a complex interplay between topography and climate, with mountain glaciers that experience similar external forcing having the potential to respond differently depending on local conditions.**
- **Áak'w T'áak Sít' as well as the broader Juneau Icefield and its outlet glaciers have been suggested as a potential mountain glacier tipping system, with the segmentation of the glacier into multiple components ("glacier disconnection") and the bedrock hypsometry leading to nonlinear mass loss and glacial retreat.**
- **Rapid deglaciation of Áak'w T'áak Sít' and other glaciers disrupts the relationship between Indigenous communities, glaciers, and glacial landscapes, depriving future generations of this component of their identity and history, which are inseparable from the land.**
- **The retreat of Áak'w T'áak Sít''s tributary glaciers has led to annual outburst floods in Juneau; future occurrence of these floods will depend on the rates and pattern of ice retreat.**
- **Rapid mass loss of Áak'w T'áak Sít' could negatively impact tourism in Juneau as the glacier retreats from the Mendenhall Glacier Visitor Center viewshed, which is visited, on average, by every third visitor to the state of Alaska.**
- **The economic consequences of crossing a glaciological tipping point on fishing and salmon stocks are less clear, given the complex interplay of water temperature, air temperature, nutrient availability, and riverbed scouring in glacially influenced aquatic ecosystems.**

Recommendations:

- **At the local level, anticipatory governance considerations regarding the loss of glaciers must involve multiple partners and rights holders, including Indigenous governments, state and federal agencies, and local government, as well as community members, particularly in the context of resource management and the opening of navigable U.S.-Canada border crossings following ice retreat.**



Executive Summary

Mountain glaciers are undergoing rapid retreat in response to global warming, yet their potential for non-linear responses (i.e. "tipping") remains poorly understood. While most studies suggest glaciers outside Greenland and Antarctica will, as a collective, respond linearly to temperature increases this century, under higher emissions pathways and over longer timescales, regional and local tipping points have already been identified at the individual glacier-, ice cap-, and icefield-scale. These variations are driven by local topography, microclimates and other site-specific factors, complicating predictions of glacier stability and reversibility.

Despite the limited research, the stakes are high. Mountain glaciers contribute disproportionately to global sea-level rise, accounting for 21% between 2005 and 2019, with Alaska alone responsible for nearly a quarter of this loss. Nearly one billion people live in glacially-influenced watersheds globally, where they play an important role in freshwater availability, influence hazard susceptibility, shape cultural identity, and contribute to local economies. Focused investigations of key glaciers are therefore critical for anticipating the consequences of climate change in these settings.

The Juneau Icefield (JIF), the fifth-largest body of ice in North America, is experiencing accelerated retreat under present-day warming, with its temperate, low-elevation glaciers particularly vulnerable to small temperature increases. Áak'w T'áak Sít' (Mendenhall Glacier) illustrates these changes: since its Little Ice Age maximum around 1760, it has retreated over 4 km, now losing appx. 48 m annually. Recent work suggests that, under continued warming, the unique characteristics of the icefield's physical setting may lead Áak'w T'áak Sít' and other JIF glaciers to "tip" into a state of rapid, irreversible, and self-sustained ice loss. Already, the retreat of Áak'w T'áak Sít' has created a proglacial lake and altered downstream hydrology, affecting salmon habitats, water quality, and the residents of Juneau's most populated valley.

The continued retreat of Áak'w T'áak Sít' is already driving profound ecological and cultural change. For indigenous Tlingit communities, glaciers are more than components of the landscape: they are sentient beings woven into oral histories, spiritual practices and cultural identity. Their retreat and disappearance represent not only ecological disruption but also cultural trauma, severing deep intergenerational ties and depriving future generations of relationships central to place, memory and identity.

At the same time, glacier retreat creates escalating physical hazards. Most pressing are glacial lake outburst floods (GLOFs) from Suicide Basin, a tributary to Áak'w T'áak Sít'. Since 2011, annual floods have released tens of millions of cubic meters of water, with recent events destroying homes, prompting disaster declarations, and forcing multi-million-dollar investments in levees and flood barriers. Despite these interventions, flooding events have affected hundreds of properties, underscoring the growing risks as glacier retreat reshapes valley hydrology. The likelihood of future GLOFs is high, with additional unstable basins potentially forming as ice thins and disconnects. On long timescales, the continued loss of glacier ice will lead to the opening of navigable borders between the United States and Canada, and expose previously inaccessible georesources for potential extraction.

Together, these dynamics reveal a poly-crisis which includes material risks to downstream communities and cultural and environmental losses of immeasurable value. Effective governance will require integrating Indigenous voices, recognizing cultural heritage as central to adaptation, and addressing both the physical hazards and intangible dimensions of glacier decline. Preserving cultural continuity and community resilience demands that governance strategies extend beyond technical fixes to honour the full meaning of glaciers in Tlingit homelands.

Introduction and Motivation

In comparison to other Earth system components, relatively limited research has investigated the capacity for mountain glaciers to respond non-linearly to climate change–i.e., to "tip". This is despite their important role in many communities and ecosystems, as well as indications that critical thresholds likely exist for many mountain glacial systems (Kääb et al., 2023). That they are already changing rapidly in response to a warming climate is well-documented (IPCC, 2019). More specific investigations into potential nonlinear responses to warming, i.e. mountain glaciers' "tipping behaviour", have found that, considered in the aggregate, glaciers outside the Greenland and Antarctic ice sheets are expected to respond linearly to temperature change within this century (Rounce et al., 2023). However, at more rapid warming rates induced by high emissions pathways in the 21st century (Bolibar et al., 2022) and on longer timescales beyond the year 2100 (Marzeion et al., 2018), they may exhibit nonlinear responses. Additionally, nonlinear behavior has been identified at the individual glacier, ice cap, and icefield scales (Åkesson et al., 2017; Criscitiello et al., 2010; Davies et al., 2022; 2024; McNeil et al., 2020; Zekollari et al., 2017), indicating that there may be important regional tipping points for specific glaciers.

Though influenced by the same regional atmospheric forcings (i.e., temperature and precipitation), the response of individual, and even neighbouring, mountain glaciers can differ according to local topography and microclimate(s) (Oerlemans, 2001). Because of these and other complexities, mountain glacier tipping potential, timing, dynamics, and potential reversibility are poorly-understood, and likely driven by combinations of locally-specific factors (Kääb et al., 2023). The limited body of research on mountain glacier tipping dynamics stands in stark contrast to their disproportionate contribution to global sea level rise (Hugonnet et al., 2021); their centrality for mountain ecosystems; and their role in sustaining human societies (IPCC, 2019). Globally, mountain glaciers lost more than 250 billion tons of ice during the 2005-2019 period and are responsible for 21% of the contemporaneous global sea-level rise (Hugonnet et al., 2021). Of that, glaciers from Alaska account for nearly one quarter of total ice loss (appx. 67 billion tons; Hugonnet et al., 2021).

While careful investigation of the dynamics of the hundreds of thousands of individual mountain glaciers worldwide is prohibitive, investigations of key glaciers are nevertheless necessary, particularly for the nearly 1 billion people living in glacier-influenced regions (Viviroli et al., 2020) who may be impacted by their potential loss and/or tipping. In these settings, glaciers exert important controls on the local environment as sources of freshwater (Hamish, 2019; Ultee et al., 2022; Immerzeel et al., 2020); the cause of glaciogenic natural hazards (Zhang et al., 2022); as important cultural touchstones (Cruikshank, 2001); or as economic drivers for local communities (Salim et al., 2021). This case study summarises the possible causes and implications of tipping in a localised mountain glacier system, serving as an analogue for furhter local-scale tipping system evaluations. In the setting of interest here (Áak'w T'áak Sít' and the Juneau Icefield), the even more rapid loss of glacier ice due to the crossing of critical local warming thresholds would impact, among other systems, regional glacial hazards, salmon habitats, and water quality, all of which may be particularly responsive to the crossing of tipping points.

1. Áak'w T'áak Sít' and the Juneau Icefield

The Juneau Icefield (JIF) is a large (~3,700 km^2) temperate icefield straddling the Alaska-Canada border, situated roughly between Skagway and Juneau, the capital of the U.S. state of Alaska, and Atlin, British Columbia (Canada). It is the fifth-largest contiguous body of ice in North America and consists of hundreds of constituent glaciers which flow from a north-south orientated central plateau at ~1900 m a.s.l (Davies et al., 2022; Sprenke et al., 1999). Excepting the Taku glacier (which terminates in the ocean as a tidewater glacier, thus exhibiting more complex flow dynamics than other mountain glaciers; see McNeil et al., 2020), the major outlet glaciers of the JIF have been in retreat since the mid- to late-18th century (Clague et al., 2010; Miller, 1964; Motyka, 2003), with ice retreat rates increasing rapidly into the 21st century (Davies et al., 2024). As a temperate icefield with many low-elevation outlet glaciers, the JIF is sensitive to relatively small changes in regional temperature and therefore particularly susceptible to present-day warming (Davies et al., 2022; 2024; Larsen et al., 2007).

Áak'w T'áak Sít' (Mendenhall Glacier; place name cited by Central Council Tlingit & Haida) is a large JIF outlet glacier approximately 20 km in length and 120 km^2 in area, with ice thicknesses reaching over 500 m (Motyka et al., 2002; Ziemen et al., 2016). It flows south and west from an ice divide at 1700 m a.s.l., and drains, along with the Taku Glacier, the southwestern quadrant of the icefield (Boyce et al., 2007; Figure 1).

The glacier reached its Little Ice Age maximum extent around 1760 (Miller, 1964; Molnia, 2007), since which it has retreated nearly 4.3 km, with present-day retreat rates of approximately 48 m per year (Davies et al., 2024). This corresponds to an annual area change of appx. 0.52 per cent, compared to an average of 1.52 per cent per year across all JIF outlet glaciers (Davies et al., 2024). The present-day glacier terminates in a proglacial lake (Sit'.áa; Mendenhall Lake; place name cited by Central Council Tlingit & Haida), formed by glacial meltwater runoff collecting in the basin eroded by Áak'w T'áak Sít' in its previously extended states (Figure 1). A river (Wooch Eel'óox-'u Héen; Mendenhall River; place name cited by Central Council Tlingit & Haida) carries glacier meltwater down-valley from the lake, flowing through the city of Juneau before eventually connecting to the ocean (Kienholz et al., 2020). Downstream of the glacier, the Mendenhall Valley supports the highest density and proportion of homes in Juneau. Due to its ease of access and the popular Mendenhall Glacier Visitor Center, Áak'w T'áak Sít' is a significant driver of regional tourism. Nearly 700,000 tourists, one in every three tourists visiting Alaska, stop at Áak'w T'áak Sít' or the Mendenhall Glacier Visitor Center each year (USFS, 2019). Likewise, tributaries of the Wooch Eel'óox-'u Héen watershed provide salmon spawning and rearing habitat, fishing opportunities, and food resources since settlement by Indigenous peoples nearly 10,000 years ago (Cruikshank, 2005).

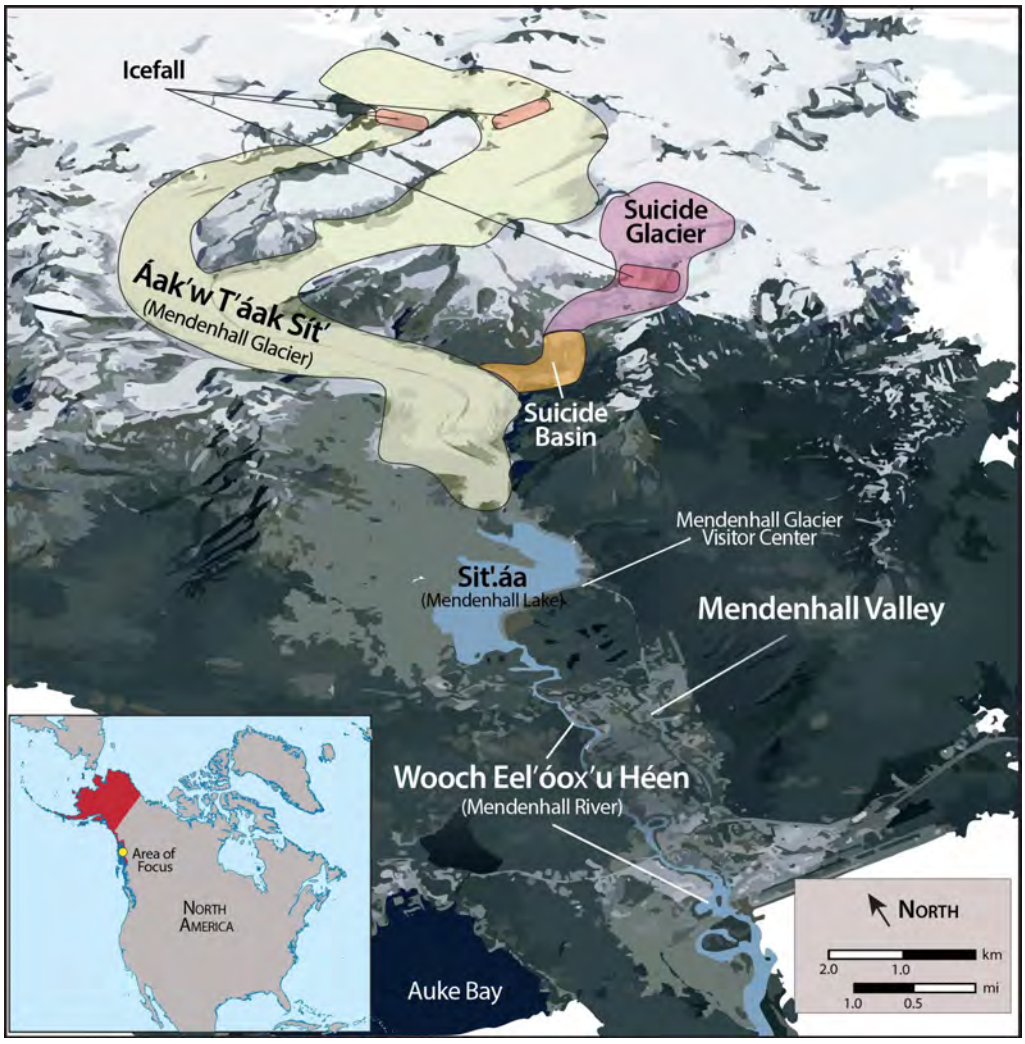


Figure 1. Overview of Áak'w T'áak Sít's glaciological and topographic setting.

2. Ecological and environmental feedback loops in Áak'w T'áak Sít' tipping dynamics

A glacier's mass balance is the difference between the annual influx of new ice in the form of high elevation snow accumulation and the mass lost due to low elevation melting and discharge. The elevation band separating the accumulation and melting zones is referred to as the equilibrium line altitude (ELA). A glacier's mass balance is sensitive to the distribution of its surface area at varying elevations (i.e., its "hypsometry"; Jiskoot et al., 2007; McGrath et al., 2017). Glaciers fed from high, plateau icefields such as the JIF have a 'top-heavy' hypsometry that is particularly susceptible to non-linear responses to climatic changes, because a relatively small rise in the ELA leads to a large area of the glacier switching from gaining mass to losing mass (Figure 2). This instigates disproportionately large, nonlinear changes in mass loss in response to a small climate forcing (Åkesson et al., 2017; Davies et al., 2022; Jiskoot et al., 2007; McGrath et al., 2017; Zekollari et al., 2017). This nonlinear feedback is compounded when enhanced thinning along the glacier profile causes glacier segmentation ("disconnection"), where ice from the plateau no longer connects with the low lying outlet glacier tongues, causing rapid deterioration of the lower glacier segment (Åkesson et al., 2017; Davies et al., 2024; Jiskoot et al., 2009; Figure 2).

In the case of the JIF, enhanced thinning and segmentation occurs at icefalls, features created by ice flowing off the high elevation plateau over steep topographic gradients and into lower elevation valleys (analogous to a waterfall resulting from a river flowing over a cliff). Icefalls have characteristic rough surfaces and extensive fracturing which increases the ice surface area exposed to ambient atmospheric temperature fluctuations (Figures 1 & 2). They are thus more susceptible to melting than the rest of the glacier (Davies et al., 2022; Davies et al., 2024). Icefalls occur at relatively uniform elevations on the JIF with the majority falling between 1400 and 1700 m a.s.l.. Currently, the ELA sits between 800-1600 m a.s.l. for many glaciers draining the JIF (McNeil et al., 2020; Pelto et al., 2013; Ziemen et al., 2016). However, as air temperatures rise, the ELA will shift up-glacier, sitting at higher elevation bands (Figure 2). This has already been observed for some key glaciers in the region, e.g., Taku Glacier (McNeil et al., 2020). If the ELA migrates above an icefall, the icefall will be within the new ablation zone, where it will regularly be exposed to above freezing air temperatures (Ramage and Isacks, 2017) and where precipitation is more likely to fall as rain than as snow (Ing et al., 2025).

The intersection of the ELA with the icefall-line-altitude and subsequent segmentation of the icefield's outlet glaciers may constitute a second tipping point not only for individual glaciers, but icefield-wide (Davies et al., 2022), leading to rapid mass loss and a near total collapse of the JIF-glacier system. These local and glacier-specific dynamics will likely compound with other consequences of warming known to induce non-linear responses (e.g., decreased englacial freezing/increased runoff, the melt-elevation feedback, etc.; Schuster et al., 2025).

On Áak'w T'áak Sít', icefalls occur at approximately 1450 m a.s.l. on both of the glacier's main tributary trunks, where the ice intersects with the western extent of the underlying bedrock (Figure 1). Modeling studies anticipate considerable mass loss for Áak'w T'áak Sít' and other JIF outlet glaciers given present warming trends, particularly in the second half of the 21st century (Ing et al., 2023; Ziemen et al., 2016). Ziemen et al. (2016) investigated the future evolution of the JIF under the RCP 6.0 scenario (van Vuuren et al., 2011), and found widespread glacier loss, particularly at lower elevations peripheral to the ice plateau. This and other ice dynamics modeling studies do not, however, account for the enhanced melting at Áak'w T'áak Sít's icefalls in their simulations and thus cannot mechanistically represent the hypothesised tipping behaviour, in part due to the difficulty in capturing (brittle and fractured) icefall flow dynamics in continuum glacier models (e.g., Colgan et al., 2012; Riikilä et al., 2015).

While these projections of Áak'w T'áak Sít' and the JIF do find rapid glacier wastage at low elevation, their ice loss rates may underestimate true future rates expected given the melt-enhancing feedbacks (e.g., lower bedrock albedo adjacent the ice, reduced total snow cover, lower ice surface albedo due to dust deposition) which result from glacier segmentation (Davies et al., 2022). Necessary future work on JIF tipping as well as the broader mountain cryosphere should include implementing and developing ice dynamical models that are able to capture or represent the expected tipping mechanisms at appropriate spatial scales, given the highly-localised nature of mountain glacier tipping, and thus be able to resolve the hysteresis behaviour of segmented glaciers proposed by Davies et al. (2024).

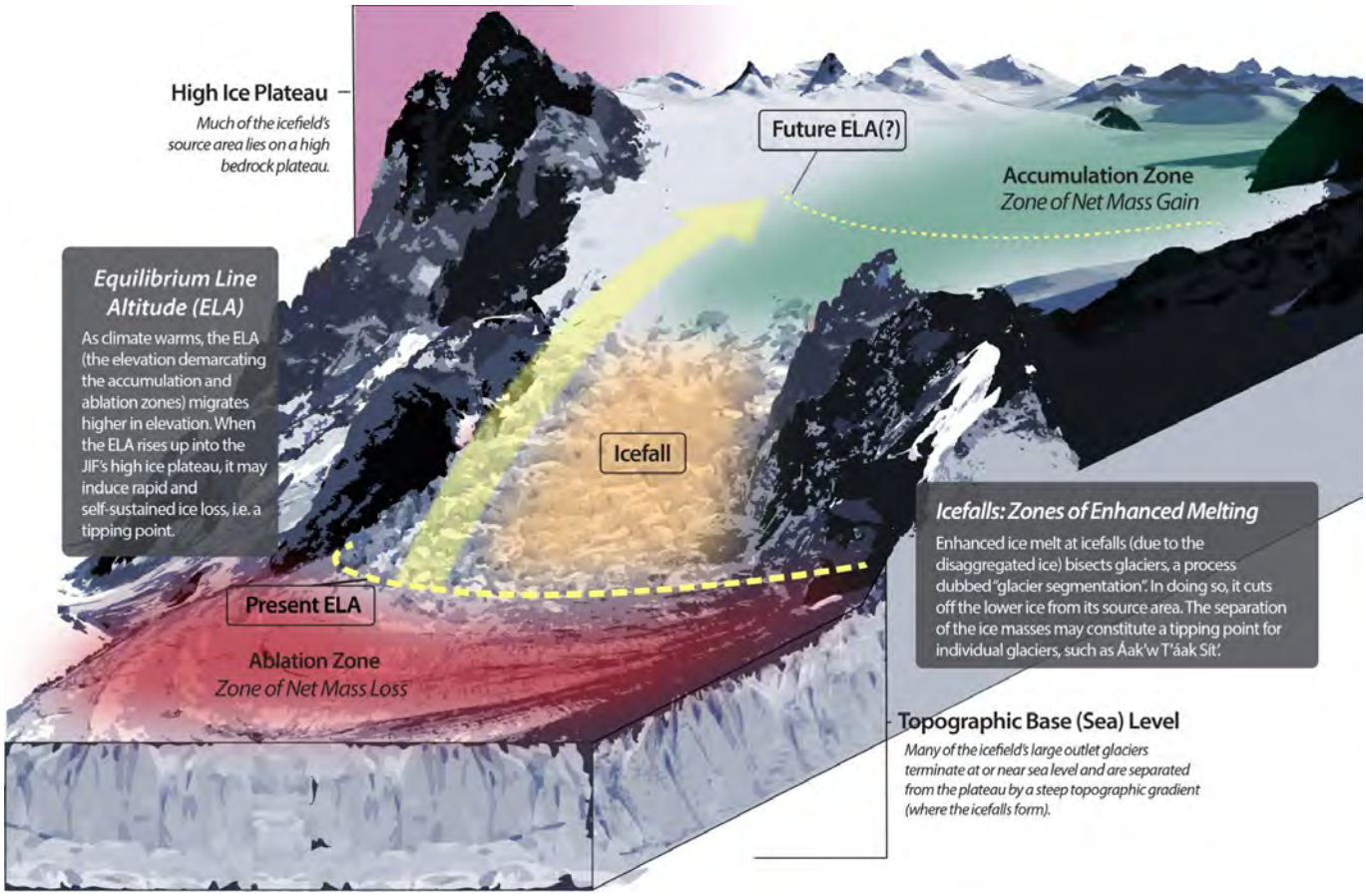


Figure 2. Theoretical overview of proposed tipping mechanisms for Juneau Icefield outlet glaciers.

3. Socio-biophysical connections and impacts

Glaciers are deeply interwoven into southeast Alaska's physical and human geographies, often linking or lying at the interface between terrestrial, marine, and human ecosystems (Bidlack et al., 2021; O'Neel et al., 2015; Ord, 2024; Figure 4). With the exception of a more rapid rate of ice volume loss, the impacts specific to the tipping of mountain glaciers might be difficult to differentiate from that of broader and longer-term deglaciation and glacier loss. Where possible below, the consequences and impacts specific to tipping and (rapid) rates of ice loss are highlighted.

The human-earth system

Tlingit communities have lived in and stewarded the coastal rainforests and waters of southeast Alaska and southwest Canada for at least the last 10,000 years (Cruikshank, 2005; Lindo et al. 2017); Dauenhauer and Dauenhauer, 1987). Tlingit knowledge of the lands, waters, and animals have been passed down over millennia, shaping culture, sense of place and identity, and sustainable management practices. As landscapes change,

Tlingit communities have expressed a deep sense of grief and loss, describing their culture and identity as being inseparable from the land (Cruikshank, 2005; Thornton, 2008; Ord, 2024).

Tlingit knowledge portrays glaciers, like Áak'w T'áak Sít,' as gendered, sentient beings, "willful and sometimes capricious." Tlingit teachings taught respect and gratitude towards glacier spirits (Figure 3), which helped to secure safe travel and passage. In response to acts of disrespect, glaciers were known to respond with devastating consequences, such as by overrunning villages (Crowell, 2024; Cruikshank, 2005; Dauenhauer and Dauenhauer, 1987; Nyman & Leer, 1993; Hebda et al. 2017). This is illustrated in oral histories of Glacier Bay, northwest of Juneau, in which a young woman violates social taboos by communicating with a glacier during her seclusion, calling it to advance which eventually leads to the destruction of her village:



Figure 3. Tlingit formline drawing by Maka Monture depicting the spirit of Sít' Tlein / Hubbard Glacier, a living guardian of Yakutat. In Tlingit cultures, glaciers are not only ice, but ancient beings whose breath shapes the land and whose presence protects the Tlingit people. Through this piece, Monture seeks to share their strength, memory, and enduring spirit.

Gathéeni,
the bay where the glacier was.
It was where people lived.
Salmon of all kinds ran there.
That's why the people lived there;
they made it a village.
Many kinds of salmon are there.
Good salmon ran there."
[...]
Through the mountains there
you could see the glacier waaaaaay up the bay;
it was only a tiny piece.
It was hanging there up the bay.
It couldn't be seen much from the river;
it could only
be seen from way out.
But she knew the glacier was there.
That is why she called the glacier
like a dog,
"Glacier,
here,
here." **(James, 1987)**

This and the many other oral histories from the southeast Alaska region demonstrate the dynamic relationships and exchanges that occurred (and continue to occur) between Tlingit communities and glaciers. Glaciers served as pathways for travel and trade, embodied sentience, and engaged in dialogue with Tlingit people, acting as a driver of change in social, marine and terrestrial landscapes (Cruikshank, 2005; Dauenhauer and Dauenhauer, 1987; Nyman & Leer, 1993; Gray, 2022). To understand how the loss of glaciers will impact downstream human and non-human communities, it is essential to recognize the dynamic and multifaceted relationships that continue to this day.

Describing the relationship between her Tlingit community and Hubbard Glacier on the Alaska-Yukon border, Tlingit anthropologist Judith Daxoots̲ú Ramos has described the loss of glaciers in her homeland as "very traumatic", as they are deep relationships that stretch back for generations, shaping cultural identity and harvest practices (Ord, 2024). Rapid deglaciation further disrupts the relationship between Indigenous communities and their connection to glaciers and glacial landscapes, depriving future generations of this component of their identity and history. With respect to Áak'w T'áak Sít', members of the Juneau community (including non-Indigenous persons) maintain a strong connection to the experiences and memories attached to the glacier, valuing its proximity to the city, the educational and recreational opportunities its presence affords, as well as the intangible connections across generations of Juneauites (Bruns and Andersen, 2023; Ord, 2024).

Local hydrology and water security

Freshwater discharge and hydrology

Rapid deglaciation of Áak'w T'áak Sít' stands to dramatically alter the hydrography and microclimates of the Wooch Eel'óox̲'u Héen (Mendenhall River) and downstream environments. Áak'w T'áak Sít' contributes up to half of Wooch Eel'óox̲'u Héen's discharge and, like other mountain glaciers, acts to stabilise discharge throughout the melt season by buffering the low-flow, late summer period when contributions from snowmelt decrease (Motyka et al., 2002; Neal et al., 2002). Glacier melt furthermore buffers interannual variability in regional precipitation, with runoff in warmer, dryer years augmented by enhanced glacial melt (Motyka et al., 2002). Increased melting in the short term will increase annual discharge until around 2080 (Shanley and Albert, 2009), followed by a decrease in annual discharge as the glacier's volume decreases, though these projections do not include rapid ice loss due to potential tipping.

As temperatures rise and glaciers surpass peak discharge, reduced snowpack volume will lead to reduced summer discharge. Reductions in total glacier cover will increase the available landscape for evapotranspiration and plant cover, further reducing total runoff (O'Neel et al., 2015). Greater variability in the timing and volume of freshwater delivered to coastal waters, especially during the winter, will likely affect the dominant circulation pattern in nearshore waters, influencing the transport and delivering of materials and nutrients to offshore ecosystems potentially impacting local food webs (Hood and Scott, 2008; O'Neel et al., 2015; Spencer et al., 2014).

Water quality stressors

Water quality and supply in glacially-dominated and influenced watersheds are intimately linked. More rapid deglaciation following the transgression of a tipping point may impact not only the supply of water, but also it's suitability for consumption by communities and ecosystems.

Investigations of the Wooch Eel'óox̲'u Héen and a nearby watershed (Lemon Creek) have revealed that both glacial rivers carry high annual watershed yields (total exports) of particulate-bound mercury, believed to be sourced primarily from the erosion of local bedrock (Vermilyea et al., 2017; Nagorski et al., 2021). The high volume of entrained sediment leads to high mercury fluxes compared with clearwater streams, although filtered water concentrations are exceedingly low. Deglaciation will likely lead to less erosion of the Hg-bearing bedrock as well as continued sediment trapping in Sit'.áa (Mendenhall Lake) and other lakes that may form in place of the glacier (Nagorski et al., 2021). Peatlands are conducive to mercury methylation (i.e., the process by which relatively harmless inorganic mercury is converted into more a toxic form) in soils, but the Mendenhall area does not include these types of land covers, and so this is of low concern (Nagorski et al., 2014).

Other sources of toxic or potentially hazardous material have not been reported from Áak'w T'áak Sít', though studies from similar glaciers worldwide have shown that sediment ("cryoconite") on the glacier surface can concentrate heavy metals (Łokas et al., 2016), antibiotic resistant genes (Makowska et al., 2020), microplastics (Ambrosini et al., 2019; Zhang et al., 2021), and (occasionally extreme levels of) fallout radionuclides (Baccolo et al., 2020; Łokas et al., 2016; 2022; Owens et al., 2019).

While these contaminants generally pose low threats due to dilution by high rates of runoff discharge, their concentration in proglacial sediments following mobilisation can nevertheless pose hazards to human, plant, and animal health (Owens et al., 2019). High sediment loads in glacial rivers can likewise degrade overall water quality and pose management challenges. Deglaciation can elevate sediment supply to rivers as previously sub- and en-glacial sediments become exposed to subaerial remobilisation processes (Moore et al., 2009). The presence of proglacial lakes such as Sit'.áa modulates the impacts of increased sediment load (Hood and Berner, 2009; Milner et al. 2000), and may continue to do so for the Áak'w T'áak Sít', assuming the lake continues to serve as a sediment trap and does not fill with sediment.

Biological systems

Glacier ecosystems in southeast Alaska are vibrant ecological environments closely linked to downstream systems (e.g., O'Neel et al., 2015; Bidlack et al., 2021), and serve as an important source of bioavailable carbon for microorganisms in rivers and highly productive nearshore ecosystems that receive their runoff (Hood et al. 2009; Fellman et al. 2010). Reductions in total glacier inputs to downstream ecosystems including Áak'w T'áak Sít's are likely to result in predictable changes to dissolved organic matter (DOM) delivery, including a shift from ancient, highly bioavailable, aliphatic dominated DOM toward terrestrial-derived, modern DOM, though the extent to which this organic matter subsidizes downstream microbial food webs is unclear (Holt et al., 2023).

Salmon

Pacific salmon are a critical local resource, are culturally significant and are a key part of coastal food webs. Pacific salmon are affected by hydroclimatic factors at every stage of their lifecycle, beginning with egg incubation in freshwater habitats, during which water temperatures have the greatest effect on development rates (Quinn, 2005; Shanley and Albert, 2009).

As glaciers retreat, it is expected that new proglacial streams and rivers will be exposed that may be suitable for salmon spawning and rearing, while continued inputs of glacial melt will keep river and lake temperatures cool. In the medium- to long-term, however, the response of salmon to deglaciation and streamwater warming will impact species differently (Pitman et al., 2020). Temperature increases are likely to affect growth and survival of sockeye fry that rear in lakes such as Sit'.áa, with increasing temperatures leading to an increase in growth rates (and consequent metabolic requirements; Bryant, 2009). Nevertheless, McDonald et al. (1996) found that food resources (zooplankton) did not increase in Sit'.áa, and therefore they predict decreases in salmon populations. While on medium- to long-timescales, the reduction of (cold) glacier water may improve the conditions for salmon, as the cold Wooch Eel'óox̲'u Héen temperatures are below the ideal lower threshold for salmon (Fellman et al., 2013), the reduction in aquatic habitat heterogeneity (i.e., glacial versus non-glacial watersheds) may have negative consequences for salmon as different hydrological forcings produce variable food resource pulses and timings (Bellmore et al. 2022; Dunkle et al., 2024; Hood & Berner, 2009; Hood and Scott, 2008; Fellman et al., 2023). In short, continued glacial retreat could create environmental conditions more suitable for fish growth, but greater stochasticity in environmental conditions could increase year-to-year variability in fish populations.



Figure 4. Overview of impacts from glacier loss in the Juneau region of southeast Alaska.

Regional Hazards, Security, and Economies

Glacial lake outburst floods (GLOFs)

The climate change-driven retreat and disconnection of Suicide Glacier, a tributary of Áak'w T'áak Sít', and the subsequent damming of its meltwater by Áak'w T'áak Sít' have led to the annual release of lake outburst flood water since 2011. Already-large floods in 2018 and 2019 released ~3.0 × 107 m^3 of water from Suicide Basin, adjoining to Áak'w T'áak Sít' (Figure 4), with the lake level falling more than 50 m over the course of a few days (Kienholz et al., 2020). Floods in 2023, 2024, and 2025 set subsequent records for the volume of water released, with the August 2024 flood approaching 5.53 × 107 m^3 of water discharge (Thiem, 2024; Rosen, 2025). The then-record-breaking flood in August 2024 destroyed several and damaged nearly 300 homes, prompting state and federal disaster emergency declarations. Costs for mitigation efforts proposed by local and U.S. federal agencies have approached $8 million, with immediate costs for the installation of military-grade flood barriers expected to amount to $4 million, including a direct cost to homeowners estimated between $6000 and $8000 per property (Canny, 2024). These barriers, installed following the 2024 event, protected hundreds of homes during the record-breaking 2025 GLOF, though levee failures and constraints in installation areas led to the flooding of several dozen homes. In addition to the economic costs of intervention, the installation of these and other flood barriers will have additional consequences for riverbank stability (Pinto et al., 2018) as well as downstream ecosystems. Juneau-specific studies on the impact of barrier installation are underway (City and Borough of Juneau, 2024b).

Both the floods and the consequent installation of barriers may threaten already sensitive historical and cultural sites, such as the Montana Creek Fish Trap Site (Carrlee, 2006), connected to Tlingit communities. High 2025 floodwaters have prompted the need for additional bank stabilisation strategies and levee construction in forthcoming years (Solimon, 2025a) prior to a planned long-term solution (Solimon, 2025b). Local, state, and federal officials have begun property appraisals as part of an optional buyout program for those homes not protected by the levee–a project estimated to cost up to $20 million (Solimon 2025b).

GLOFs sourced from Áak'w T'áak Sít's adjoining Suicide Basin are very likely to continue into the next decades (Kienholz et al., 2020). The risk of future glacier lake outburst floods sourced from different basins and tributary glaciers adjacent Áak'w T'áak Sít' will depend on the deglaciation pattern and shape of the underlying glacier bed (Kienholz et al., 2020). A disconnection formed at the two icefall(s), however, could yield morphologic conditions suitable for outburst floods if the disconnected, downvalley ice is sufficiently thick to dam precipitation and melt from the upstream glacier. Furthermore, the retreat and separation of several tributary glaciers up-valley of Suicide Basin or the separation of Áak'w T'áak Sít''s two tributary trunks could lead to additional basins wherein the formation of ice-marginal lakes and possible consequent outburst flooding can occur. Over the long term, more rapid (tipping-induced) retreat or thinning of the main trunk of Áak'w T'áak Sít' could attenuate the risk of ice-dammed outburst floods earlier than incremental deglaciation, as retreat above Suicide Basin would prevent water from being damned in the first place.

Hillslope hazards

In populated regions, landslides, rockfalls, and glacier collapses pose major threats to human life, livelihoods, and infrastructure. In cold, glacial regions, rockfalls and landslides commonly occur as a result of both deglaciation and permafrost thaw. Disentangling the compound effects of deglaciation and mountain permafrost thaw for rockfall hazards is difficult, as both occur simultaneously and in response to the same external driving conditions (warming) (Dennis, 2025; Draebing et al., 2021; Ravanel et al., 2017). Landsliding due to deglaciation, where oversteepened valley sidewalls fail due to the loss of ice buttressing following retreat, will continue and expand as more bedrock is exposed. Landslides linked to permafrost thaw (wherein the loss of cohesion due to permafrost thaw leads to hillslope destabilisation) are more likely to occur at higher elevation regions of the icefield's interior, though they may still impact downstream communities if they intersect with glaciers or expanding proglacial lakes and/or rivers (e.g., Cook et al., 2018; Petley, 2025; Wells et al., 2025). Landslides on glaciers are common elsewhere in Alaska (e.g., Dunning et al., 2016; Smith et al., 2023), though a high-resolution hazard evaluation of the JIF region does not yet exist. Permafrost around Juneau is likely limited to high-elevation peaks such as those in the interior of the icefield (Jorgenson et al., 2008). Evaluating potential rockfall hazards will take on greater importance as Áak'w T'áak Sít' continues to deglaciate alongside the rest of the icefield. Hazard assessments should, and can only, occur as part of a long-term evaluation of the future evolution of the Mendenhall Valley and the broader JIF region.

Local and regional tourism

Juneau is a hotspot for Alaska's tourism industry. In 2023 alone, Juneau hosted over 1.65 million tourists (McKinley Research Group, 2023b), which represents approximately $375 million in spending (McKinley Research Group, 2023a). Twenty percent of Juneau households (total population is approximately 32,000) reported a member having been employed in the tourism industry in 2022. Nearly 700,000 tourists, one in three visitors to the state of Alaska, visit the easily-accessible Mendenhall Glacier Visitor Center each year (U.S. Forest Service, 2019), a site built to accommodate less than 500,000 visitors. Current estimates expect the glacier to recede from the view of the current visitor center (Figure 1) by 2050, prompting the U.S. Forest Service to explore new locations for glacier viewsheds in its latest masterplan (U.S. Forest Service, 2019). Managing the Áak'w T'áak Sít' and other glacier viewsheds is a key management issue for southeast Alaska, highlighted by the case of Begich, Boggs Visitor Center near Portage Glacier in southcentral Alaska, which consistently lost visitors following the loss of its glacier viewshed due to retreat around 1994 (O'Neel et al., 2015). Rapid retreat of Áak'w T'áak Sít' into increasingly difficult to access terrain could diminish the appeal of Juneau and the Mendenhall Glacier Visitor Center as a tourism destination. The USFS currently plans expansion of the Mendenhall Glacier Recreation Area to account for glacier retreat (U.S. Forest Service, 2019), though this has been met with mixed response by residents who frequently object to the impact on the local environment (Bruns and Anderson, 2023).

Commercial, sport, and subsistence fishing

The productive salmon streams of the Tongass National Forest in southeast Alaska make the Tongass the United States' top salmon-producing forest, yielding more wild salmon than all other U.S. National Forests combined (U.S.F.S. Alaska Region, 2015). In 2023, 3,604 persons were employed in the commercial fishing industry regionally, earning almost $225 million in labor income and $261 million in catch value, making up 8% of earnings and jobs in the region (Southeast Conference, 2023). In 2023, sport fishing harvests of salmon, a substantial portion of the food people put away in their freezers every year, were estimated at 43,625 salmon for the Juneau survey area (Alaska Department of Fish and Game, 2025), determined through voluntary participation in a statewide mail survey. Additional, reported, non-commercial personal use and subsistence harvests of salmon totaled 10,831 salmon in 2020 within the Juneau sub-region, for which 628 permits were fished (Brown et al., 2023). While these estimates provide an order of magnitude estimate of salmon catches, they likely do not represent the true values relied upon by local residents, and are instead rather a minimum estimate.

The region's glaciers, including the Juneau Icefield and Áak'w T'áak are an important component of these commercially productive southeast Alaskan coastal ecosystems (O'Neel et al., 2015). Assessments of the impacts of tipping-induced glacier loss, as well as that of glacier loss more broadly, on the commercial fishing industry at the catchment-scale are not available. The outlooks for salmon stocks in the region highlight that the complex response of individual salmon species will depend on numerous anthropogenic (e.g., hatchery release) and natural factors, some of which link to the retreat of glaciers, but many of which that do not (e.g., changing ocean conditions such as marine heat waves, ocean acidification, shifting food webs).

4. Governance considerations at the regional and local scale

Given the severity of potential and current impacts and potential irreversibility of Áak'w T'áak Sít' and JIF glacier loss on applicable (decadal to century) timescales (Ziemen et al., 2016; Ing et al., 2024), preventing the crossing of any potential tipping points should remain a high priority. Nearly all Áak'w T'áak Sít' mass loss is driven by changes in climate, with the timescales of glacier response ranging from decades to millennia (Roe and O'Neal, 2009), meaning immediate reductions in temperature may not lead to an immediate decrease in ice volume loss. Prevention governance efforts should therefore center on preventing global temperature rise by reducing carbon emission as quickly as possible to limit the consequent loss of glaciers, along with related essential habitats, species, and lifeways. As current tipping temperature thresholds for the JIF are not yet identified or constrained, decision-making with respect to mitigation and impacts governance must be undertaken under conditions of deep uncertainty. Modeling studies focused on mountain glaciers do indicate, however, that a global mean temperature exceeding 2.0 C of warming will likely result in significant and large-scale retreat, if not the total loss, of most mountain glaciers. Successfully limiting warming to within 1.5 C, however, could mean that many of these glaciers would likely survive (ICCI, 2024; Rounce et al., 2016; Ziemen et al., 2016; Zekollari et al., 2025).

Here, we discuss governance considerations regarding prevention and impacts at the regional and local scale, highlighting the critical need to integrate Indigenous voices in governance considerations at every level. For a thorough discussion of global-scale governance efforts towards reducing total global atmospheric CO_2 concentrations, we direct the reader to Section 4.1, the AMOC case study.

Preventing rapid glacier loss due to tipping

Limiting global warming to prevent glacial melt

Present-day glacier mass loss is driven primarily by global warming, itself a consequence of increasing atmospheric carbon dioxide concentration. The Paris Climate Agreement commits signatories to reducing emissions in line with global warming well below 2.0 C, with the intention of remaining at 1.5 C. While the United States initially joined as signatory of the agreement in 2016, it withdrew less than two years later, in 2017. In 2021 the United States rejoined, only to announce in 2025 its intention to withdraw again. Preserving glaciers requires consistent, sustained, and enforced international policy which commits signatories to reducing global greenhouse gas emissions (Huss, 2024; IPCC, 2022). In the absence of extensive modeling, it is difficult to estimate the absolute increase in temperature necessary forÁak'w T'áak Sít to reach a tipping point. Additional research is necessary to reduce uncertainty regarding when rapid ice loss, tipping behaviour, and irreversible ice loss may be triggered for the JIF (e.g., Davies et al., 2024; Ziemen et al., 2016), but these are understood to be likely long-term outcomes of the current warming path. Nevertheless, as every unit of warming corresponds to enhanced or additional melting irrespective of tipping, every effort should be made to limit increases in global atmospheric carbon dioxide concentrations (Hock et al., 2019; Rounce et al., 2023).

Local and regional stakeholders in Juneau are limited in their capacity to induce meaningful governance that prevents or slows global warming. Nearly all electrical power in Juneau is generated via zero-emissions hydropower. In response to climate change, the City and Borough of Juneau plan to expand the city's hydropower generation anticipating an expanded demand for commercial heat pump heating systems (Powell et al., 2022). Nevertheless, legal frameworks to protect glaciers and, importantly, to provide recourse for those affected by the failure to preserve them have been proposed for various local, sub-national, and national jurisdictions (Bütler, 2007; Cox, 2016). In Taijikistan, for example, the Law on the Protection of Glaciers defines their protection in light of the impacts of their loss on regional freshwater availability (Republic of Tajikistan, 2024). Similar laws could be introduced at the state or national level in Alaska and the United States. Glacier protection laws implemented for southeast Alaska and elsewhere should take care not to impede hazards mitigation and climate adaptation activities (e.g., Anacona et al., 2018). Governance strategies must include and learn from Indigenous knowledges (or ways of knowing), by expanding definitions of loss and damage to include non-biogeophysical evaluations, such as the loss of cultural heritage (e.g., La Rose vs. Her Majesty The Queen, 2020) and constructing legal frameworks that both reflect the depth and severity of the risk for these communities. This means providing commensurate recourse in the absence of glacier loss prevention.

Interventions to minimise ice loss in the absence of reduced atmospheric greenhouse gas concentrations

Human-engineered ("geoengineering") interventions have, with respect to mountain glaciers, so far focused primarily on highly-localised efforts to increase glacier mass balance and prevent surface melt. Strategies primarily focus on surface albedo (surface reflectivity) modification and artificial precipitation. In the European Alps, ski resort operators and other stakeholders have locally deployed geotextiles on glaciers to increase surface albedo and reduce surface melt since the 1940s. These methods have proven effective across the area of deployment (typically at the 10s to 100s of meters scale; Huss et al., 2021; Fischer et al., 2016; Olefs and Fischer, 2008). This is in contrast to artificial precipitation, which yielded little mass balance gain in Alpine settings (Huss et al., 2021) and moderate gain in limited applications in the Altai (Wang et al., 2020). While effective locally, rigorous investigation of the effectiveness of geotextile emplacement in Switzerland has demonstrated management costs of up to 8 CHF (~10 USD) per cubic meter of ice preserved and up to 3 EUR per cubic meter in Italy and Austria (Huss et al., 2021). Annual ice loss from 2010 to present-day for the entire JIF has been estimated at 5.91 ± 0.80 × 109 m^3 (Davies et al., 2024). To preserve the total volume of present-day JIF ice loss using geotextiles, it would cost between roughly 23-58 billion USD (20-50 billion EUR) based on these price estimates.

Artificial albedo management and implementation are thus not viewed as long-term solutions to reducing glacier loss at the scales necessary to prevent widespread JIF or Áak'w T'áak Sít' tipping and/or deglaciation, and as the Juneau region is not presently water-stressed, interventions to preserve critical water resources are not immediately necessary. Recent investigations into the environmental impacts of geotextile emplacement have furthermore highlighted the environmental toll of geotextile-derived microplastics, which have been found at heightened levels in textile-bearing glaciers and can have negative consequences for aquatic ecosystems, including fish (Picece, 2021). Given the insurmountably high cost, limited feasibility and utility, and the likely negative environmental impacts for Juneau's aquatic ecosystems and resources, we do not find either geotextile or artificial precipitation to be feasible, responsible, or ethical means of interrupting widespread ice loss. The only known safe and effective solution to prevent extensive ice loss and preserve glaciers into the future is to limit future warming by reducing carbon emissions (Siegert et al., 2025; Huss, 2024). Money that might be spent on geo-engineering to preserve glaciers could accomplish more if applied to decarbonization efforts without sacrificing standards with regards to safety and justice. Nevertheless, should geoengineering interventions move forward in any capacity, robust governance mechanisms are needed to evaluate their feasibility and to monitor and regulate their testing and deployment. As Áak'w T'áak Sít' falls within the Tongass National Forest, governance around potential physical interventions would presumably fall under the U.S. Forest Service jurisdictional purview.

Impact governance

Indigenous cultural practices and community priorities

The impacts of both Áak'w T'áak Sít' and JIF deglaciation will be felt far beyond the confines of the icefield. Among those most affected are the Indigenous communities who have stewarded the land and ecosystems for millennia. To respond to climate change, Tribes in southeast Alaska have developed widespread adaptation plans for implementation at the federated tribal and sub-tribal scale. In southeast Alaska, including the Juneau Icefield region, the Council of Tlingit and Haida Indian Tribes of Alaska developed a Climate Change Action Plan to anticipate the socioeconomic impacts of climate change (Central Council of the Tlingit & Haida Indian Tribes of Alaska, 2021). The report authors highlight the threat posed to Indigenous cultures and practices, including traditional subsistence practices, rising temperatures and threats to aquatic ecosystems, and threats from extreme weather events. While deglaciation is not specifically addressed, the threats to salmon resources due to environmental change are highlighted as having an irreplaceable social cost as well as priceless economic cost. Adaptation strategies for a range of community priorities, including subsistence activities, traditional practices, sacred sites and practices, water supply, water quality, and health are outlined (Central Council of the Tlingit & Haida Indian Tribes of Alaska, 2021).

The Central Council of the Tlingit and Haida Indian Tribes of Alaska have furthermore entered into a formal arrangement with the U.S. Department of Agriculture and the U.S. Forest Service (USFS) to serve as co-stewards of the Mendenhall Glacier Recreation Area, over which the USFS has historically claimed jurisdiction. The aim of this arrangement is to formalise efforts to preserve and protect historic and cultural resources in the region, and to support Indigenous governance of their traditional territory (Central Council of the Tlingit & Haida Indian Tribes of Alaska, 2023). Following U.S. Federal funding cuts in 2025, budget allocations from the Juneau Assembly will provide funding for additional staff within the cultural ambassadors program, underscoring the resilience of local means of governance in the absence of state- or national-level support for responding to climate change's impacts (Krumrey, 2025).

Glacial lake outburst floods

Effective governance in Juneau with respect to glacial lake outburst floods (GLOFS) requires both long-term capacity building as well as shorter-term mitigation and adaptation. Current efforts are the result of a multi-layered, co-managed approach involving a range of actors, from the local city-borough government to U.S. Federal agencies, highlighting the centrality of national (federal) agency resources in local capacity building. The contributions of the various governance actors for GLOFs and other impacts of glacial retreat are summarised in Table 1.

Engagement from the national (U.S. Federal) government and agencies

The U.S. Army Corps of Engineers, in cooperation with the U.S. Geological Survey have funded studies to develop long-term GLOF mitigation strategies to be implemented in collaboration with the U.S. Forest Service who manage the Tongass National Forest and Mendenhall Glacier Recreation Area (City and Borough of Juneau, 2025b). The U.S. Geological Survey and the affiliated Alaska Climate Adaptation Science Center, in collaboration with partners at the University of Alaska Southeast and the National Weather Service, monitor flood risk through a network of stream gauges and time-lapse cameras (U.S. Geological Survey, 2021; Garrett, 2024). The Juneau Glacial Flood Dashboard (see: juneauflood.com, 2025) provides an important hub for this information, serving as a platform for the public to engage with real-time monitoring efforts, interactive flood maps, active warnings and alerts from the National Weather Service, resources for flood preparedness and response, and historic data. The tool is the product of extensive collaboration between local scientists, agencies, and community partners and aims to increase education and flood preparedness (Garrett, 2025). All efforts have been advocated for by the Central Council of the Tlingit and Haida Indian Tribes of Alaska, whose backing helped secure federal emergency declaration status and funding (City and Borough of Juneau, 2024a). The U.S. Department of Agriculture's Natural Resources Conservation Service (NRCS) administers the Emergency Watershed Protection Program (EWP) to assist project sponsors in protecting lives and property from flooding or soil erosion after a natural disaster and is exploring property buyouts for qualifying homes, with costs supported by local government partners (Soliman, 2025b).

State of Alaska and local government response to GLOFs

In the event of a GLOF, the burden of the response falls to local governments with the support of state and federal coordinating agencies. The City and Borough of Juneau issue emergency notifications, deploy flood barriers and coordinate response strategies, including post-flood debris and hazardous waste collection (Garret, J., 2024; KTOO News Department, 2024). The Council of the Tlingit and Haida Indian Tribes of Alaska provide emergency shelter to tribal members displaced by the flooding, as well as conduct door-to-door wellness checks (Larson, 2024; Central Council of the Tlingit & Haida Indian Tribes of Alaska, 2025). Private non-profit organisations like the American Red Cross of Alaska and Juneau Community Foundation provide immediate emergency assistance for those affected by the flooding (KTOO News Department, 2024). The State of Alaska coordinates state and federal emergency funding including the distribution of Federal Emergency Management Agency (FEMA) and U.S. Department of Housing and Urban Development (HUD) grants (State of Alaska, 2025). For the 2024 flood, U.S. HUD relief expenditures amounted to $6.05 million. At least 30 FEMA support grants of $605,000 or more were issued to community members (Sabbatini, 2024).

Mineral, hydrological, and ecological resources

The Juneau region has a long history of industrial mineral resource extraction, beginning with the establishment of gold mining camps in the late 19th century. The city sits within the "Juneau gold belt," stretching from Juneau to Tracy Arm, within which copper, lead, zinc and gold have historically been mined (Stowell, 2006). Several mineral mines are currently active in the region, and the recent allocation of $7.5 million will allow for further investigation of Alaska's critical mineral potential, including around Juneau (Herbert, 2025).

Deglaciation will continue to expose new mineral resources well into the future. Tensions between actors promoting mineral resource development in the region and the emergence of new glacially-cooled salmon habitat in the region have already emerged (Moore et al., 2023). Governance around resource use will, necessarily, require coordination between partner groups and local communities, including the City and Borough of Juneau and Tribes, such as the Central Council of the Tlingit & Haida Indian Tribes of Alaska, who have a vested interest both in economic development and sustainable ecosystem stewardship. State and national actors may not always act in consideration of local priorities and instead, respond to economic pressures and national concerns, for example, around the procurement of critical mineral resources (e.g., Dame et al., 2023). Balancing activities which have historically resulted in degraded ecosystems, such as mining and commercial forestry, with more sustainable stewardship practices will require adaptive, flexible, and anticipatory governance and coordination across local, state, tribal, U.S. federal, and international governments and agencies, including native corporations. Recent efforts such as Sustainable Southeast's Community Forest Partnerships for salmon stream restoration highlight the early success of such anticipatory efforts (House, 2023).

It is important to highlight that, as glacier retreat is expected to proceed even (a) absent tipping behavior and (b) in the event of global warming mitigation (e.g., Ziemen et al., 2016), anticipatory governance demands early consideration of these concerns, particularly with respect to industries reliant on healthy ecosystems, like commercial fishing (Moore et al., 2023).

Transnational access and national security concerns

While Áak'w T'áak Sít' falls entirely within the confines of the State of Alaska, the broader Juneau Icefield straddles the U.S.-Canada border. Continued deglaciation thus stands to alter the accessibility of the border and border regions, as well as the distribution and access to freshwater and mineral resources in the region. Though the location of the U.S.-Canada border was subject to arbitration in 1903 (Great Britain–United States Alaska Boundary Tribunal, 1903), because it has been defined using a system of boundary peaks and fjords rather than watersheds (as in other glaciated regions), the location of national boundaries is unlikely to change despite the consequences of deglaciation. Managing and mitigating the consequences of resource development from mining in transboundary river systems is an ongoing concern in the region, including in the Taku River watershed which is fed by the Juneau Icefield and flows from BC into Southeast Alaska and has a number of proposed and historic mining sites, including acid leaching from the abandoned Tulsequah Chief Mine (Moore et al., 2023).

Geo-engineering ice preservation strategies for the JIF would likewise require international negotiation and cooperation between the United States and Canada, as it is not possible to intentionally manipulate the icefield in such a way as to only impact the portion of the icefield that falls within one country's borders. Any effort to manipulate one side of the icefield in isolation could have dramatic consequences for ice dynamics across the full icefield-glacier system, with likely non-local impacts to surface mass balance and runoff potentially leading to disruption or redistribution of the meltwater-fed river systems. An intervention in one country could therefore lead to a change in GLOF behavior or negatively impact ecosystem functioning in the other, as examples. If the geo-engineering intervention were to involve the introduction of potentially hazardous materials into the ecosystem, the environmental impacts of that hazard are very unlikely to be contained within existing geopolitical borders, further heightening the risk of these strategies. Anticipating and governing eventualities, and drawing on existing resources, frameworks, and agreements such as the Convention on the Law of the Non-Navigational Uses of International Watercourses (within which glaciers may be included, e.g., Quilleré-Majzou & Majzoub 2010) and the International Joint Commission established by the Boundary Waters Treaty of 1909 between US and Canada (Sergeant et al., 2022), will become increasingly necessary as deglaciation proceeds irrespective of tipping.

Table 1. Summary of agency and stakeholder roles regarding glacial lake outburst floods; mineral, hydrological, and ecosystem resources; and national security in the Juneau Icefield region of southeast Alaska (USA).

Stakeholder / Agency	Agency Type	GLOF Response and Management Role	Mineral Resources Management Role	Hydrological and Ecological Resources Management Role	Border and Transnational Access Management Role	Key Interests
City and Borough of Juneau (CBJ)	Local Government	Emergency response, zoning regulations, and infrastructure repair	Local permitting/ zoning reviews	Local watershed and infrastructure management		Protect residents and infrastructure; promote tourism and local economic activities, including commercial fishing and other natural resources
Central Council of the Tlingit & Haida Indian Tribes of Alaska	Tribal Government	Engages in long-term planning, tribal consultation to assess and mitigate impacts on indigenous communities	Consulting on mine permitting and land use	Provides and consults on ecosystem stewardship	Advocates for cross-border Indigenous mobility and consultation	Protect tribal lands, natural and ecological resources and habitats; ensure tribal sovereignty; preserve indigenous cultures, knowledge and traditions; protect cross-border mobility
Alaska Division of Homeland Security and Emergency Management (DHSEM)	State Agency	Coordinates disaster declarations and FEMA aid		Works with DEC and FEMA on hazard mitigation	Coordinates with DHS for disaster-related security concerns	Minimize hazard exposure and ensure interagency response readiness
Alaska Department of Natural Resources (DNR)	State Agency		Primary regulator of mining claims and leases	Coordinates with DEC/ADF&G on land and water use		Economic development, efficient permitting, resource revenue
Alaska Department of Environmental Conservation (DEC)	State Agency	Monitors water quality during floods	Regulates pollution/ discharges from mining	Oversees water quality and hydrologic permitting		Maintain clean water, enforce state/federal environmental standards
Alaska Department of Fish and Game (ADF&G)	State Agency		Provides ecological input for mine permits	Manages salmon and aquatic ecosystems as well as state-owned hatcheries		Ensure biodiversity, regulate and maintain salmon fisheries; protect ecosystem health
Alaska Department of Transportation & Public Facilities (DOT&PF)	State Agency	Repairs roads and bridges after floods	Approves mining-related infrastructure	Manages flood-prone transport corridors		Maintain infrastructure integrity and access
Federal Emergency Management Agency (FEMA)	Federal Agency	Provides federal disaster aid and flood mapping		Supports floodplain management and resilience with USACE	Coordinates with border security if floods alter access routes	Disaster response, risk reduction, cost containment
U.S. Forest Service (USFS)	Federal Agency	Studies and implements flood mitigation with CBJ in Mendenhall Glacier Recreation Area	Manages mining access on National Forest lands	Oversees watershed and forest health		Balance public land use, conservation, recreation, and resources
U.S. Fish and Wildlife (FWS)	Federal Agency		Consults on permitting for activities which may impact wetlands and streams in accordance with the Clean Water Act	Collaborates with USFS on wildlife and aquatic habitat conservation within and around Tongass National Forest	Partners with DHS to prevent invasive species from entering the U.S.	Habitat conservation and management and the protection of endangered or threatened species; management of subsistence harvests; monitor ecological systems in collaboration with local, state, Tribal, and federal agencies
U.S. Bureau of Land Management (BLM)	Federal Agency		Manages federal mineral leases and exploration	Balances mining and ecological values under FLPMA		Balance land use with respect to resource exploitation, conservation, and public use and recreation
U.S. Army Corps of Engineers (USACE)	Federal Agency	Co-leads engineering studies for GLOF resilience	Permits wetland/ dredge impacts under Clean Water Act	Hydrological and slope stability modeling		Mitigate flood risk and damage; ensure navigable waters; protect infrastructure resilience

Stakeholder / Agency	Agency Type	GLOF Response and Management Role	Mineral Resources Management Role	Hydrological and Ecological Resources Management Role	Border and Transnational Access Management Role	Key Interests
U.S. Geological Survey (USGS)	Federal Science Agency	Monitors glacial change and watershed conditions as well as flood hazard tracking	Maps mineral potential and geological deposits;	Climate-hydrology monitoring and terrain stability analysis;	Supplies mapping to inform border infrastructure planning	Scientific accuracy; data collection to inform policy decisions
National Weather Service (NWS)	Federal Science Agency	Real-time weather forecasts prior to and during GLOF events				Facilitate public safety through accurate weather and hazard forecasting
National Oceanic and Atmospheric Administration (NOAA)	Federal Science Agency	Supports climate and hydrologic data collection as well as climate, glacial, and atmospheric modeling		Supports watershed and habitat analysis with monitoring data		Advance climate resilience and coastal resource protection
U.S. Customs and Border Protection (CBP)	Federal Agency				Responsible for monitoring new access routes across Canada-U.S. boundary due to glacier retreat; patrols remote terrain	Manage border access and control and monitor new transboundary threats
U.S. Department of Homeland Security (DHS)	Federal Cabinet Department	Supports FEMA in disaster coordination		National coordination on flood-related security	Oversees CBP and FEMA; monitors transnational risks from newly accessible terrain	National security, disaster resilience, international coordination
Environmental NGOs (e.g., Southeast Alaska Watershed Coalitionl)	NGO	Advocate for GLOF mitigation and impacts management	Oppose high-risk mining near glacial watersheds	Promote ecosystem protection and climate resilience		Promote and enhance environmental integrity, public participation, climate justice
Mining Companies	Private Sector		Stake claims, explore and develop mineral deposits	Subject to hydrological and ecological regulations	May seek access to cross-border geological resources as glaciers retreat	Access to critical minerals, investor returns
Local Tourism Operators & Commercial Fishers	Public Stakeholders	Depend on salmon runs and ecotourism, including access to key tourist sites like Mendenhall Glacier Recration Area		Depend on salmon runs and ecotourism		Ensure high water quality standards, sustainable ecosystem management, and promote long-term economic stability
University of Alaska - Southeast (UAS) / University of Alaska - Fairbanks (UAF) / Alaska Climate Adaptation Science Center (AK CASC)	Public Universities and Affiliated Institutes	Flood risk modeling; geoscientific and glaciological research	Assess mineral and terrain potential, as well as associated risks	Study watershed, permafrost, and glacial changes due to climate change	Provide spatial data for cross-border hazard and resource assessments; Investigate geopolitical and economic consequences of increased border access	Provide independent investigations for informed decision making and to support evidence-based policy

Appendix 1: Glossary

Term	Definition
Abruptness	A change in a system that is faster than the factors forcing it.
Agency	The capacity of an agent (human or non-human) to act in a given environment.
Agent	A person, organisation or organism that takes an active role in a system.
Anomie	A state of a society or community characterised by a breakdown of social norms, social ties and social reality, resulting in social disorder and disorientation, mental health deterioration, increased suicide rates, and/or increased deviant behaviour.
Attractor	A state or set of states towards which a system tends to evolve for a wide range of initial conditions (or perturbations away from the attractor).
Bi-stability	Property of some systems whereby they exhibit two stable states or attractors under the same external conditions. This is a special case of multi-stability.
Bifurcation point	Where a system moves from one stable state/attractor to a different one under a small change in boundary conditions (where a small change in a parameter in a differential equation leads to a qualitative change in the long-time solution).
Bifurcation tipping	Where a small change in forcing causes a multi-stable system to undergo a catastrophic bifurcation and move into a qualitatively different state/attractor.
Cascade effect	A causal chain whereby a small change in a system triggers a further change in another system and so on, resulting in a large overall change across systems. Synonymous with chain reaction and domino effect. (Sharpe, 2023).
Catastrophic bifurcation	Where a system moves discontinuously from one stable state/attractor to another at the crossing of a bifurcation point.
Climate	The mean state of the weather, typically averaged over 30 years.
Climate colonialism	The deepening or expanding of domination of less powerful countries and peoples through initiatives that intensify foreign exploitation of poorer nations' resources or undermine the sovereignty of native and Indigenous communities in the course of responding to the climate crisis.
Climate system	The parts of the Earth system that govern the climate at the surface of the Earth.
Complex system	A system consisting of a large number of interconnected components that interact with each other, making its behaviour difficult to predict.
Complex adaptive system	A complex system that has the ability to change in response to changing (internal or external) conditions in a way that maintains or enhances its function.
Contagion	The spread of a particular phenomenon or behaviour through a population or network of agents. In simple contagion, the phenomenon/behaviour is assumed to spread on contact with a single agent, as in disease epidemiology; in complex contagion, spreading requires multiple contacts with multiple agents (Centola, 2018).
Counterfactual	A statement or proposition that expresses what might have happened if something that did not actually happen had occurred. It is a way of describing a hypothetical situation that contradicts what actually happened in the past or what is happening in the present.
Critical mass	A type of tipping point in a social system where one more person adopting a behaviour or technology causes everybody else to adopt.
Critical slowing down	A phenomenon in which the rate (speed) at which a system recovers from small disturbances slows down before a tipping point. This characteristic is exploited to create early indicators of tipping (~see Early indicator).
Critical transition	An abrupt shift in a system that occurs at a specific (critical) threshold in external conditions.
Demand-side solution	Solutions that reduce GHG emissions and other harmful stressors by changing consumption habits, norms and lifestyles; as opposed to supply-side solutions that focus on technologies.
Diffusion of innovation	The process whereby new ideas, products or services spread through social systems over time, often following a non-linear, S-shaped trajectory (Rogers, 1962).
Early indicator/ Early warning signal/ Early opportunity indicator	A statistical indicator that a system is moving towards a tipping point, usually due to critical slowing down. This is termed an early warning signal prior to an undesirable tipping point (usually in a biophysical system) and an early opportunity indicator prior to a desirable, positive tipping point, signalling an opportunity to intervene to trigger it.
Earth system	The complex system at the surface of the planet Earth, comprising the atmosphere, hydrosphere (including oceans and freshwaters), cryosphere (including ice sheets), biosphere (living organisms), and lithosphere (land, soils, sediments, and parts of the Earth's crust).
Earth system tipping point	Tipping point in the Earth system.
Ecological tipping point	Tipping point in a population, community or ecosystem.
Ecosystem	An ecological system consisting of living organisms coupled to their physical and chemical environment.

Term	Definition
Emergent property	Property of a complex system that cannot be reduced to the properties of its component parts because it also depends on their interactions.
Enabling conditions	System conditions (for example price, or population size) that can allow a positive tipping point to be triggered.
Feedback (mechanism or loop)	A closed-loop of causality within a system whereby an initial change feeds back to amplify or dampen that change. Feedbacks can be mathematically positive or negative.
Green sacrifice zones	Ecologies, places and populations that will be severely affected by the sourcing, transportation, installation and operation of solutions for powering low-carbon transitions, as well as end-of-life treatment of related material waste.
Human systems	Complex, often adaptive, systems created by humans. They are embedded in, and interact with, the Earth system. Human systems can be divided into domains such as socio-behavioural, technological, political and economic. Human and Earth systems are often defined together as coupled systems (e.g. social-ecological-technological) to emphasise their interconnection. Also called social systems.
Hysteresis	The dependence of a system's current state on its history, such that, when forced in one direction, it may pass a tipping point from one stable state to another, but when the forcing is reversed it must be reduced further until a different tipping point is reached to return to the initial state.
Irreversibility	A change in a system that is not reversed under the same boundary conditions that triggered it, or that takes significantly longer to recover from than the time it took to reach.
Leverage point	A place to intervene in a system such that a small input can have a large beneficial effect (Meadows, 1999).
Multi-stability	Property of some systems whereby they exhibit multiple stable states or attractors under the same boundary conditions.
Negative/damping /balancing feedback	Feedback that dampens/counteracts an initial change.
Negative tipping point	A tipping point that is predominantly detrimental to humans and the natural systems we rely on.
Negative social tipping point	A negative tipping point in a human (social) system that leads, for example, to a financial collapse, political radicalisation or conflict.
Noise	Stochastic variability that a system is subject to.
Noise-induced tipping	Where a multi-stable system is tipped out of its present state (or attractor) into an alternative state (or attractor) by a perturbation.
Non-linearity	Any situation where a change in output is not proportional to a change in input.
Path dependence	Any situation where past events constrain future events.
Percolation	Phenomenon that occurs when adding or activating nodes or links in a network, whereby the network abruptly becomes globally connected, allowing change to spread throughout (whereas before, change was locally contained).
Positive/amplifying /reinforcing feedback	Feedback that amplifies/reinforces an initial change.
Positive tipping point	A predominantly beneficial tipping point. Specifically, one that accelerates change which a) reduces the likelihood of negative Earth system tipping points, and/or b) increases the likelihood of achieving just social foundations, both of which are needed to secure a sustainable future for all (Rockström et al., 2023; Gupta et al., 2023; Raworth, 2017). Sometimes referred to as a 'social tipping point'.
Qualitative change	Change in the qualities of a system, which can mean the appearance or disappearance of important features and change in the balance of feedback. Sometimes quantifiable as change that is (much) larger than the standard deviation of a system's normal variability. Where non-quantifiable, a qualitative change is a judgement based on ontological, epistemological and normative subjectivity (Tàbara et al., 2021; Milkoreit et al., 2018; Lenton el., 2008).
Rate-induced tipping	When the rate of forcing of a system is faster than the force that restores it to steady state, causing it to leave that state/attractor and undergo a qualitative (irreversible or reversible) change.
Regime shift	A shift in a system state from one stable state to another. Regime shifts are often large, sudden and long-lasting (Biggs, 2009). Where used in this report, we define on a case-by-case basis.
Resilience	The capacity of a system to resist (or deal with) change and continue to function in its present state. In quantitative analyses, resilience is often defined as the capacity of a system to return to a stable state/attractor after a perturbation, measured as its recovery rate from disturbance.
Self-perpetuation	Change in a system that continues even if forcing is removed until a new state is reached. Synonymous with self-sustained change.
Sensitive intervention point	A place to intervene to help trigger positive tipping points in human systems (Mealy et al., 2023). Similar to "Leverage point".
Social system	See "Human systems".
Social tipping intervention	An intervention leading to a small change in forcing that has a big, normatively 'positive' effect on a crucial human (social) system feature (Otto et al., 2020).

Term	Definition
Social tipping point	Tipping point in a human (social) system, which can have a predominantly beneficial (positive social tipping point) or harmful (negative social tipping point) effect (Winkelmann et al., 2022).
Social-ecological system	A coupled system including human (e.g. cities, land-uses, economies) and ecological (e.g. oceans, forests, soils) components.
Social-ecological tipping point	A tipping point that arises because of the coupling of the social and ecological components of a system.
Socio-behavioural system	A human system that encompasses social norms, behaviours and lifestyles, communities and their cultures, and institutions.
Socio-technical system	A system consisting of multiple elements of human systems including actors, organisations, technologies, markets, practices, infrastructures, policies and supply chains (Köhler et al., 2019).
Socio-technical tipping point	A tipping point that arises because of the coupling of the social and technological components of a system.
Social-ecological-technological system	A complex adaptive system composed of interacting social, ecological and technological components.
Social-ecological-technological tipping point	A tipping point that arises because of the coupling of the social, ecological and technological components of a system.
Stable state	A state that a system will return to for some range of initial conditions or perturbations away from that state. Stability is maintained by negative feedback loops that resist change.
Strategic intervention	A deliberate input into a system designed to have maximum impact by influencing the enabling conditions, reinforcing feedbacks and/or trigger for a positive tipping point.
Super-leverage point	A strategic intervention capable of catalysing tipping cascades across multiple systems (Meldrum et al., 2023).
Supply-side solution	Solutions that reduce greenhouse gas emissions and other harmful stressors with technological innovation; as opposed to demand-side solutions that focus on consumption habits, norms and lifestyles.
Sustainability	An aggregate measure of the Earth's biophysical capacities (planetary boundaries) and social foundations that ensure a minimum level of wellbeing for a given population, indefinitely.
System	A group of interacting or interrelated things that act according to a shared set of rules to form a recognisable, unified whole.
Threshold	The point or level at which a physical effect begins to be produced. A tipping point involves a threshold but thresholds are a much broader class of phenomena.
Tipping cascade	Where passing one tipping point triggers at least one other tipping point.
Tipping dynamics	The changes in a system over time that result from crossing a tipping point.
Tipping element	Originally introduced to describe large parts of the climate system (greater than ~1000km length scale) that could pass a tipping point (Lenton et al., 2008). Also used more broadly to describe a part or subsystem of a larger system that can pass a tipping point.
Tipping event	The crossing of a tipping point.
Tipping point	Occurs when change in part of a system becomes self-perpetuating beyond some threshold, leading to substantial, widespread, often abrupt and irreversible, impacts.
Tipping system	A system that can cross a tipping point.
Transformation	The process of rapid and fundamental change of social-ecological-technological systems needed for humanity to secure a sustainable future (Patterson et al., 2017).
Transition	A process of managed, often sector-specific, socio-technical change.
Trigger	A change that causes a system to pass a tipping point.

Appendix 2: Contributing Authors

Author		Affiliation	Funder acknowledgement
Carlo	Aall	Western Norway Research Institute, Norway	
Beniamino	Abis	Starion Group	
Jesse	Abrams	Global Systems Institute, University of Exeter, UK	
Yevgeny	Aksenov	National Oceanography Centre, Southampton, UK	Horizon Europe project EPOC, EU grant 101059547 and UKRI grant 10038003, EC Horizon Europe project OptimESM "Optimal High Resolution Earth System Models for Exploring Future Climate Changes", grant 101081193 and UKRI grant 10039429, and from the UK NERC projects LTS-M BIOPOLE (NE/W004933/1), CANARI (NE/W004984/1) and UK LTS-S Atlantic Climate & Environment Strategic Science – ATLANTIS and Interacting ice Sheet and Ocean Tipping - Indicators, Processes, Impacts and Challenges (ISOTIPIC) NE/Y503320/1. For the EU projects the work reflects only the authors' view; the European Commission and their executive agency are not responsible for any use that may be made of the information the work contains.
Floor	Alkemade	Eindhoven University of Technology	FA gratefully acknowledge support from the European Union (ERC, FAST, 101044076).
Hassan	Alkhayuon	School of Mathematical Sciences, University College Cork, Western Road, Cork, Ireland	
Lorenzo	Alvarez-Filip	Universidad Nacional Autónoma de México, Instituto de Ciencias del Mar y Limnologia. Puerto Morelos. Quintana Roo. Mexico	
Nadia	Ameli	Institute for Sustainable Resources, University College London, UK	
Beatriz	Arellano Nava	Global Systems Institute, University of Exeter, UK	Horizon project COMFORT (grant No. 820989) and ARIA AdvanTip Project (grant SCOP-PR01-P003).
Jesús Ernesto	Arias-González	Centro de Investigacion y Estudios Avanzados I.P.N.-Unidad Merida. Carr. Ant. Progreso Km. 6, A.P. 73 Cordemex, Merida, Yucatan, Mexico	
David I.	Armstrong McKay	Geography, School of Global Studies, University of Sussex, UK; Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden; Global Systems Institute, University of Exeter, UK	
Constantin	Arnscheidt	Centre for the Study of Existential Risk, University of Cambridge, UK	
Marius	Årthun	Geophysical Institute, University of Bergen, Norway	The Research Council of Norway (project "Overturning circulation in the new Arctic," grant 335255).
Peter	Ashwin	Department of Mathematics and Statistics, University of Exeter, UK	
Rune	Baastrup	Democracy X	
Emma	Bailey	Global Systems Institute, University of Exeter, UK	
Mike	Barrett	WWF-UK	
Bjørn	Bedsted	Democracy X	
Avit	Bhowmik	Risk and Environmental Studies, Karlstad University, Sweden	
Alina	Bill-Weilandt	Asian School of the Environment, Nanyang Technological University, Singapore; Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany	ABW was supported by the Ministry of Education, Singapore, under its NTU Singapore International Graduate Award.
Claudia R.	Binder	Laboratory on Human-Environment Relations in Urban Systems, École Polytechnique Fédérale de Lausanne, Switzerland	
Fenna	Blomsma	Faculty of Economics and Social Sciences, University of Hamburg, Germany	

Author		Affiliation	Funder acknowledgement
Nils	Bochow	Department of Mathematics and Statistics, Faculty of Science and Technology, UiT The Arctic University of Norway, Tromsø, Norway	
Amber	Boot	IMAU, Department of Physics, Utrecht University, Netherlands	ERC-AdG, TAOC (project 101055096).
Andreas	Born	Department of Earth Science, University of Bergen, Norway	
Chris A.	Boulton	Global Systems Institute, University of Exeter, UK	CAB acknowledges support from the UK Advanced Research and Innovation Agency (ARIA) via the AdvanTip project (grant SCOP-PR01-P003), and from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101137601 as part of the ClimTip project, of which this is ClimTip contribution #116.
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Tristan	Cann	University of Exeter, UK	
Tomas	Chaigneau	Environment and Sustainability Institute, University of Exeter, UK	
Ruth	Chapman	Physics of Ice, Climate and Earth, Niels Bohr Institute, University of Copenhagen, Denmark	
Hugues	Chenet	IESEG School of Management, Univversity of Lille, CNRS UMR 9221 - LEM, France	
Cristiano M.	Chiessi	School of Arts, Sciences and Humanities, University of São Paulo, Brazil	CC acknowledges the financial support from FAPESP (grant 2024/00949-5), CNPq (grant 305285/2025-4) and CAPES-COFECUB (grants 425 8881.712022/2022-1 and 49558SM).
Joseph	Clarke	Global Systems Institute, University of Exeter, UK	
Sara	Constantino	Doerr School of Sustainability, Stanford University, USA	
Christopher E.	Cornwall	School of Biological Sciences and Coastal People Southern Skies Centre of Research Excellence, Victoria University of Wellington, New Zealand	CEC was supported by funding from Coastal People Southern Skies Centre of Research Excellence.
Vasilis	Dakos	ISEM, Univ Montpellier, CNRS, IRD, Montpellier, France	
Bethan Joan	Davies	School of Geography, Politics and Sociology, Newcastle University, UK	Fieldwork to Juneau Icefield was supported by the Royal Geographical Society and the Geological Society.
Judith	Daxootsú Ramos	University of Alaska Southeast, Juneau, Alaska, USA	
Donovan P.	Dennis	Earth Resilience Science Unit, Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany and Max-Planck-Institute of Geoanthropology, Jena, Germany	
Frank	Dentener	European Commission, Joint Research Center, Italy	
Henk	Dijkstra	IMAU, Department of Physics, Utrecht University, Netherlands	ERC-AdG, TAOC (project: 101055096).
Jonathan F.	Donges	Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany; Department Integrative Earth System Science, Max Planck Institute of Geoanthropology, Jena, Germany; Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden	EU Horizon Europe project ClimTIP (Grant No. 100018693).
Sybren	Drijfhout	Royal Netherlands Meteorological Institute, Netherlands	

Author		Affiliation	Funder acknowledgement
Norman C.	Duke	Smithsonian Tropical Research Institute, Balboa, Panama; Centre for Tropical Water and Aquatic Ecosystem Research, James Cook University, Townsville, Australia	
Ida	Edling Müller	Faculty of Science, Stockholm Resilience Centre, Stockholm University, Sweden.	
Shivani	Ehrenfeucht	Earth Resilience Science Unit, Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany	
Sibel	Eker	International Institute of Applied Systems Analysis, Austria	
Grace	Ellsworth	Net Zero and Resilient Farming, Rothamsted Research, UK	
Jeremy C.	Ely	School of Geography and Planning, University of Sheffield, UK	
Matthew H.	England	Centre for Marine Science and Innovation (CMSI), and ARC Australian Centre for Excellence in Antarctic Science, University of New South Wales, Australia	MHE receives support from the Australian Research Council (Grants SR200100008, DP190100494 and DP250100759).
Bernardo M	Flores	EqualSeaLab, University of Santiago de Compostela, Santiago de Compostela, Spain; Instituto Juruá, Manaus, Brazil	
Morten	Friis	Democracy X	
Ajay	Gambhir	Accelerator for Systemic Risk Assessment (ASRA); Grantham Institute for Climate Change and the Environment, Imperial College London, UK	
Julius	Garbe	Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Germany	European Union's Horizon 2020 research and innovation programme under grant agreement no. 820575 (TiPACCs).
Ahjond	Garmestani	Utrecht Centre for Water, Oceans and Sustainability Law, Utrecht University, Netherlands	
Franziska	Gaupp	Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany; Ministry of Science and Culture of Lower Saxony, Germany	
Lauren	Gifford	Department of Ecosystem Science and Sustainability, Colorado State University, USA	
Kai	Greenlees	Global Systems Institute, University of Exeter, UK	
Kathryn	Gunn	School of Ocean and Earth Science, University of Southampton, UK	
Andrew	Hartley	Met Office, UK	
Maria Anna	Hecher	Laboratory on Human-Environment Relations in Urban Systems, École Polytechnique Fédérale de Lausanne, Switzerland	
Dag O.	Hessen	Center for Biogeochemistry in the Anthropocene, Dept. Biosciences, University of Oslo, Norway	
Marina	Hirota	Instituto Relva, Brazil; Federal University of Santa Catarina, Brazil	Serrapilheira Institute (grant number Serra-1709-18983).
Annika	Högner	International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria; Geography Department, Humboldt-Universität zu Berlin, Germany	
Milena	Holmgren	Department of Environmental Sciences, Wageningen University, Netherlands	
Courtney	Howard	Global Climate and Health Alliance	
Ben	Hudson	University of Exeter Law School, UK	
Chris	Huntingford	UK Centre for Ecology and Hydrology, Wallingford, Oxfordshire, UK	
Margot	Hurlbert	Johnson-Shoyama Graduate School of Public Policy, University of Regina, Canada	
Sirkku	Juhola	Helsinki Institute of Sustainability Science, Universty of Helsinki, Finland	
Andreas	Kääb	Department of Geosciences, University of Oslo, Norway	European Space Agency Glaciers_CCI, X-ECV, and EarthExplorer Harmony.

Author		Affiliation	Funder acknowledgement
Caroline	Katsman	Department of Civil Engineering, TU Delft, Netherlands	
Sonia	Kéfi	ISEM, Univ Montpellier, CNRS, IRD, Montpellier, France; Santa Fe Institute, USA	
Rakhyun	Kim	Copernicus Institute of Sustainable Development, Utrecht University, Netherlands	European Research Council (grant agreement no. 949252).
Björn	Kjerfve	Universidade Federal Fluminense, Departamento de Geoquímica, Niterói, RJ, CEP 24 210-5100, Brazil, and University of South Carolina, School of the Earth, Ocean, and Environment, Columbia, SC 29208, USA	
Steven	Lade	Fenner School of Environment and Society, The Australian National University, Australia	
Petra M.	Langebroek	NORCE Research AS, Bjerknes Centre for Climate Research, Bergen, Norway; iC3—Centre for Ice: Cryosphere, Carbon and Climate, Department of Geosciences, UiT The Arctic University, Norway	PL's work is part of the TiPACCs project, which receives funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 820575.
Laurie	Laybourn	Strategic Climate Risks Initiative, UK	
Timothy M.	Lenton	Global Systems Institute, University of Exeter, UK	Advanced Research and Invention Agency (ARIA); V. K. Rasmussen Foundation.
Johannes	Lohmann	Physics of Ice, Climate and Earth, Niels Bohr Institute, University of Copenhagen, Denmark	
Sina	Loriani	Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany; Max-Planck Institute of Geoanthropology, Jena, Germany	
Valerio	Lucarini	School of Computing and Mathematical Sciences, University of Leicester, UK	VL acknowledges financial support from the EU Horizon Europe projects ClimTIP (Grant No. 100018693) and Past2Future (Grant No. 101184070), and by ARIA SCOP-PR01-P003 - Advancing Tipping Point Early Warning AdvanTip.
Kerstin	Lux-Gottschalk	Centre for Analysis, Scientific Computing and Applications, Eindhoven University of Technology, Eindhoven, Netherlands	
Aaron	Marr Page	University of Iowa College of Law; Forum Nobis PLLC, USA	
Melanie	McField	Healthy Reefs for Healthy People, Mexico, Belize, Guatemala, Honduras, and the USA. Fort Lauderdale, FL 33312, USA	Summit Foundation, Mesoamerican Reef Fund, Global Fund for Coral Reefs, Oak Hill Foundation. BNP-PARIBAS with CORESCAM project.
Claire	Mellier	Iswe Foundation, UK	
Gabriele	Messori	Dept. of Earth Sciences, Uppsala University, Sweden; Swedish Centre for Impacts of Climate Extremes (climes), Uppsala University, Uppsala, Sweden	GM acknowledges funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101137601 (ClimTip).
Rasmus	Mikkelsen	Democracy X	
Manjana	Milkoreit	Department of Sociology and Human Geography, University of Oslo, Norway; Global Systems Institute, University of Exeter, UK	
Helen	Millman	Global Systems Institute, University of Exeter, UK	HM acknowledges support from the PREDICT project which has received funding from the European Space Agency (ESA) under ESA Contract No. 4000146344/24/I-LR.
Tessa	Möller	International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria; Geography Department, Humboldt-Universität zu Berlin, Germany	
Silvia	Montagnani	Economic, Social, Planning and Management Sciences, University of Lille, France	
Kyle	Morgan	Asian School of the Environment, Nanyang Technological University, Singapore; Earth Observatory of Singapore, Nanyang Technological University, Singapore	KM was supported by the National Research Foundation Singapore (NRF) under its NRF Fellowship scheme (Award NRF-NRFF14-2022-0004).
Karen	Morrow	School of Law, Swansea University, UK	

Author		Affiliation	Funder acknowledgement
Aarón Israel	Muñiz-Castillo	Healthy Reefs for Healthy People, Mexico, Belize, Guatemala, Honduras, and the USA. Fort Lauderdale, FL 33312, USA; Smithsonian Environmental Research Center, Edgewater, USA	Summit Foundation, Mesoamerican Reef Fund, Global Fund for Coral Reefs, Oak Hill Foundation. BNP-PARIBAS with CORESCAM project.
Leila	Niamir	International Institute for Applied Systems Analysis, Austria	
Lindsey	Nicholson	Department of Atmopsheric and Cryospheric Sciences, University of Innsbruck, Austria	Fieldwork to Juneau Icefield was supported by the Faculty of Geo and Atmospheric Sciences of the University of Innsbruck.
Femke	Nijsse	Global Systems Institute, University of Exeter, UK	
Jan	Nitzbon	Permafrost Research Section, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Germany	
Yuki	Numata	Rocky Mountain Institute, USA	
Annika	Ord	Alaska Climate Adaptation Science Center, University of Alaska Fairbanks and Sustainable Southeast Partnership, USA	
Ilona M.	Otto	Wegener Center for Climate and Global Change, University of Graz, Austria	
Isobel	Parry	Global Systems Institute, University of Exeter, UK	IP acknowledges support from the Quadrature Climate Foundation (grant reference number 01-21-000336).
Francesco	Pasimeni	Eindhoven University of Technology, Netherlands	FP gratefully acknowledge support from the European Union (ERC, FAST, 101044076).
Paul	Pearce-Kelly	Zoological Society of London, Regent's Park, London, UK	
Laura	Pereira	Global Change Institute, University of the Witwatersrand, Johannesburg, South Africa; Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden	
Benoît	Pichon	ISEM, Univ Montpellier, CNRS, IRD, Montpellier, France	
Patricia	Pinho	Amazon Enivironmental Research Institute - IPAM, Brazil	
Valentin	Portmann	EPOC, Université de Bordeaux, Pessac, France	
Tom	Powell	Global Systems Institute, University of Exeter, UK	
Marie-Aude	Pradal	Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, MD 21218, USA	
Courtney	Quinn	School of Natural Sciences, University of Tasmania, Hobart, Tasmania, Australia	
Paul	Ritchie	Global Systems Institute, University of Exeter, UK	
Malcolm	Rogge	Global Systems Institute; University of Exeter Law School, UK	
Rosa M	Roman-Cuesta	European Commission, Joint Research Centre, Ispra, Italy; School of Life Sciences,Technical University of Munich, Germany	Support is acknowledged to BNP Paribas foundation (2019-2022) and their research funding for CORESCAM, on the resilience of Caribbean coastal ecosystems under extreme climate events.
JB	Ruhl	Vanderbilt University Law School, Nashville, Tennessee, USA	
Stefanie	Rynders	National Oceanography Centre, Southampton, UK	Horizon Europe EPOC (grants 101059547 and 10038003) and OptimESM (grants 101081193 and 10039429), and from the UK Programmes BIOPOLE (NE/W004933/1), CANARI (NE/W004984/1), AtlantiS (NE/Y005589/1), and ISOTIPIC (NE/Y503320/1).
Boris	Sakschewski	Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany	BS is part of the Planetary Boundaries Science Lab's research effort at the Potsdam Institute of Climate Impact Research (PIK).
José A.	Sanabria-Fernández	Department of Ecology and Evolution, Doñana Biological Station (EBD-CSIC), Sevilla, Spain; College of Science and Engineering, James Cook University, Townsville, Queensland, Australia	

Author		Affiliation	Funder acknowledgement
Jürgen	Scheffran	Institute of Geography, University of Hamburg, Germany	JS acknowledges support in the CLICCS Excellence Cluster funded by the Deutsche Forschungsgemeinschaft (DFG).
Carl-Friedrich	Schleussner	International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria; Geography Department, Humboldt-Universität zu Berlin, Germany	
Jörg	Schwinger	NORCE Climate & Environment, Bjerknes Centre for Climate Research, Bergen, Norway	
Ashwin K	Seshadri	Indian Institute of Science, India	
Jana	Sillmann	Faculty of Mathematics, Informatics and Natural Sciences, University of Hamburg, Germany	
Sacha	Sinet	Department of Physics, Institute for Marine and Atmospheric Research Utrecht, Utrecht University, Utrecht, Netherlands	
Bablu	Sinha	National Oceanography Centre, Southampton, UK	Horizon Europe EPOC (grants 101059547 and 10038003) and OptimESM (grants 101081193 and 10039429), and from the UK Programmes BIOPOLE (NE/W004933/1), CANARI (NE/W004984/1), AtlantiS (NE/Y005589/1), and ISOTIPIC (NE/Y503320/1).
Steven R.	Smith	Global Systems Institute, University of Exeter, UK; World Economic Forum	
Niko	Soininen	University of Eastern Finland, Finland	
Melina	Soto	Healthy Reefs for Healthy People, Mexico, Belize, Guatemala, Honduras, and the USA. Fort Lauderdale, FL 33312, USA	Summit Foundation, Mesoamerican Reef Fund, Global Fund for Coral Reefs, Oak Hill Foundation. BNP-PARIBAS with CORESCAM project.
Viktoria	Spaiser	School of Politics and International Studies, University of Leeds, UK	UKRI (UK Research and Innovation), Grant Nr: MR/V021141/1.
Bryan M.	Spears	UK Centre for Ecology & Hydrology, UK	
Laurens	Speelman	Rocky Mountain Institute, USA	
Carla	Staver	Department of Ecology and Evolutionary Biology, Princeton University, USA	
Norman J.	Steinert	CICERO Center for International Climate Research, Norway; Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany	
Johnny	Stormonth-Darling	Iswe Foundation, UK	
Simone	Stuenzi	Geography Department, Humboldt-Universität zu Berlin, Germany; Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Potsdam, Germany	
Ivan	Sudakow	School of Mathematics and Statistics, The Open University, UK	IS acknowledges NSF Grant OPP-2438993.
Didier	Swingedouw	Environnements et Paléoenvironnements Océaniques et Continentaux (EPOC)—Université de Bordeaux, Pessac, France	Horizon Europe, TipESM (project: 101137673).
J. David	Tàbara	Autonomous University of Barcelona, Spain	
Thejna	Tharammal	Interdisciplinary Centre for Water Research (ICWaR), Indian Institute of Science, Bengaluru-560012, India	TT is supported by the DST-INSPIRE Faculty Fellowship awarded by the Department of Science and Technology, India and Anusandhan National Research Foundation (ANRF) Early Career Research Grant.
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Bregje	van der Bolt	Earth Systems & Global Change Group, Wageningen University & Research, Netherlands.	
Larissa	van der Laan	Physics of Ice, Climate and Earth, Niels Bohr Institute, University of Copenhagen, Denmark	

Author		Affiliation	Funder acknowledgement
René	van Westen	IMAU, Department of Physics, Utrecht University, Netherlands	ERC-AdG, TAOC (project: 101055096).
Sebastian	Villasante	Oportunius Researcher Professor, EqualSea Lab-CRETUS, University of Santiago de Compostela, Spain	SV gratefully acknowledges the financial support from EQUALSEA (Transformative adaptation towards ocean equity) project, under the European Horizon 2020 Program, ERC Consolidator (Grant Agreement # 101002784) funded by the European Research Council. SV also thanks the support of the Earth Commission and Future Earth.
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Tabitha	Watson	Global Systems Institute, University of Exeter, UK	
Claudia	Wieners	Institute for Marine and Atmospheric Research, Utrecht (IMAU), Utrecht University, Netherlands	CW's work is supported by the Dutch government via the Sectorplan Science and Technology programme.
Simon	Willcock	School of Environmental and Natural Sciences, Bangor University, UK; Net Zero and Resilient Farming, Rothamsted Research, UK	SW is funded by the Biotechnology and Biological Sciences Research Council (BBSRC) via workpackage two (BBS/E/RH/230004B) of the Resilient Farming Futures project (BB/X010961/1), and the Natural Environment Research Council (NERC) via RESTORE: Recovery pathways for lake ecosystems (NE/X014150/1).
Hywel	Williams	University of Exeter, UK	
Ricarda	Winkelmann	Max-Planck-Institute of Geoanthropology, Jena, Germany and Earth Resilience Science Unit, Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany	
Nico	Wunderling	"Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany; Center for Critical Computational Studies, Geothe University Frankfurt, Frankfurt am Main, Germany; Senckenberg Research Institute and Natural History Museum, Frankfurt am Main, Germany	NW acknowledges the Center for Critical Computational Studies at Goethe University Frankfurt am Main for providing funding for this research and acknowledges support from the KTS (Klaus Tschira Stiftung) under the project DETECT (ID 25545).
Hatty	Wylder-Hopkinson	Global Systems Institute, University of Exeter, UK	
Yulia	Yamineva	Center for Climate, Energy and Environmental Law, University of Eastern Finland, Finland	
Chris	Yesson	Zoological Society of London, Regent's Park, London, UK	CY is supported by Research England.
Danielle	Young	School of Politics and International Studies, University of Leeds, UK	
Kirsten	Zickfeld	Department of Geography, Simon Fraser University, Vancouver, British Columbia, Canada	

Appendix 3: Reviewers

Section 1 - Governance of Earth system tipping points	
Michele Betsill	Professor of Global Environmental Politics, University of Copenhagen, Netherlands
Maja Groff, Esq.	Convenor/Executive Director, Climate Governance Commission
Louis J. Kotzé	Chair of the Law Group and Professor of Law, Wageningen University and Research, Netherlands
Saara Leppänen	Finnish Meteorological Institute, Finland
Annalisa Savaresi	Professor of International Environmental Law, University of Eastern Finland, Finland and University of Sterling, UK
Jessica Seddon	Senior Lecturer, Yale Jackson School of Global Affairs, USA

Section 2 - Earth system tipping points and risks	
Robbin Bastiaansen	Assistant Professor, Mathematical Institute, Utrecht University, Netherlands
Sebastian Bathiany	Researcher at Earth System Modelling, School of Engineering and Design, Technical University of Munich, Munich, Germany; Potsdam Institute for Climate Impact Research, Potsdam, Germany
John Dearing	Emeritus Professor in Physical Geography, Geography and Environmental Science, University of Southampton, UK
Swinda Falkena	Researcher, Institute for Marine and Atmospheric Research, Utrecht University, Netherlands
Ed Gasson	Department of Earth and Environmental Science, University of Exeter, UK
Goran Georgievski	Scientist, Max Planck Institute for Meteorology, Hamburg, Germany
Kai Kornhuber	Senior Research Scholar, International Institute for Applied Systems Analysis, Austria
Nicole C. Laureanti	Postdoctoral Researcher, Potsdam Institute for Climate Impact Research, Germany
Tim Lenton	Professor of Climate Change and Earth System Science, Global Systems Institute, University of Exeter, UK
Carlos López-Martínez	Associate Professor at the Universitat Politècnica de Catalunya-BarcelonaTech, Spain
Catherine Lovelock	Professor, School of Environment, University of Queensland, Australie
Ben Marzeion	Professor, Institute of Geography, University of Bremen, Germany
David Obura	Director, Coastal Oceans Research and Development in the Indian Ocean East Africa, Mombasa, Kenya
Paul Pearce-Kelly	Senior Curator, Zoological Society of London, UK
Juan Rocha	Research Scientist, Stockholm Resilience Centre, Stockholm University, Sweden
Jonathan Rosser	Research Officer, London School of Economics, UK
René van Westen	Researcher, Institute for Marine and Atmospheric Research Utrecht, Utrecht University, Netherlands

Section 3 - Positive tipping points	
Martina Ayoub	Lecturer in Sustainability and Strategy, University of Edinburgh, UK
Claudia Binder	Professor of Human-Environment Relations in Urban Systems, École Polytechnique Fédérale de Lausanne, Switzerland
Iain Black	Professor of Practice Marketing, University of Strathclyde, UK
Fenna Blomsma	Professor of Circular Economy and Systemic Innovation, University of Hamburg, Germany
Kingsmill Bond	Director of Energy Strategy, Ember, UK
Sibel Eker	Senior Research Scholar, International Institute for Applied Systems Analysis, Austria
Lukas Fesenfeld	Senior Researcher and Lecturer, ETH Zurich, Switzerland
Kate Findlay	WWF-UK
Owen Gaffney	Chief Impact Officer, Nobel Prize Outreach, Co-Lead, Earth4All
Peter Lefort	Green Futures Network, University of Exeter, UK
Ilona Otto	Professor of Societal Impacts of Climate Change, University of Graz, Austria
Viktoria Spaiser	Professor of Climate Politics and Computational Social Science, University of Leeds, UK
Laurens Speelman	Principal, Strategy Team, Rocky Mountain Institute, USA
Caroline Zimm	Senior Research Scholar, International Institute for Applied Systems Analysis, Earth Commission, Austria

Section 4 - Case Studies	
The Amazon rainforest	
Richard Betts	Head of Climate Impacts Research in the Met Office Hadley Centre, UK; Chair in Climate Impacts at the University of Exeter, UK
Lana Blaschke	Potsdam Institute for Climate Impact Research, Potsdam, Germany

Atlantic Ocean circulation	
Wilbert Weijer	Los Alamos National Laboratory, Los Alamos, USA
Richard Wood	Met Office, UK
Warm-water coral reefs	
David O. Obura	CORDIO East Africa, Kenya
Chris T. Perry	Professor in Tropical Coastal Geoscience, University of Exeter, UK
Mountain glaciers: Áak'w T'áak Sít' (Mendenhall Glacier)	
Jeremy Fellman	University of Alaska Southeast, USA
Eran Hood	University of Alaska Southeast, USA
Sonia A. Nagorski	University of Alaska Southeast, USA
Allen Pope	U.S. National Science Foundation; Williams College, USA; Juneau Icefield Research Program
Helen Werner	Helmholtz-Center for Geoscience GFZ, Germany; Potsdam Institute for Climate Impact Research, Germany

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References

Goreau, T. J. F. and R. L. Hayes (2024). "2023 Record marine heat waves: coral reef bleaching HotSpot maps reveal global sea surface temperature extremes, coral mortality, and ocean circulation changes." Oxford Open Climate Change 4(1).

IPBES (2024). IPBES Transformative Change Assessment: Summary for Policymakers. K. O'Brien, L. A. Garibaldi, A. Agrawal et al. Bonn, Germany, IPBES Secretariat.

IPCC (2022). Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. H.-O. Pörtner, D. C. Roberts, M. Tignor et al. Cambridge, UK and New York, NY, USA, Cambridge University Press: 3-33.

Kopp, R. E., E. A. Gilmore, R. L. Shwom, H. Adams, C. Adler, M. Oppenheimer, A. Patwardhan, C. Russill, D. N. Schmidt and R. York (2025). "'Tipping points' confuse and can distract from urgent climate action." Nature Climate Change 15(1): 29-36.

Lenton, T. M., H. Held, E. Kriegler, J. Hall, W. Lucht, S. Rahmstorf and H. J. Schellnhuber (2008). "Tipping Elements in the Earth's Climate System." Proceedings of the National Academy of Sciences 105(6): 1786-1793.

Levin, L. A., D. J. Amon and H. Lily (2020). "Challenges to the sustainability of deep-seabed mining." Nature Sustainability 3(10): 784-794.

Nijsse, F., S. Sharpe, R. Sahastrabuddhe and T. M. Lenton (2024). A positive tipping cascade in power, transport and heating, University of Exeter / EEIST / S-curve economics.

Otto, I. M., J. F. Donges, R. Cremades, A. Bhowmik, R. J. Hewitt, W. Lucht, J. Rockström, F. Allerberger, M. McCaffrey, S. S. P. Doe, A. Lenferna, N. Morán, D. P. van Vuuren and H. J. Schellnhuber (2020). "Social tipping dynamics for stabilizing Earth's climate by 2050." Proceedings of the National Academy of Sciences 117(5): 2354-2365.

Pereira, L. M., I. Gianelli, T. Achieng, D. Amon, S. Archibald, S. Arif, A. Castro, T. P. Chimbadzwa, K. Coetzer, T. L. Field, O. Selomane, N. Sitas, N. Stevens, S. Villasante, M. Armani, D. M. Kimuyu, I. J. Adewumi, D. M. Lapola, D. Obura, P. Pinho, F. Roa-Clavijo, J. Rocha and U. R. Sumaila (2024). "Equity and justice should underpin the discourse on tipping points." Earth System Dynamics 15(2): 341-366.

Pereira, L. M., S. R. Smith, L. Gifford, P. Newell, S. Villasante, T. Achieng, A. Castro, S. M. Constantino, T. Powell, A. Ghadiali, B. Smith, C. Vogel and C. Zimm (2025). "Beyond tipping points: risks, equity, and the ethics of intervention." Earth System Dynamics 16: 1267-1285.

Smith, S. R., M. Milkoreit, F. W. Geels and T. M. Lenton (2025). "Advancing science, policy and action in tipping points research." Nature Climate Change 15(6): 576-577.

UNDP (2024). Viet Nam Multi-Sector Assessment (VMSA) Report for Typhoon Yagi Recovery, United Nations Viet Nam.

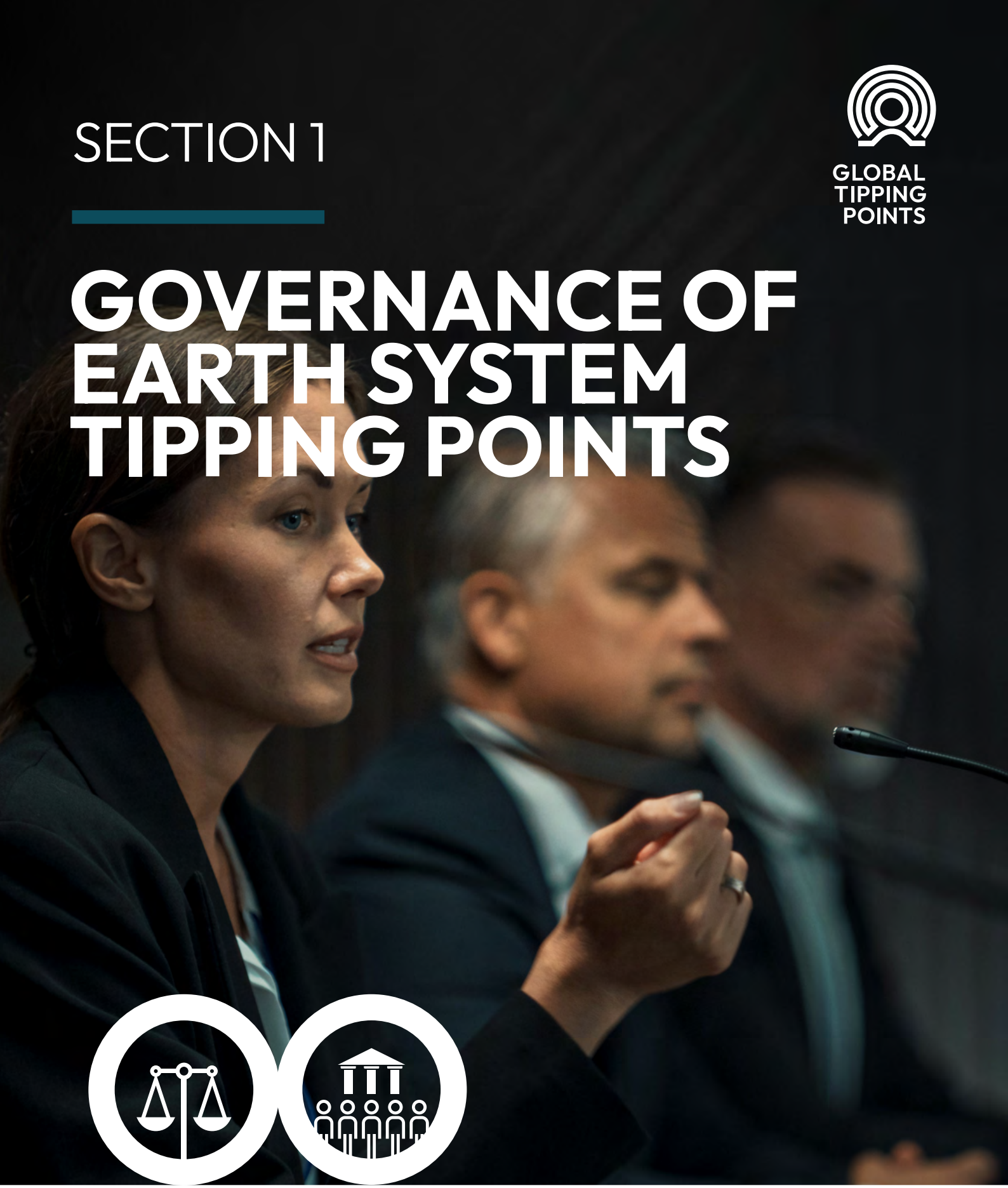
Villasante, S., L. Shannon, C. Liao, E. Betemariam, S. Cunningham, E. Ellis, V. Hausner, Q. Huang, L. Mannetti, I. Otero, G. Piñeiro, A. Prasad Gautam, S. Waddock, H. Wheeler, T. Fouqueray, O. Karasov, G. Tasse Taboue and C. Guibal (2025). IPBES Transformative Change Assessment: Chapter 2. Visions of a sustainable world - for nature and people (Version v3). Zenodo. https://doi.org/10.5281/zenodo.16310763.

WMO (2025). State of the Global Climate 2024. Geneva, World Meteorological Organization.

SECTION 1

GLOBAL TIPPING POINTS

GOVERNANCE OF EARTH SYSTEM TIPPING POINTS



Section lead authors:
Manjana Milkoreit, Simon Willcock

References 1.1

Armstrong McKay D, Staal A, Abrams JF, et al. (2022) Exceeding 1.5°C global warming could trigger multiple climate tipping points. Science 377(6611): eabn7950. https://doi.org/10.1126/science.abn7950

Armstrong McKay DI (2024) Two decades of climate tipping points research: Progress and outlook. Dialogues on Climate Change. SAGE Publications: 29768659241293272. https://doi.org/10.1177/29768659241293272

Bellomo K, Angeloni M, Corti S, et al. (2021) Future climate change shaped by inter-model differences in Atlantic meridional overturning circulation response. Nature Communications 12(1). Nature Publishing Group: 3659. https://doi.org/10.1038/s41467-021-24015-w

Ben-Yami M, Morr A, Bathiany S, et al. (2024) Uncertainties too large to predict tipping times of major Earth system components from historical data. Science Advances 10(31). American Association for the Advancement of Science: eadl4841. https://doi.org/ https://doi.org/10.1126/sciadv.adl4841

Bevacqua E, Schleussner C-F and Zscheischler J (2025) A year above 1.5°C signals that Earth is most probably within the 20-year period that will reach the Paris Agreement limit. Nature Climate Change. Nature Publishing Group: 1–4. https://doi.org/10.1038/s41558-025-02246-9

Biermann F (2014) The Anthropocene: A governance perspective. The Anthropocene Review 1(1): 57–61. https://doi.org/10.1177/2053019613516289

Biesbroek R, Haasnoot M, Mach KJ, et al. (2025) Adaptation planning in the context of a weakening and possibly collapsing Atlantic Meridional Overturning Circulation (AMOC). Regional Environmental Change 25(3): 93. https://doi.org/10.1007/s10113-025-02434-5

Hansen JE, Kharecha P, Sato M, et al. (2025) Global Warming Has Accelerated: Are the United Nations and the Public Well-Informed? Environment: Science and Policy for Sustainable Development 67(1). Routledge: 6–44. https://doi.org/10.1080/00139157.2025.2434494

IPBES (2024) Thematic Assessment Report on the Interlinkages among Biodiversity, Water, Food and Health of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (eds PA Harrison, PD McElwee and TL Van Huysen). Bonn, Germany: IPBES Secretariat. Available at: https://doi.org/10.5281/zenodo.13850054.

Jackson LS, Crook JA, Jarvis A, et al. (2015) Assessing the controllability of Arctic sea ice extent by sulfate aerosol geoengineering. Geophysical Research Letters 42(4): 1223–1231. https://doi.org/ https://doi.org/10.1002/2014GL062240

Kelly J, Kljun N, Cai Z, et al. (2024) Wildfire impacts on the carbon budget of a managed Nordic boreal forest. Agricultural and Forest Meteorology 351: 110016. https://doi.org/10.1016/j.agrformet.2024.110016

Kim RE (2022) Taming Gaia 2.0: Earth system law in the ruptured Anthropocene. The Anthropocene Review 9(3). SAGE Publications: 411–424. https://doi.org/10.1177/20530196211026721

Kotzé LJ and Kim RE (2019) Earth system law: The juridical dimensions of earth system governance. Earth System Governance 1: 100003. https://doi.org/10.1016/j.esg.2019.100003

Laybourn L, Evans J and Dyke J (2023) Derailment risk: A systems analysis that identifies risks which could derail the sustainability transition. Earth System Dynamics 14(6). Copernicus GmbH: 1171–1182. https://doi.org/10.5194/esd-14-1171-2023

McElwee PD, Harrison PA, van Huysen TL, et al. (2025) IPBES Nexus Assessment: Summary for Policymakers. 16 June. Zenodo. Available at: https://zenodo.org/records/15673657 (accessed 3 September 2025).

Migliavacca M, Grassi G, Bastos A, et al. (2025) Securing the forest carbon sink for the European Union's climate ambition. Nature 643(8074). Nature Publishing Group: 1203–1213. https://doi.org/ https://doi.org/10.1038/s41586-025-08967-3

Milkoreit M, Hodbod J, Baggio J, et al. (2018) Defining tipping points for social-ecological systems scholarship—an interdisciplinary literature review. Environmental Research Letters 13(3): 033005. https://doi.org/10.1088/1748-9326/aaaa75

Milkoreit M, Boyd E, Constantino SM, et al. (2024) Governance for Earth system tipping points – A research agenda. Earth System Governance 21: 100216. https://doi.org/10.1016/j.esg.2024.100216

Möller T, Högner AE, Schleussner C-F, et al. (2024) Achieving net zero greenhouse gas emissions critical to limit climate tipping risks. Nature Communications 15(1). Nature Publishing Group: 6192. https://doi.org/10.1038/s41467-024-49863-0

O'Brien K, Garibaldi LA, Agrawal A, et al. (2025) IPBES Transformative Change Assessment: Summary for Policymakers. June. Zenodo. Available at: https://zenodo.org/records/15645812 (accessed 3 September 2025).

Pan Y, Birdsey RA, Phillips OL, et al. (2024) The enduring world forest carbon sink. Nature 631(8021). Nature Publishing Group: 563–569. https://doi.org/10.1038/s41586-024-07602-x

Pattberg P and Zelli F (2016) Global environmental governance in the Anthropocene: An introduction. In: Environmental Politics and Governance in the Anthropocene. Routledge.

Ruhl JB and Ruhl HJ (2022) Pre-planning transformation to avoid collapse—Is it possible? Futures 144: 103058. https://doi.org/10.1016/j.futures.2022.103058

Tàbara JD, Frantzeskaki N, Hölscher K, et al. (2018) Positive tipping points in a rapidly warming world. Current Opinion in Environmental Sustainability 31. Sustainability governance and transformation 2018: 120–129. https://doi.org/10.1016/j.cosust.2018.01.012

Thienen P van, Maat H ter and Stofberg S (2025) Climate tipping points and their potential impact on drinking water supply planning and management in Europe. Cambridge Prisms: Water 3: e3. https://doi.org/10.1017/wat.2024.14

van Westen RM and Baatsen MLJ (2025) European Temperature Extremes Under Different AMOC Scenarios in the Community Earth System Model. Geophysical Research Letters 52(12): e2025GL114611. https://doi.org/10.1029/2025GL114611

Walker B, Crépin A-S, Nyström M, et al. (2023) Response diversity as a sustainability strategy. Nature Sustainability 6(6). 6. Nature Publishing Group: 621–629. https://doi.org/10.1038/s41893-022-01048-7

Winkelmann R, Donges JF, Smith EK, et al. (2022) Social tipping processes towards climate action: A conceptual framework. Ecological Economics 192: 107242. https://doi.org/10.1016/j.ecolecon.2021.107242

Wood RA, Crucifix M, Lenton TM, et al. (2023) A Climate Science Toolkit for High Impact-Low Likelihood Climate Risks. Earth's Future 11(4): e2022EF003369. https://doi.org/10.1029/2022EF003369

Wunderling N, Winkelmann R, Rockström J, et al. (2022) Global warming overshoots increase risks of climate tipping cascades in a network model. Nature Climate Change. Nature Publishing Group UK London: 1–8. https://doi.org/10.1038/s41558-022-01545-9

Wunderling N, von der Heydt AS, Aksenov Y, et al. (2024) Climate tipping point interactions and cascades: a review. Earth System Dynamics 15(1). Copernicus GmbH: 41–74. https://doi.org/10.5194/esd-15-41-2024

Zhang R, Sutton R, Danabasoglu G, et al. (2019) A Review of the Role of the Atlantic Meridional Overturning Circulation in Atlantic Multidecadal Variability and Associated Climate Impacts. Reviews of Geophysics 57(2): 316–375. https://doi.org/10.1029/2019RG000644

References 1.2

Ameli, N., Chenet, H., Falkenberg, M., Kothari, S., Rickman, J. and Lamperti, F., 2025. Driving sustainability transitions through financial tipping points. Earth System Dynamics, 16(1), pp.333-345. https://doi.org/10.5194/esd-16-333-2025

Armstrong McKay, D.I., Staal, A., Abrams, J.F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S.E., Rockström, J. and Lenton, T.M., 2022. Exceeding 1.5 C global warming could trigger multiple climate tipping points. Science, 377(6611), p.eabn7950. https://doi.org/10.1126/science.abn7950

Asutosh, A., Tilmes, S., Bednarz, E.M. and Fadnavis, S., 2025. South Asian Summer Monsoon under stratospheric aerosol intervention. npj Climate and Atmospheric Science, 8(1), p.3. https://doi.org/10.1038/s41612-024-00875-z

Bednarz, E.M., Goddard, P.B., MacMartin, D.G., Visioni, D., Bailey, D. and Danabasoglu, G., 2025. Stratospheric aerosol injection could prevent future Atlantic Meridional Overturning Circulation decline, but injection location is key. Earth's Future, 13(8), p.e2025EF005919. https://doi.org/10.1029/2025EF005919

Beerling, D.J., Kantzas, E.P., Lomas, M.R., Wade, P., Eufrasio, R.M., Renforth, P., Sarkar, B., Andrews, M.G., James, R.H., Pearce, C.R., Mercure, J.F., Pollitt, H., Holden, P.B., Edwards, N.R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N.F., Janssens, I.A., Hansen, J. & Banwart, S.A. 2020. Potential for large-scale CO2 removal via enhanced rock weathering with croplands. Nature, 583(7815), pp.242-248. https://doi.org/10.1038/s41586-020-2448-9

Bevacqua, E., Schleussner, C.F. and Zscheischler, J., 2025. A year above 1.5° C signals that Earth is most probably within the 20-year period that will reach the Paris Agreement limit. Nature Climate Change, 15(3), pp.262-265. https://doi.org/10.1038/s41558-025-02246-9

Beveridge, C.F., Espinoza, J.C., Athayde, S., Correa, S.B., Couto, T.B., Heilpern, S.A., Jenkins, C.N., Piland, N.C., Utsunomiya, R., Wongchuig, S. and Anderson, E.P., 2024. The Andes–Amazon–Atlantic pathway: A foundational hydroclimate system for social–ecological system sustainability. Proceedings of the National Academy of Sciences, 121(22), p.e2306229121. https://doi.org/10.1073/pnas.2306229121

Biermann, F., Oomen, J., Gupta, A., Ali, S.H., Conca, K., Hajer, M.A., Kashwan, P., Kotzé, L.J., Leach, M., Messner, D. and Okereke, C., 2022. Solar geoengineering: The case for an international non-use agreement. Wiley Interdisciplinary Reviews: Climate Change, 13(3), p.e754. https://doi.org/10.1002/wcc.754

Borràs-Pentinat, S., 2025. 'Rights of Nature', in M. Wewerinke-Singh and S. Mead (eds.) The Cambridge Handbook on Climate Litigation. Cambridge: Cambridge University Press (Cambridge Law Handbooks), pp. 275–298.

Bossio, D.A., Cook-Patton, S.C., Ellis, P.W., Fargione, J., Sanderman, J., Smith, P., Wood, S., Zomer, R.J., Von Unger, M., Emmer, I.M. and Griscom, B.W., 2020. The role of soil carbon in natural climate solutions. Nature Sustainability, 3(5), pp.391-398. https://doi.org/10.1038/s41893-020-0491-z

Boulton, C.A., Lenton, T.M. and Boers, N., 2022. Pronounced loss of Amazon rainforest resilience since the early 2000s. Nature Climate Change, 12(3), pp.271-278. https://doi.org/10.1038/s41558-022-01287-8

Carney, M, 2015. Breaking the tragedy of the horizon – climate change and financial stability, speech given at Lloyd's of London, 29 September 2015. Bank of England. Available at: https://www.bankofengland.co.uk/speech/2015/breaking-the-tragedy-of-the-horizon-climate-change-and-financial-stability (Accessed: 1 September 2025).

Chapron, G., Epstein, Y. and López-Bao, J.V., 2019. A rights revolution for nature. Science, 363(6434), pp.1392-1393. https://doi.org/10.1126/science.aav5601

Chenet, H., Kedward, K., Ryan-Collins, J. and van Lerven, F., 2022. Developing a precautionary approach to financial policy – from climate to biodiversity. INSPIRE Sustainable Central Banking Toolbox Policy Briefing Paper No. 2. SOAS Centre of Sustainable Finance and LSE Grantham Research Institute on Climate Change and the Environment. Published 27 April 2022. Available at: https://www.inspiregreenfinance.org/wp-content/uploads/2022/04/Chenet-et-al-April-2022-Developing-a-precautionary-approach-to-financial-policy-from-climate-to-biodiversity.pdf (Accessed: 1 September 2025).

Chenet, H., Ryan-Collins, J. and Van Lerven, F., 2021. Finance, climate-change and radical uncertainty: Towards a precautionary approach to financial policy. Ecological Economics, 183, p.106957. https://doi.org/10.1016/j.ecolecon.2021.106957

Chidichimo, M.P., Perez, R.C., Speich, S., Kersalé, M., Sprintall, J., Dong, S., Lamont, T., Sato, O.T., Chereskin, T.K., Hummels, R. and Schmid, C., 2023. Energetic overturning flows, dynamic interocean exchanges, and ocean warming observed in the South Atlantic. Communications Earth & Environment, 4(1), p.10. https://doi.org/10.1038/s43247-022-00644-x

Climate Governance Commission, 2023. Governing Our Planetary Emergency. Available at: https://www.stimson.org/wp-content/uploads/2023/11/Governing-Our-Planetary-Emergency-Report_WEB-1.pdf (Accessed: 1 September 2025).

Climate Policy Initiative (CPI), 2024. Global Landscape of Climate Finance 2024: Insights for COP29. London: Climate Policy Initiative. Available at: https://climatepolicyinitiative.org/publication/global-landscape-of-climate-finance-2024 (Accessed: 1 September 2025).

Convention on Biological Diversity (CBD), 2025. Decision adopted by the Conference of the Parties to the Convention on Biological Diversity on 27 February 2025 (CBD/COP/16/Dec.34). Montreal-Kunming, 27 February 2025. Available at: https://www.cbd.int/doc/decisions/cop-16/cop-16-dec-34-en.pdf (Accessed: 1 September 2025).

Cooper, G.S., Willcock, S. and Dearing, J.A., 2020. Regime shifts occur disproportionately faster in larger ecosystems. Nature Communications, 11(1), p.1175. https://doi.org/10.1038/s41467-020-15029-x

Corrigan, D. P. and Oksanen, M. (eds.),2021. Rights of Nature: A Re-examination. 1st edn. London: Routledge. https://doi.org/10.4324/9780367479589

Crona, B., Folke, C. and Galaz, V., 2021. The Anthropocene reality of financial risk. One Earth, 4(5), pp.618-628. https://doi.org/10.1016/j.oneear.2021.04.016

Directorate-General for Research and Innovation (European Commission) and Group of Chief Scientific Advisors (European Commission), 2024. Solar radiation modification. Publications Office of the European Union. https://doi.org/10.2777/391614 (Accessed: 1 September 2025).

Du Toit, L. and Kotzé, L.J., 2022. Reimagining international environmental law for the Anthropocene: An earth system law perspective. Earth System Governance, 11, p.100132. https://doi.org/10.1016/j.esg.2022.100132

Edling Müller, I. (2025) Justice for the whole forest: How legal recognition of interspecies justice could help avoid triggering forest-related Earth system tipping points. Master's thesis, Stockholm University, Faculty of Science, Stockholm Resilience Centre. Available at: https://su.diva-portal.org/smash/record.jsf?pid=diva2%3A1967625 (Accessed: 1 September 2025).

Eker, S., Lenton, T.M., Powell, T., Scheffran, J., Smith, S.R., Swamy, D. and Zimm, C., 2024. Cross-system interactions for positive tipping cascades. Earth System Dynamics, 15(3), pp.789-800. https://doi.org/10.5194/esd-15-789-2024

Fasullo, J.T., Tilmes, S., Richter, J.H., Kravitz, B., MacMartin, D.G., Mills, M.J. and Simpson, I.R., 2018. Persistent polar ocean warming in a strategically geoengineered climate. Nature Geoscience, 11(12), pp.910-914. https://doi.org/10.1038/s41561-018-0249-7

Felgenhauer, T., Bala, G., Borsuk, M., Brune, M., Camilloni, I., Wiener, J.B., Xu, J., 2022. Solar Radiation Modification: A Risk-Risk Analysis, Carnegie Climate Governance Initiative (C2G), March, New York, NY: www.c2g2.net

Financial Stability Board (FSB), 2025. Assessment of Climate-related Vulnerabilities: Analytical Framework and Toolkit. Published 16 January 2025. Available at: https://www.fsb.org/uploads/P160125.pdf (Accessed: 1 September 2025).

Flores, B.M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R.A., Levis, C., Lapola, D.M., Esquível-Muelbert, A., Jakovac, C. and Nobre, C.A., 2024. Critical transitions in the Amazon forest system. Nature, 626(7999), pp.555-564. https://doi.org/10.1038/s41586-023-06970-0

Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T. and Luderer, G., 2018. Negative emissions—Part 2: Costs, potentials and side effects. Environmental research letters, 13(6), p.063002. https://doi.org/10.1088/1748-9326/aabf9f

Futerman, G., Adhikari, M., Duffey, A., Fan, Y., Gurevitch, J., Irvine, P. and Wieners, C., 2025. The interaction of solar radiation modification with Earth system tipping elements. Earth System Dynamics, 16(4), pp.939-978. https://doi.org/10.5194/esd-16-939-2025

Galaz, V., Crona, B., Dauriach, A., Scholtens, B. and Steffen, W., 2018. Finance and the Earth system–Exploring the links between financial actors and non-linear changes in the climate system. Global Environmental Change, 53, pp.296-302. https://doi.org/10.1016/j.gloenvcha.2018.09.008

García Ruales, J., 2024. Forest moralities, kindred knowledge and Sacha Runakuna: Kawsak Sacha as law. The International Journal of Human Rights, 28(10), pp.1662-1686. https://doi.org/10.1080/13642987.2024.2362837

Garmestani, A., Ruhl, J.B., Chaffin, B.C., Craig, R.K., van Rijswick, H.F., Angeler, D.G., Folke, C., Gunderson, L., Twidwell, D. and Allen, C.R., 2019. Untapped capacity for resilience in environmental law. Proceedings of the National Academy of Sciences, 116(40), pp.19899-19904. https://doi.org/10.1073/pnas.1906247116

Gonon, M., Svartzman, R. and Althouse, J., 2024. Bridging the Gap in Biodiversity Financing: A review of assessments of existing and needed financial flows for biodiversity, and some considerations regarding their limitations and potential ways forward. UCL Institute for Innovation and Public Purpose, Working Paper Series (IIPP WP 2024-14). Available at: https://www.ucl.ac.uk/bartlett/public-purpose/WP2024-14 (Accessed: 1 September 2025).

Gregory, J.M., Bouttes, N., Griffies, S.M., Haak, H., Hurlin, W.J., Jungclaus, J., Kelley, M., Lee, W.G., Marshall, J., Romanou, A. and Saenko, O.A., 2016. The Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP) contribution to CMIP6: Investigation of sea-level and ocean climate change in response to CO 2 forcing. Geoscientific Model Development, 9(11), pp.3993-4017. https://doi.org/10.5194/gmd-9-3993-2016

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikamäki, J.V., Smith, P. and Woodbury, P., 2017. Natural climate solutions. Proceedings of the National Academy of Sciences, 114(44), pp.11645-11650. https://doi.org/10.1073/pnas.1710465114

Gupta, A., Biermann, F., Van Driel, E., Bernaz, N., Jayaram, D., Kim, R.E., Kotzé, L.J., Ruddigkeit, D., VanDeveer, S.D. and Wewerinke-Singh, M., 2024. Towards a non-use regime on solar geoengineering: Lessons from international law and governance. Transnational Environmental Law, 13(2), pp.368-399. https://doi.org/10.1017/S2047102524000050

Hadji-Lazaro, P., Salin, M., Svartzman, R., Espagne, E., Gauthey, J., Berger, J., Calas, J., Godin, A. and Vallier, A., 2024. Biodiversity loss and financial stability as a new frontier for central banks: An exploration for France. Ecological Economics, 223, p.108246. https://doi.org/10.1016/j.ecolecon.2024.108246

Hall, C., 2023. Diffusing the legal conceptions of the global south and decolonizing international law: crystallizing animal rights through inter-judicial dialogue. Frontiers in Animal Science, 4, p.1241318. https://doi.org/10.3389/fanim.2023.1241318

Hirasawa, H., Hingmire, D., Singh, H., Rasch, P.J. and Mitra, P., 2023. Effect of regional marine cloud brightening interventions on climate tipping elements. Geophysical Research Letters, 50(20), p.e2023GL104314. https://doi.org/10.1029/2023GL104314

Inter-American Court of Human Rights (IACHR), 2025. Advisory Opinion OC-32/25: The Climate Emergency and Human Rights. San José, Costa Rica: Inter-American Court of Human Rights. Available at: https://www.corteidh.or.cr/tablas/OC-32-2025/index-eng.html (Accessed: 1 September 2025).

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2022. Methodological assessment of the diverse values and valuation of nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Zenodo. https://doi.org/10.5281/zenodo.7687931

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2024. Thematic Assessment Report on the Underlying Causes of Biodiversity Loss and the Determinants of Transformative Change and Options for Achieving the 2050 Vision for Biodiversity of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Transformative Change Assessment). O'Brien, K., Garibaldi, L., and Agrawal, A. (eds.). IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.11382215

International Court of Justice (ICJ), 2025. Advisory Opinion of 23 July 2025 — Obligations of States in Respect of Climate Change. Case No. 187, Doc. 187-20250723-ADV-01-00-EN. The Hague: International Court of Justice.

International Tribunal for the Law of the Sea (ITLOS), 2024. Request for an Advisory Opinion submitted by the Commission of Small Island States on Climate Change and International Law, Advisory Opinion (Case No. 31), 21 May 2024. Hamburg: ITLOS. Available at: https://www.itlos.org/fileadmin/itlos/documents/cases/31/Advisory_Opinion/C31_Adv_Op_21.05.2024_orig.pdf (Accessed: 1 September 2025).

Irvine, P., Emanuel, K., He, J., Horowitz, L.W., Vecchi, G. and Keith, D., 2019. Halving warming with idealized solar geoengineering moderates key climate hazards. Nature climate change, 9(4), pp.295-299. https://doi.org/10.1038/s41558-019-0398-8

Iyer, G., Ou, Y., Edmonds, J., Fawcett, A.A., Hultman, N., McFarland, J., Fuhrman, J., Waldhoff, S. and McJeon, H., 2022. Ratcheting of climate pledges needed to limit peak global warming. Nature Climate Change, 12(12), pp.1129-1135. https://doi.org/10.1038/s41558-022-01508-0

Kedward, K., Ryan-Collins, J. and Chenet, H., 2023. Biodiversity loss and climate change interactions: financial stability implications for central banks and financial supervisors. Climate Policy, 23(6), pp.763-781. https://doi.org/10.1080/14693062.2022.2107475

Kotzé, L.J. and Adelman, S., 2023. Environmental law and the unsustainability of sustainable development: a tale of disenchantment and of hope. Law and critique, 34(2), pp.227-248. https://doi.org/10.1007/s10978-022-09323-4

Kreibiehl, S., T. Yong Jung, S. Battiston, P. E. Carvajal, C. Clapp, D. Dasgupta, N. Dube, R. Jachnik, K. Morita, N. Samargandi, M. Williams, 2022: Investment and finance. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.017

Lenton, T. M., 2018. 'Can emergency geoengineering really prevent climate tipping points?', in Geoengineering Our Climate? Ethics, Politics, and Governance. London: Routledge. Available at: https://www.taylorfrancis.com/chapters/edit/10.4324/9780203485262-8/emergency-geoengineering-really-prevent-climate-tipping-points-timothy-lenton (Accessed: 1 September 2025).

Lenton, T. M., Armstrong McKay, D. I., Loriani, S., Abrams, J. F., Lade, S. J., Donges, J. F., Milkoreit, M., Powell, T., Smith, S. R., Zimm, C., Buxton, J. E., Bailey, E., Laybourn, L., Ghadiali, A., & Dyke, J. G. 2023. The global tipping points report 2023 (University of Exeter) https://global-tipping-points.org/

Lenton, T.M., 2011. Beyond 2 C: redefining dangerous climate change for physical systems. Wiley Interdisciplinary Reviews: Climate Change, 2(3), pp.451-461. https://doi.org/10.1002/wcc.107

Lobelle, D., Beaulieu, C., Livina, V., Sevellec, F. and Frajka‐Williams, E., 2020. Detectability of an AMOC decline in current and projected climate changes. Geophysical Research Letters, 47(20), p.e2020GL089974. https://doi.org/10.1029/2020GL089974

Lohmann, J. and Ditlevsen, P.D., 2021. Risk of tipping the overturning circulation due to increasing rates of ice melt. Proceedings of the National Academy of Sciences, 118(9), p.e2017989118. https://doi.org/10.1073/pnas.2017989118

Loreau, M., Barbier, M., Filotas, E., Gravel, D., Isbell, F., Miller, S.J., Montoya, J.M., Wang, S., Aussenac, R., Germain, R. and Thompson, P.L., 2021. Biodiversity as insurance: from concept to measurement and application. Biological Reviews, 96(5), pp.2333-2354. https://doi.org/10.1111/brv.12756

Mace, M.J., Fyson, C.L., Schaeffer, M. and Hare, W.L., 2021. Large‐scale carbon dioxide removal to meet the 1.5 C limit: key governance gaps, challenges and priority responses. Global Policy, 12, pp.67-81. https://doi.org/10.1111/1758-5899.12921

Marsden, L., Ryan-Collins, J., Abrams, J. and Lenton, T., 2024. Financial interactions with ecosystem tipping points: evidence from the Brazilian Amazon and Indonesian peatlands. UCL Institute for Innovation and Public Purpose, Working Paper Series (IIPP WP 2024-11). Available at: https://www.ucl.ac.uk/bartlett/public-purpose/publications/WP-2024-11 (Accessed: 1 September 2025).

Maxwell, L., Mead, S. and Van Berkel, D., 2022. Standards for adjudicating the next generation of Urgenda-style climate cases. Journal of Human Rights and the Environment, 13(1), pp.35-63. https://doi.org/10.4337/jhre.2022.01.02

Mercure, J.F., Lam, A., Buxton, J., Boulton, C. and Lenton, T., 2024. Evidence of a cascading positive tipping point towards electric vehicles. https://doi.org/10.21203/rs.3.rs-3979270/v1

Möller, T., Högner, A.E., Schleussner, C.F., Bien, S., Kitzmann, N.H., Lamboll, R.D., Rogelj, J., Donges, J.F., Rockström, J. and Wunderling, N., 2024. Achieving net zero greenhouse gas emissions critical to limit climate tipping risks. Nature Communications, 15(1), p.6192. https://doi.org/10.1038/s41467-024-49863-0

Morrow, K., 2025. 'Will a Human Right to a Clean, Healthy and Sustainable Environment Address the Wrongs of Environmental Degradation?', in Bakan, A. B. and Abu-Laban, Y. (eds.) Human Rights and the United Nations: Paradox and Promise. 1st edn. London: Routledge, chapter [online]. Available at: https://doi.org/10.4324/9781003404453-13 (Accessed: 1 September 2025).

National Academies of Sciences, Engineering, and Medicine, 2021. Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance. Washington, DC: The National Academies Press. https://doi.org/10.17226/25762 (Accessed: 1 September 2025).

Network for Greening the Financial System (NGFS), 2024. Synthesis Report on the Greening of the Financial System: Insights for Financial Actors in Advanced and Emerging Economies. Published on the occasion of COP29, Baku, 14 November 2024. Available at: https://www.ngfs.net/system/files/import/ngfs/medias/documents/ngfs_synthesis_report_on_the_greening_of_the_financial_system.pdf (Accessed: 1 September 2025).

Nielsen, J., 2025. The big green button: stratospheric aerosol injection as a geopolitical dilemma during strategic competition between the United States and China, and implications for expanding aerosol injection near-term research. Oxford Open Climate Change, 5(1), p.kgaf009. https://doi.org/10.1093/oxfclm/kgaf009

Norwegian Government 2024 Prop. 1 S (2024–2025) – For budsjettåret 2025 under Klima- og miljødepartementet. Regjeringen.no. Available at: https://www.regjeringen.no/no/dokumenter/prop.-1-s-20242025/id3057446/?ch=3#kap6 (Accessed: 1 September 2025).

O'Donnell, E., Poelina, A., Pelizzon, A. and Clark, C., 2020. Stop burying the Lede: The essential role of indigenous law (s) in creating rights of nature. Transnational Environmental Law, 9(3), pp.403-427. https://doi.org/10.1017/S2047102520000242

O'Donnell, E.L. and Talbot-Jones, J., 2018. Creating legal rights for rivers. Ecology and Society, 23(1). https://doi.org/10.5751/ES-09854-230107

Pereira, J.C. and Terrenas, J., 2022. Towards a transformative governance of the Amazon. Global Policy, 13, pp.60-75. https://doi.org/10.1111/1758-5899.13163

Pflüger, D., Wieners, C.E., Van Kampenhout, L., Wijngaard, R.R. and Dijkstra, H.A., 2024. Flawed emergency intervention: Slow ocean response to abrupt stratospheric aerosol injection. Geophysical Research Letters, 51(5), p.e2023GL106132. https://doi.org/10.1029/2023GL106132

Poorter, L., Craven, D., Jakovac, C.C., Van Der Sande, M.T., Amissah, L., Bongers, F., Chazdon, R.L., Farrior, C.E., Kambach, S., Meave, J.A. and Muñoz, R., 2021. Multidimensional tropical forest recovery. Science, 374(6573), pp.1370-1376. https://doi.org/10.1126/science.abh3629

Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A.C. and Tavoni, M., 2019. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nature communications, 10(1), p.3277. https://doi.org/10.1038/s41467-019-10842-5

Ritz, V., 2024. Climate tipping points: Tracing the limits of political discretion. Leiden Journal of International Law, pp.1-22. https://doi.org/10.1017/S0922156524000487

RiverOfLife, M., Poelina, A., Bagnall, D. and Lim, M., 2020. Recognizing the Martuwarra's first law right to life as a living ancestral being. Transnational Environmental Law, 9(3), pp.541-568. https://doi.org/10.1017/S2047102520000163

Rockström, J., Kotzé, L., Milutinović, S., Biermann, F., Brovkin, V., Donges, J., Ebbesson, J., French, D., Gupta, J., Kim, R. and Lenton, T., 2024. The planetary commons: A new paradigm for safeguarding Earth-regulating systems in the Anthropocene. Proceedings of the National Academy of Sciences, 121(5), p.e2301531121. https://doi.org/10.1073/pnas.2301531121

Schwinger, J., Asaadi, A., Goris, N. and Lee, H., 2022. Possibility for strong northern hemisphere high-latitude cooling under negative emissions. Nature Communications, 13(1), p.1095. https://doi.org/10.1038/s41467-022-28573-5

Science Panel for the Amazon (SPA), 2021. Amazon Assessment Report 2021. Available at: https://www.sp-amazon.org/publications/#ar2021 (Accessed: 1 September 2025).

Setzer, J. and Higham, C., 2025. Global Trends in Climate Change Litigation: 2025 Snapshot. London: Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science. Available at: https://www.lse.ac.uk/granthaminstitute/publication/global-trends-in-climate-change-litigation-2025-snapshot/ (Accessed: 1 September 2025).

Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I. and Vaughan, N. E. (eds.), 2024. The State of Carbon Dioxide Removal 2024 – 2nd Edition. https://doi.org/10.17605/OSF.IO/F85QJ

Sun, X., Wang, P., Ferris, T., Lin, H., Dreyfus, G., Gu, B.-H., Zaelke, D., and Wang, Y., 2022. Fast action on short-lived climate pollutants and nature-based solutions to help countries meet carbon neutrality goals. Advances in Climate Change Research, 13(4), pp.564-577. https://doi.org/10.1016/j.accre.2022.06.003

Tănăsescu, M., 2020. Rights of nature, legal personality, and indigenous philosophies. Transnational environmental law, 9(3), pp.429-453. https://doi.org/10.1017/S2047102520000217

Tilmes, S., MacMartin, D.G., Lenaerts, J., Van Kampenhout, L., Muntjewerf, L., Xia, L., Harrison, C.S., Krumhardt, K.M., Mills, M.J., Kravitz, B. and Robock, A., 2020. Reaching 1.5 and 2.0 C global surface temperature targets using stratospheric aerosol geoengineering. Earth System Dynamics, 11(3), pp.579-601. https://doi.org/10.5194/esd-11-579-2020

Trust, S., Saye, L., Bettis, O., Bedenham, G., Hampshire, O., Lenton, T. M., and Abrams, J. F., 2025. Planetary Solvency – finding our balance with nature [Working Paper]. Publication date: 16 January 2025. Available at: https://actuaries.org.uk/media/wqeftma1/planetary-solvency-finding-our-balance-with-nature.pdf (Accessed: 1 September 2025)

United Nations Environment Programme (UNEP) and Climate and Clean Air Coalition (CCAC) (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. Nairobi: United Nations Environment Programme. Available at: https://www.ccacoalition.org/resources/global-methane-assessment-full-report (Accessed: 1 September 2025).

United Nations Environment Programme (UNEP), 2023. One Atmosphere: An Independent Expert Review on Solar Radiation Modification Research and Deployment. Nairobi: United Nations Environment Programme. Published 28 February 2023. Available at: https://www.unep.org/resources/report/Solar-Radiation-Modification-research-deployment (Accessed: 1 September 2025).

United Nations Environment Programme (UNEP), 2024. Emissions Gap Report 2024: No more hot air … please! https://doi.org/10.59117/20.500.11822/46404

United Nations Framework Convention on Climate Change (UNFCCC) 2024. Periodic Review. UNFCCC. Available at: https://unfccc.int/topics/science/workstreams/periodic-review#Continuation-of-the-periodic-review (Accessed: 1 September 2025).

Van Westen, R.M., Kliphuis, M. and Dijkstra, H.A., 2024. Physics-based early warning signal shows that AMOC is on tipping course. Science advances, 10(6), p.eadk1189. https://doi.org/10.1126/sciadv.adk1189

Walker, W.S., Gorelik, S.R., Baccini, A., Aragon-Osejo, J.L., Josse, C., Meyer, C., Macedo, M.N., Augusto, C., Rios, S., Katan, T. and de Souza, A.A., 2020. The role of forest conversion, degradation, and disturbance in the carbon dynamics of Amazon indigenous territories and protected areas. Proceedings of the National Academy of Sciences, 117(6), pp.3015-3025. https://doi.org/10.1073/pnas.1913321117

Willcock, S., Cooper, G.S., Addy, J. and Dearing, J.A., 2023. Earlier collapse of Anthropocene ecosystems driven by multiple faster and noisier drivers. Nature Sustainability, 6(11), pp.1331-1342. https://doi.org/10.1038/s41893-023-01157-x

Willis, R., Curato, N. and Smith, G., 2022. Deliberative democracy and the climate crisis. Wiley Interdisciplinary Reviews: Climate Change, 13(2), p.e759. https://doi.org/10.1002/wcc.759

World Commission on the Ethics of Scientific Knowledge and Technology (COMEST), 2023. Report of the World Commission on the Ethics of Scientific Knowledge and Technology (COMEST) on the ethics of climate engineering. Paris: UNESCO. Available at: https://unesdoc.unesco.org/ark:/48223/pf0000386677 (Accessed: 1 September 2025).

Wunderling, N., Winkelmann, R., Rockström, J., Loriani, S., Armstrong McKay, D.I., Ritchie, P.D., Sakschewski, B. and Donges, J.F., 2023. Global warming overshoots increase risks of climate tipping cascades in a network model. Nature Climate Change, 13(1), pp.75-82. https://doi.org/10.1038/s41558-022-01545-9

Xie, M., Moore, J.C., Zhao, L., Wolovick, M. and Muri, H., 2022. Impacts of three types of solar geoengineering on the Atlantic Meridional Overturning Circulation. Atmospheric Chemistry and Physics, 22(7), pp.4581-4597. https://doi.org/10.5194/acp-22-4581-2022

Yamineva, Y., Kulovesi, K. and Recio, E. eds., 2024. Reducing Emissions of Short-Lived Climate Pollutants: Perspectives on Law and Governance. Brill/Nijhoff. ISBN: 978-90-04-68408-9

Zemp, D.C., Schleussner, C.F., Barbosa, H.M., Hirota, M., Montade, V., Sampaio, G., Staal, A., Wang-Erlandsson, L. and Rammig, A., 2017. Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. Nature communications, 8(1), p.14681. https://doi.org/10.1038/ncomms14681

References 1.3

Appleby JK (2025) The United States, Europe, and the Global Compacts: Honoring the Right to Remain and the Right to Migrate. Journal on Migration and Human Security 13(1). SAGE Publications Inc: 151–167. https://doi.org/10.1177/23315024241306416

Battiston S, Mandel A, Monasterolo I, et al. (2017) A climate stress-test of the financial system. Nature Climate Change 7(4). Nature Publishing Group: 283–288. https://doi.org/10.1038/nclimate3255

Berkhout F, Dow K and Thomas A (2024) Delayed, abrupt and unjust: An institutionalist perspective on limits to climate change adaptation. Climate Risk Management 44: 100611. https://doi.org/10.1016/j.crm.2024.100611

Biesbroek R, Haasnoot M, Mach KJ, et al. (2025) Adaptation planning in the context of a weakening and possibly collapsing Atlantic Meridional Overturning Circulation (AMOC). Regional Environmental Change 25(3): 93. https://doi.org/10.1007/s10113-025-02434-5

Bolton P, Morgan D, Pereira da Silva LA, et al. (2020) The Green Swan: Central banking and financial stability in the age of climate change. Bank for International Settlements. Available at: https://www.bis.org/publ/othp31.pdf.

Carbon Brief (2023) Three major gaps in climate-adaptation finance for developing countries. In: Carbon Brief. Available at: https://www.carbonbrief.org/guest-post-three-major-gaps-in-climate-adaptation-finance-for-developing-countries/ (accessed 4 September 2025).

Costanza R, d'Arge R, de Groot R, et al. (1997) The value of the world's ecosystem services and natural capital. Nature 387(6630). Nature Publishing Group: 253–260. https://doi.org/ https://doi.org/10.1038/387253a0

Costanza R, de Groot R, Braat L, et al. (2017) Twenty years of ecosystem services: How far have we come and how far do we still need to go? Ecosystem Services 28: 1–16. https://doi.org/10.1016/j.ecoser.2017.09.008

Curato N, Dryzek JS, Levai D, et al. (2025) Where next for global climate deliberation: From proof of concept to a role in transformation. Earth System Governance 25: 100280. https://doi.org/10.1016/j.esg.2025.100280

Dakos V, Boulton CA, Buxton JE, et al. (2024) Tipping point detection and early warnings in climate, ecological, and human systems. Earth System Dynamics 15(4). Copernicus GmbH: 1117–1135. https://doi.org/10.5194/esd-15-1117-2024

Dasgupta P (2021) The Economics of Biodiversity: The Dasgupta Review. 20 August. UK. Available at: https://www.gov.uk/government/publications/final-report-the-economics-of-biodiversity-the-dasgupta-review (accessed 4 September 2025).

Desmet K, Kopp RE, Kulp SA, et al. (2021) Evaluating the Economic Cost of Coastal Flooding. American Economic Journal: Macroeconomics 13(2): 444–486. https://doi.org/10.1257/mac.20180366

Dryzek JS (2016) Institutions for the Anthropocene: Governance in a Changing Earth System. British Journal of Political Science 46(4): 937–956. https://doi.org/v10.1017/S0007123414000453

EEA (2024) European Climate Risk Assessment. 10 March. European Environment Agency. Available at: https://www.eea.europa.eu/en/analysis/publications/european-climate-risk-assessment (accessed 4 September 2025).

Escobar O and Elstub S (2025) Climate Assemblies: New Civic Institutions for a Climate-changed World. Berlin: De Gruyter. https://doi.org/10.1515/9783111328393

EU (2021) Forging a climate-resilient Europe - the new EU Strategy on Adaptation to Climate Change. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN (accessed 4 September 2025).

FSB (2025) Assessment of Climate-related Vulnerabilities: Analytical framework and toolkit. 16 January. Available at: https://www.fsb.org/2025/01/assessment-of-climate-related-vulnerabilities-analytical-framework-and-toolkit/ (accessed 6 September 2025).

Galaz V, Sterblom HÖ, Bodin Ö, et al. (2016) Global networks and global change-induced tipping points. International Environmental Agreements 16: 189–221. https://doi.org/10.1007/s10784-014-9253-6

Galmarini S, Roman Cuesta RM, Dentener F, et al. (2025) Raising Awareness of Earth System Tipping Points: Implications for EU Governance : Workshop Report. Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2760/9047293 (accessed 4 September 2025).

Gao C, Lan X, Li N, et al. (2024) Large language models empowered agent-based modeling and simulation: a survey and perspectives. Humanities and Social Sciences Communications 11(1). Palgrave: 1259. https://doi.org/10.1057/s41599-024-03611-3

Ghaffarzadegan N, Majumdar A, Williams R, et al. (2024) Generative agent-based modeling: an introduction and tutorial. System Dynamics Review 40(1): e1761. https://doi.org/10.1002/sdr.1761

Gupta J, Liverman D, Prodani K, et al. (2023) Earth system justice needed to identify and live within Earth system boundaries. Nature Sustainability. Nature Publishing Group: 1–9. https://doi.org/10.1038/s41893-023-01064-1

Hilson C and Arnall A (2025) Sea level rise, claims-making and managed retreat in Fairbourne, North Wales. Climate Policy 25(6). Taylor & Francis: 852–865. https://doi.org/10.1080/14693062.2024.2420739

IPBES (2024) Thematic Assessment Report on the Interlinkages among Biodiversity, Water, Food and Health of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (eds PA Harrison, PD McElwee, and TL Van Huysen). Bonn, Germany: IPBES Secretariat. Available at: https://doi.org/10.5281/zenodo.13850054.

IPCC (2023) Climate Change 2023: Synthesis Report. In: Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (Eds.)]. Geneva, Switzerland: Intergovernmental Panel on Climate Change, pp. 35–115. Available at: 10.59327/IPCC/AR6-9789291691647.

Juhola S, Filatova T, Hochrainer-Stigler S, et al. (2022) Social tipping points and adaptation limits in the context of systemic risk: Concepts, models and governance. Frontiers in Climate 4. https://doi.org/10.3389/fclim.2022.1009234

Kedward K, Ryan-Collins J and Chenet H (2023) Biodiversity loss and climate change interactions: financial stability implications for central banks and financial supervisors. Climate Policy 23(6). Taylor & Francis: 763–781. https://doi.org/10.1080/14693062.2022.2107475

Kousky C (2019) Threats to Insurability. In: Kunreuther H, Meyer RJ, and Michel-Kerjan EO (eds) The Future of Risk Management. University of Pennsylvania Press, pp. 251–266. Available at: https://www.jstor.org/stable/j.ctv16t6ggg.17 (accessed 6 September 2025). https://doi.org/978-0-8122-2508-2

Kwadijk JCJ, Haasnoot M, Mulder JPM, et al. (2010) Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. WIREs Climate Change 1(5): 729–740. https://doi.org/10.1002/wcc.64

Laybourn L, Abrams J, Benton D, et al. (2024) The security blind spot: Cascading climate impacts and tipping points threaten national security. Institute for Public Policy Research, IPPR. Available at: http://www.ippr.org/articles/security-blind-spot.

Lenton TM, Rockström J, Gaffney O, et al. (2019) Climate tipping points — too risky to bet against. Nature 575(7784). 7784. Nature Publishing Group: 592–595. . https://doi.org/10.1038/d41586-019-03595-0

Lorenzoni I, Jordan AJ, Sullivan-Thomsett C, et al. (2025) A review of National Citizens' Climate Assemblies: learning from deliberative events. Climate Policy 0(0). Taylor & Francis: 1–17. https://doi.org/10.1080/14693062.2024.2449416

Marsden L, Ryan-Collinss J, Abrams J, et al. (2024) Ecosystem tipping points: Understanding the risks to the economy and the financial system | Bartlett Faculty of the Built Environment. 25 April. UK: UCL Institute for Innovation and Public Purpose. Available at: https://www.ucl.ac.uk/bartlett/publications/2024/apr/ecosystem-tipping-points-understanding-risks-economy-and-financial-system (accessed 4 September 2025).

McNamara KE and Jackson G (2019) Loss and damage: A review of the literature and directions for future research. WIREs Climate Change 10(2): e564. https://doi.org/10.1002/wcc.564

Merikanto J, Makonen R, Thölix L, et al. (2024) The Significance of Climate Tipping Points for Finland: Latest Information on the Possible Shutdown of the Atlantic Meridional Overturning Circulation (AMOC) and Preventive Climate Actions. Atmosphere and Climate Competence Center (ACCC). Available at: https://www.acccflagship.fi/wp-content/uploads/Tipping_points_Policy_Brief_english.pdf.

Meyerson D, Mackenzie C and MacDermott T (eds) (2020) Procedural Justice and Relational Theory: Empirical, Philosophical, and Legal Perspectives. London: Routledge. https://doi.org/10.4324/9780429317248

Micinski NR and Lefebvre C (2024) The Geopolitics in the Global Compacts: Sovereignty, Emerging Norms, and Hypocrisy in Global Migration Governance. Geopolitics 29(1). Routledge: 1–12. https://doi.org/10.1080/14650045.2023.2265321

Milkoreit M, Boyd E, Constantino SM, et al. (2024) Governance for Earth system tipping points – A research agenda. Earth System Governance 21: 100216. https://doi.org/10.1016/j.esg.2024.100216

NGSF (2022) Central banking and supervision in the biosphere: an agenda for action on biodiversity loss, financial risk and system stability. Available at: https://www.ngfs.net/en/publications-and-statistics/publications/central-banking-and-supervision-biosphere-agenda-action-biodiversity-loss-financial-risk-and-system (accessed 6 September 2025).

NGSF (2025) NGFS Short-term Climate Scenarios for central banks and supervisors. Available at: https://www.ngfs.net/en/publications-and-statistics/publications/ngfs-short-term-climate-scenarios-central-banks-and-supervisors (accessed 4 September 2025).

Norway M of F (2018) NOU 2018: 17 - Climate risk and the Norwegian economy. NOU, 12 December. regjeringen.no. Available at: https://www.regjeringen.no/en/dokumenter/nou-2018-17/id2622043/ (accessed 4 September 2025).

OECD (2023) Assessing biodiversity-related financial risks. OECD Environment Policy Papers No. 36, 26 April. Paris: OECD. Available at: https://www.oecd.org/en/publications/assessing-biodiversity-related-financial-risks_d52137a5-en.html (accessed 6 September 2025).

OECD (2025) OECD deliberative Democracy Database. Available at: https://www.peoplepowered.org/resources-content/oecd-deliberative-democracy-database (accessed 6 September 2025).

Parsons ES, Jowell A, Veidis E, et al. (2024) Climate change and inequality. Pediatric Research. Nature Publishing Group: 1–8. https://doi.org/10.1038/s41390-024-03153-z

Pescaroli G, Dryhurst S and Karagiannis GM (2025) Bridging gaps in research and practice for early warning systems: new datasets for public response. Frontiers in Communication 10. Frontiers: 1451800. https://doi.org/10.3389/fcomm.2025.1451800

Roman Cuesta R, Dentener F, Galmarini S, et al. (2025) Earth System Tipping Points are a threat to Europe. Ispra (Italy): European Commission.

Ruhl JB and Salzman J (2023) The Greens' Dilemma: Building Tomorrow's Climate Infrastructure Today. Emory Law Journal 73(1): 1. https://scholarlycommons.law.emory.edu/elj/vol73/iss1/1

Schweizer PJ and Juhola S (2024) Navigating systemic risks: governance of and for systemic risks. Global Sustainability 7(e38). https://doi.org/10.1017/sus.2024.30

Sen A (2009) The Idea of Justice. Harvard University Press. https://doi.org/10.4159/9780674054578

Stokes E and Smyth C (2024) Hope-Bearing Legislation? The Well-being of Future Generations (Wales) Act 2015. Transnational Environmental Law 13(3): 569–587. https://doi.org/10.1017/S2047102524000219

Thalheimer L, Cottier F, Kruczkiewicz A, et al. (2025) Prioritizing involuntary immobility in climate policy and disaster planning. Nature Communications 16(1). Nature Publishing Group: 2581. https://doi.org/10.1038/s41467-025-57679-9

Trust S, Saye L, Bettis O, et al. (2025) Planetary Solvency – finding our balance with nature; Global risk management for human prosperity. Institute and Faculty of Actuaries, University of Exeter.

Ullah AKMA (2025) Migration as International Relations. Global Networks 25(3): e70016. https://doi.org/10.1111/glob.70016

UNEP (2022) Prioritising nature-related disclosures: considerations for high-risk sectors. Available at: https://www.unepfi.org/publications/prioritising-nature-related-disclosures-considerations-for-high-risk-sectors/ (accessed 6 September 2025).

WEF (2020) Nature Risk Rising: Why the Crisis Engulfing Nature Matters for Business and the Economy. World Economic Forum. Available at: https://www.weforum.org/publications/nature-risk-rising-why-the-crisis-engulfing-nature-matters-for-business-and-the-economy/ (accessed 4 September 2025).

WEF (2024) Global Risks Report 2024. World Economic Forum. Available at: https://www.weforum.org/publications/global-risks-report-2024/ (accessed 6 September 2025).

Wunderling N, von der Heydt AS, Aksenov Y, et al. (2024) Climate tipping point interactions and cascades: a review. Earth System Dynamics 15(1). Copernicus GmbH: 41–74. https://doi.org/10.5194/esd-15-41-2024

Young O (2021) Grand Challenges of Planetary Governance: Global Order in Turbulent Times. Edward Elgar Publishing. https://doi.org/10.4337/9781802200720v

Wibisono RB (2024) Migration, Security, and Human Rights: The Struggle for Refugee Protection. The Sunan Ampel Review of Political and Social Sciences 4(1): 61–82. https://doi.org/10.15642/sarpass.2024.4.1.61-82

Woodworth F (2024) Exclusion of Climate Migrants from the Global Compact on Refugees. Geopolitics 29(1). Routledge: 118–147. https://doi.org/10.1080/14650045.2023.2225242

References 1.4

Ahmad, H. M. (2024) A Crosswinds of Corporate Accountability: Corporate Climate Liability in the Canadian Legal Abyss. Osgoode Digital Commons, All Papers. 393. Available at: https://digitalcommons.osgoode.yorku.ca/all_papers/393/

Amazon Cooperation Treaty Organization (ACTO) (2023) Declaration of Belém. Available at: https://otca.org/en/wp-content/uploads/2023/10/Declaration-of-Belem.pdf

Aristova, E., & Nichols, L. (2024) Climate change on the board: navigating directors' duties. Journal of Corporate Law Studies, 24(2), 479–514. https://doi.org/10.1080/14735970.2024.2414466

Avila Santamaria, R. (2024) The Systemic Theory of Law in the Jurisprudence of Nature in Ecuador: From the Machine to the Web of Life, in More Than Human Rights, César Garavito-Rodríguez (ed), NYU. Available at: https://mothrights.org/wp-content/themes/moth/assets/images/book/pdfs/More-Than-Human-Rights_Book.pdf

Basic Law for the Federal Republic of Germany. https://www.gesetze-im-internet.de/englisch_gg/englisch_gg.html

Bennett, N.J., López de la Lama, R., Le Billon, P., Ertör, I. and Morgera, E. (2023) Ocean defenders and human rights. Frontiers in Marine Science, 9, p.1089049.https://doi.org/10.3389/fmars.2022.1089049

Buhmann, K., Fonseca, A., Andrews, N., Amatulli, G. (2025) The Routledge Handbook on Meaningful Stakeholder Engagement, 494 p. Routledge.

Chapin, F.S., Weber, E.U., Bennett, E.M. et al. (2022) Earth stewardship: Shaping a sustainable future through interacting policy and norm shifts. Ambio 51, 1907–1920. https://doi.org/10.1007/s13280-022-01721-3

Civil Freedoms & HRD Database, Business and Human Rights Resource Centre. Available at: https://www.business-humanrights.org/en/from-us/human-rights-defenders-database/

Constitution of the Republic of Ecuador. Available at: https://www.defensa.gob.ec/wp-content/uploads/downloads/2021/02/Constitucion-de-la-Republica-del-Ecuador_act_ene-2021.pdf

Constitution of the Republic of South Africa. Available at: https://www.justice.gov.za/constitution/SAConstitution-web-eng.pdf

Earth Law Center (2025) A Voice for Coral Reef Ecosystems Through the Rights of Nature and Ecocentric Law. Available at: https://static1.squarespace.com/static/55914fd1e4b01fb0b851a814/t/68499257692311f024a8edcdb/1749652058340/Rights+of+Coral+Reefs+Toolkit_ELC.pdf

European Parliament, the Council and the Commission (2000) Charter of Fundamental Rights of the European Union. Official Journal of the European Communities 18.12.2000, C 364/1. Available at: https://www.europarl.europa.eu/charter/pdf/text_en.pdf

European Commission (2024) Directive on corporate sustainability due diligence (Directive 2024/1760) Available at: https://commission.europa.eu/business-economy-euro/doing-business-eu/sustainability-due-diligence-responsible-business/corporate-sustainability-due-diligence_en

Freeman, B. and Handagard, R. (2025) Business Frameworks and Actions to Support Human Rights Defenders. International Human Rights Service and Business & Human Rights Resource Centre. Available at: https://ishr.ch/latest-updates/business-frameworks-and-actions-to-support-defenders-a-retrospective-of-10-years-of-progress-and-challenges/

Front Line Defenders, Global Analysis 2024/25, 2025. Available at: https://www.ohchr.org/en/documents/thematic-reports/ahrc5646-scene-setting-report-report-special-rapporteur-promotion-and

Global Alliance for the Rights of Nature, Rights of Nature Map, 2024. Available at: https://www.garn.org/rights-of-nature-map/

Gupta, J., Liverman, D., Prodani, K., Aldunce, P., Bai, X., Broadgate, W., Ciobanu, D., Gifford, L., Gordon, C., Hurlbert, M. and Inoue, C.Y. (2023) Earth system justice needed to identify and live within Earth system boundaries. Nature Sustainability, 6(6), 630–638. https://doi.org/10.1038/s41893-023-01064-1

Hanna, P., & Vanclay, F. (2013) Human rights, Indigenous peoples and the concept of Free, Prior and Informed Consent. Impact Assessment and Project Appraisal 31(2), 146–157. https://doi.org/10.1080/14615517.2013.780373

Institute and Faculty of Actuaries (2025) Current climate policies risk catastrophic societal and economic impacts. Available at: https://actuaries.org.uk/media-release/current-climate-policies-risk-catastrophic-societal-and-economic-impacts/ (Accessed: 7 September 2025).

Inter-American Court of Human Rights (IACHR), 2012. Case of the Kichwa Indigenous People of Sarayaku v. Ecuador. Available at: https://corteidh.or.cr/docs/casos/articulos/seriec_245_ing.pdf

Inter-American Court of Human Rights (IACHR) (2025) Advisory Opinion OC-32/25: The Climate Emergency and Human Rights. San José, Costa Rica: Inter-American Court of Human Rights. Available at: https://www.corteidh.or.cr/tablas/OC-32-2025/index-eng.html (Accessed: 1 September 2025).

Intergovernmental Panel on Climate Change (IPCC) (2023) Sixth Assessment Report. Available at: https://www.ipcc.ch/assessment-report/ar6/

International Court of Justice (ICJ) (2025) Obligations of States in Respect of Climate Change (Request for Advisory Opinion). Available at: https://www.icj-cij.org/case/187

International Law Association Committee on Legal Principles Relating to Climate Change (2014) Declaration of Legal Principles Relating to Climate Change, Resolution 2/2014. Available at: https://www.ila-hq.org/en_GB/documents/conference-resolution-no-2-english-washington-2014

International Tribunal for the Law of the Sea (ITLOS) (2024) Request for an Advisory Opinion Submitted by the Commission of Small Island States on Climate Change and International Law. Available at: https://itlos.org/fileadmin/itlos/documents/cases/31/Advisory_Opinion/C31_Adv_Op_21.05.2024_orig.pdf

Jodoin, S., Savaresi, A. and Wewerinke-Singh, M. (2021) Rights-based approaches to climate decision-making. Current Opinion in Environmental Sustainability, 52, pp.45-53. https://doi.org/10.1016/j.cosust.2021.06.004

Kotzé, L.J. (2019) The Anthropocene, earth system vulnerability and socio-ecological injustice in an age of human rights. Journal of Human Rights and the Environment, 10(1), pp.62-85. https://doi.org/10.4337/jhre.2019.01.04

Kotzé LJ. (2021) Neubauer et al. versus Germany: Planetary Climate Litigation for the Anthropocene? German Law Journal. 22(8):1423-1444. https://doi.org/10.1017/glj.2021.87

Lazard, O., Bissett, M., Dyke, J. (2025) Geoengineering: Assessing Risks in the Era of Planetary Security. Available at: https://carnegie-production-assets.s3.amazonaws.com/static/files/Lazard,%20Bissett,%20Dyke_Geoengineering%20Planetary%20Risks.pdf (Accessed: 7 September 2025).

Leghari v. Federation of Pakistan, W.P. No. 25501/201, 2015. Available at: https://climatecasechart.com/non-us-case/ashgar-leghari-v-federation-of-pakistan/

Litwin, D. and Savourey, E. (2025) Human Rights in EU Sustainable Finance, Journal of Financial Regulation, Volume 11, Issue 1, Pages 41–72, https://doi.org/10.1093/jfr/fjaf001

Llurimagua Case, Corte Provincial de Justicia de Imbabura, No. 10332-2021-00937, 2023. Available at: https://www.derechosdelanaturaleza.org.ec/wp-content/uploads/2021/05/SENTENCIA-SEGUNDA-INSTANCIA-LLURIMAGUA-1.pdf

Los Cedros Case, Constitutional Court of Ecuador, No. 1149-19-JP/20, 2021. Available at: https://celdf.org/wp-content/uploads/2015/08/Los-Cedros-Decision-ENGLISH-Final.pdf

Mayer B. (2022) The judicial assessment of states' action on climate change mitigation. Leiden Journal of International Law. 35(4):801-824. https://doi.org/10.1017/S092215652200036X

McVey, M. and Savaresi, A (2025) The ICJ Advisory Opinion on Climate Change: A Business and Human Rights Perspective. Opinio Juris 04.08.25. Available at: https://opiniojuris.org/2025/08/04/the-icj-advisory-opinion-on-climate-change-a-business-and-human-rights-perspective/

Milkoreit, M., Boyd, E., Constantino, S.M., Hausner, V.H., Hessen, D.O., Kääb, A., McLaren, D., Nadeau, C., O'Brien, K., Parmentier, F.J. and Rotbarth, R. (2024) Governance for Earth system tipping points–A research agenda. Earth System Governance, 21, p.100216. https://doi.org/10.1016/j.esg.2024.100216

Moyn, S. (2019) Not Enough, 296p. Harvard University Press.

Neubauer, et al. v. Germany, 2021. Available at: https://climatecasechart.com/non-us-case/neubauer-et-al-v-germany/

OECD Guidelines for Multinational Enterprises, 2023. Available at: https://www.oecd.org/en/publications/oecd-guidelines-for-multinational-enterprises-on-responsible-business-conduct_81f92357-en.html

Office of the Compliance Advisor Ombudsman, Available at: https://www.cao-ombudsman.org/

Pariotti, E. (2023) Vulnerability and Human Rights: Which Compatibility?. International Journal for the Semiotic Law 36, 1401–1413 https://doi.org/10.1007/s11196-023-09977-y

Paris Agreement, 2015. Available at: https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

Pereira, L.M., Gianelli, I., Achieng, T., Amon, D., Archibald, S., Arif, S., Castro, A., Chimbadzwa, T.P., Coetzer, K., Field, T.L. and Selomane, O. (2024) Equity and justice should underpin the discourse on tipping points. Earth System Dynamics, 15(2), pp.341-366. https://doi.org/10.5194/esd-15-341-2024

Pereira, L. M., Smith, S. R., Gifford, L., Newell, P., Smith, B., Villasante, S., Achieng, T., Castro, A., Constantino, S. M., Ghadiali, A., Vogel, C., and Zimm, C. (2023) Risks, Ethics and Justice in the governance of positive tipping points, EGUsphere. https://doi.org/10.5194/egusphere-2023-1454

Potsdam Institute for Climate Impact Research (2024) 38 trillion dollars in damages each year: World economy already committed to income reduction of 19 % due to climate change. Available online at https://www.pik-potsdam.de/en/news/latest-news/38-trillion-dollars-in-damages-each-year-world-economy-already-committed-to-income-reduction-of-19-due-to-climate-change (Accessed: 1 September 2025)

Rammelt, C.F., Gupta, J., Liverman, J., Ciobanu, D., Abrams, J., Bai, X., Gifford, L., Gordon, C., Hurlbert, M., Inoue, C., Jacobson, L., Lade, S., Lenton, T., Armstrong McKay, D., Nakicenovic, N., Okereke, C., Otto, I., Pereira, L., Prodani, K., Rockström, J., Stewart-Koster, B., Verburg, P., & Zimm, C. (2022) Impacts of meeting minimum access on critical earth systems amidst the Great Inequality. Nature Sustainability 6, 212–221. https://doi.org/10.1038/s41893-022-00995-5

Reinsberg, B., and Steinert, C. V. (2025) The French duty of vigilance law: reconciling human rights and firm profitability. Review of International Political Economy, 1–33. https://doi.org/10.1080/09692290.2025.2519189

Ritz, V. (2024) Climate tipping points: Tracing the limits of political discretion. Leiden Journal of International Law, pp.1-22. https://doi.org/10.1017/S0922156524000487

Rockström, J., Kotzé, L., Milutinović, S., Biermann, F., Brovkin, V., Donges, J., Ebbesson, J., French, D., Gupta, J., Kim, R. and Lenton, T. (2024) The planetary commons: A new paradigm for safeguarding Earth-regulating systems in the Anthropocene. Proceedings of the National Academy of Sciences, 121(5), p.e2301531121. https://doi.org/10.1073/pnas.2301531121

Rodríguez-Garavito, C. (2022) Litigating the Climate Emergency: How Human Rights, Courts, and Legal Mobilization Can Bolster Climate Action, Cambridge University Press. https://doi.org/10.1017/9781009106214

Rodríguez-Garavito, C. (2024) More-Than-Human Rights: Law, Science, and Storytelling beyond Anthropocentrism in More Than Human Rights, César Garavito-Rodríguez (ed), NYU. Available at: https://mothrights.org/wp-content/themes/moth/assets/images/book/pdfs/More-Than-Human-Rights_Book.pdf

Rogge, M. (2022) Risk, Uncertainty and the Future of Corporate Human Rights Due Diligence. Corporate Responsibility Initiative Working Paper Series 2022.81, Mossavar-Rahmani Center for Business & Government. Available at: https://dash.harvard.edu/server/api/core/bitstreams/a1d0df07-9973-483b-9c20-42c253643703/content

Savaresi, A. (2025) Verein KlimaSeniorinnen Schweiz and Others v Switzerland: Making climate change litigation history. Review of European, Comparative & International Environmental Law, 34(1), pp.279-287. https://doi.org/10.1111/reel.12612

Savourey, E and Brabant, S. (2021) The French Law on the Duty of Vigilance: Theoretical and Practical Challenges Since its Adoption. Business and Human Rights Journal. 2021;6(1):141-152. https://doi.org/10.1017/bhj.2020.30

Sen, A. (2009) The Idea of Justice. Harvard University Press https://doi.org/10.2307/j.ctvjnrv7n

Setzer, J. and Higham, C. (2025) Global Trends in Climate Change Litigation: 2025 Snapshot. London: Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science. https://doi.org/10.21953/LSE.LH46LE9Y8SGI

Siqueira-Gay, J., Sánchez, L.E. (2021) The outbreak of illegal gold mining in the Brazilian Amazon boosts deforestation. Reg Environ Change 21, 28. https://doi.org/10.1007/s10113-021-01761-7

State of the Netherlands v. Stichting Urgenda, 2019. Available at: https://uitspraken.rechtspraak.nl/details?id=ECLI:NL:HR:2019:2007

Tigre, M.A., Murcott, M.J. and Samuel, S.A., (eds) (2025) Climate Litigation and Vulnerabilities: Global South Perspectives, Routledge. https://doi.org/10.4324/9781003470632

United Nations Economic Commission for Europe (2024) Statement regarding the four-year prison sentence imposed on Mr. Daniel Shaw for his involvement in peaceful environmental protest in the United Kingdom, United Nations Economic Commission for Europe, Michel Forst, ACSR/C/2024/26. Available at: https://unece.org/sites/default/files/2024-07/ACSR_C_2024_26_UK_SR_EnvDefenders_public_statement_18.07.2024.pdf

United Nations Economic Commission for Europe (2024) Visit to London, United Kingdom of Great Britain and Northern Ireland, 10-12 January 2024 End of Mission Statement, Michel Forst. Available at: https://unece.org/sites/default/files/2024-01/Aarhus_SR_Env_Defenders_statement_following_visit_to_UK_10-12_Jan_2024.pdf

United Nations Framework Convention on Climate Change (UNFCCC) (2024) Periodic Review. UNFCCC. Available at: https://unfccc.int/topics/science/workstreams/periodic-review#Continuation-of-the-periodic-review (Accessed: 1 September 2025).

United Nations General Assembly (UNGA) (2017) Report of the Special Rapporteur on the situation of human rights defenders, Michel Forst, A/72/170. Available at: https://docs.un.org/en/A/72/170

United Nations General Assembly (UNGA) (2022) The human right to a clean, healthy and sustainable environment. A/RES/76/300. Available at: https://docs.un.org/en/A/RES/76/300

United Nations Guiding Principles on Business and Human Rights (2011) HR/PUB/11/04 Available at: https://www.ohchr.org/sites/default/files/documents/publications/guidingprinciplesbusinesshr_en.pdf

United Nations Human Rights Committee, 2019. General comment No. 36, CCPR/C/GC/36. Available at: https://docs.un.org/en/CCPR/C/GC/36

United Nations Office of the High Commissioner for Human Rights (OHCHR) (2018) General recommendation No. 37 on gender-related dimensions of disaster risk reduction in a changing climate, CEDAW/C/GC/37. Available at: https://www.ohchr.org/en/documents/general-comments-and-recommendations/general-recommendation-no37-2018-gender-related

United Nations Office of the High Commissioner for Human Rights (OHCHR) (2023) General comment No. 26 on children's rights and the environment with a special focus on climate change, CRC/C/GC/26. Available at: https://www.ohchr.org/en/documents/general-comments-and-recommendations/crccgc26-general-comment-no-26-2023-childrens-rights

United Nations Office of the High Commissioner for Human Rights (OHCHR) (2024) Green Financing - a just transition to protect the rights of Indigenous Peoples - Report of the Special Rapporteur on the human rights of Indigenous Peoples, José Francisco Calí Tzay, A/HRC/54/31. Available at: https://www.ohchr.org/en/documents/thematic-reports/ahrc5431-green-financing-just-transition-protect-rights-indigenous

United Nations Office of the High Commissioner for Human Rights (OHCHR) (2024) Scene-setting report - Report of the Special Rapporteur on the promotion and protection of human rights in the context of climate change, Elisa Morgera, A/HRC/56/46. Available at: https://www.ohchr.org/en/documents/thematic-reports/ahrc5646-scene-setting-report-report-special-rapporteur-promotion-and

United Nations Universal Declaration of Human Rights (1948). Available at: https://www.un.org/sites/un2.un.org/files/2021/03/udhr.pdf

Verein KlimaSeniorinnen Schweiz and Others v. Switzerland (GC). Available at: https://hudoc.echr.coe.int/eng#{%22itemid%22:[%22002-14304%22]}

Wallbott, L. and Schapper, A. (2017) Negotiating by own standards? The use and validity of human rights norms in UN climate negotiations. International Environmental Agreements: Politics, Law and Economics, 17(2), pp.209-228.

Wewerinke-Singh M, Maxwell L. Human Rights. In: Wewerinke-Singh M, Mead S, eds. (2025) The Cambridge Handbook on Climate Litigation. Cambridge Law Handbooks. Cambridge University Press 171-199. https://doi.org/10.1017/9781009409155.010

World Business Council on Sustainable Development (2018) Enterprise Risk Management: Applying enterprise risk management to environmental, social and governance-related risks. Available at: https://docs.wbcsd.org/2018/10/COSO_WBCSD_ESGERM_Guidance.pdf

Zografos, C., Robbins, P. (2020) Green Sacrifice Zones, or Why a Green New Deal Cannot Ignore the Cost Shifts of Just Transitions. One Earth 3(5): 543-546. https://doi.org/10.1016/j.oneear.2020.10.012

References 1.5

Aðalgeirsdóttir, G.T., Bindoff, N., Björnsson, H., et al. (2024) Open Letter by Climate Scientists to the Nordic Council of Ministers. Available at: https://en.vedur.is/media/ads_in_header/AMOC-letter_Final.pdf (Accessed: 2 September 2025).

Ansell, C. and Gash, A. (2008) 'Collaborative Governance in Theory and Practice', Journal of Public Administration Research and Theory, 18(4), pp. 543-571. https://doi.org/10.1093/jopart/mum032

Ansell, C., Sørensen, E. and Torfing, J. (2017) 'Improving Policy Implementation Through Collaborative Policymaking', Policy & Politics, 45(3), pp. 467-486. https://doi.org/10.1332/030557317X14972799760260

BBC (2022) How pop band A-ha inspired Norway's electric car revolution. Available at: https://www.bbc.com/news/uk-scotland-63375504 (Accessed: 6 September 2025).

Biermann, F., Pattberg, P., van Asselt, H. and Zelli, F. (2009) 'The Fragmentation of Global Governance Architectures: A Framework for Analysis', Global Environmental Politics, 9(4), pp. 14-40. https://doi.org/10.1162/glep.2009.9.4.14

Boari, C. and Riboldazzi, F. (2014) 'How Knowledge Brokers Emerge and Evolve: The Role of Actors' Behaviour', Research Policy, 43(4), pp. 683-695. https://doi.org/10.1016/j.respol.2014.01.007

Figueres, C. (2022) Solving Climate Change Requires A New Social Contract. Available at: https://time.com/6140430/climate-change-trust/ (Accessed: 6 September 2025).

Guston, D.H. (2001) 'Boundary Organizations in Environmental Policy and Science: An Introduction', Science, Technology & Human Values, 26(4), pp. 399-408. https://doi.org/10.1177/016224390102600401

Howlett, M. (2009) 'Process Sequencing Policy Dynamics: Beyond Homeostasis and Path Dependency', Journal of Public Policy, 29(3), pp. 241-262. https://doi.org/10.1017/S0143814X09990158

Howlett, M., McConnell, A. and Perl, A. (2017) 'Moving Policy Theory Forward: Connecting Multiple Stream and Advocacy Coalition Frameworks to Policy Cycle Models of Analysis', Australian Journal of Public Administration, 76(1), pp. 65-79. https://doi.org/10.1111/1467-8500.12191

Ingold, K., Fischer, M. and Cairney, P. (2017) 'Drivers for Policy Agreement in Nascent Subsystems: An Application of the Advocacy Coalition Framework to Fracking Policy in Switzerland and the UK'. Policy Studies Journal, 45(3), pp. 442-463. https://doi.org/10.1111/psj.12173

Jann, W. and Wegrich, K. (2007) 'Theories of the Policy Cycle'. In: Fischer, F., Miller, G.J. and Sidney, M.S. (eds) Handbook of Public Policy Analysis: Theory, Politics, and Methods. Routledge, pp. 43-62. https://doi.org/10.4324/9781315093192

McGinnis, M.D. and Ostrom, E. (2012) 'Reflections on Vincent Ostrom, Public Administration, and Polycentricity', Public Administration Review, 72(1), pp. 15-25. https://doi.org/10.1111/j.1540-6210.2011.02488.x

Meyer, M. (2010) 'The Rise of the Knowledge Broker', Science Communication, 32(1), pp. 118-127. https://doi.org/10.1177/1075547009359797

Milkoreit, M., Boyd, E., Constantino, S.M., et al. (2024) 'Governance for Earth system tipping points – A research agenda', Earth System Governance, 21(100216), pp. 1-15. https://doi.org/10.1016/j.esg.2024.100216

Miller, C. (2001) 'Hybrid Management: Boundary Organizations, Science Policy, and Environmental Governance in the Climate Regime', Science, Technology & Human Values, 26(4), pp. 478-500. https://doi.org/10.1177/016224390102600405

Operaatio Arktis (2025) Mission. Available at: https://www.operaatioarktis.fi/ (Accessed: 8 September 2025).

Reinecke, S. (2015) 'Knowledge brokerage designs and practices in four European climate services: A role model for biodiversity policies?', Environmental Science & Policy, 54, pp. 513-521. https://doi.org/10.1016/j.envsci.2015.08.007

Schroeder, H., Beyers, F., Schäpke, N.A., et al. (2025) 'The Role of Trust in the International Climate Negotiations', Environmental Policy and Governance, 35(2), pp. 328-343. https://doi.org/10.1002/eet.2144

UK Parliament House of Lords (2024) Climate Agenda. Available at: https://hansard.parliament.uk/Lords/2024-10-24/debates/DA117E0F-1B4A-4166-A971-ACF2B4EAB310/ClimateAgenda?highlight=amoc#contribution-217E7E75-4252-4B9F-A1F2-0958A3DA7E8D (Accessed: 2 September 2025).

UK Parliament House of Lords (2024) Climate Change: Atlantic Ocean. Available at: https://questions-statements.parliament.uk/written-questions/detail/2024-09-02/hl634 (Accessed: 2 September 2025).

UN (2024) Secretary-General's special address on climate action "A Moment of Truth". Available at: https://www.un.org/sg/en/content/secretary-general/speeches/2024-06-05 (Accessed: 6 September 2025).

Verein KlimaSeniorinnen Schweiz and Others v. Switzerland, Application No. 53600/20, 9 April 2024 (ECtHR Grand Chamber).

SECTION 2

EARTH SYSTEM TIPPING POINTS AND RISKS



Section lead authors:
Jesse Abrams, David Armstrong McKay, Joshua E. Buxton, Sina Loriani, Nico Wunderling

References 2.1

Armstrong McKay, D.I., Staal, A., Abrams, J.F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S.E., Rockström, J. and Lenton, T.M. (2022). Exceeding 1.5 C global warming could trigger multiple climate tipping points. Science, 377(6611), p.eabn7950.

Arnscheidt, C.W., Beard, S.J., Hobson, T., Ingram, P., Kemp, L., Mani, L., Marcoci, A., Mbeva, K., Ó hÉigeartaigh, S.S., Sandberg, A. and Sundaram, L.S., 2025. Systemic contributions to global catastrophic risk–ERRATUM. Global Sustainability, 8, p.e29.

Department for Environment, Food and Rural Affairs (DEFRA). (2023) Environmental Principles Policy Statement. Available at: https://www.gov.uk/government/publications/environmental-principles-policy-statement/environmental-principles-policy-statement (Accessed: 4 September 2025).

European Commission. (2000). Communication from the Commission on the precautionary principle (COM(2000) 1 final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52000DC0001 (Accessed: 4 September 2025).

Franzke, C. L., Ciullo, A., Gilmore, E. A., Matias, D. M., Nagabhatla, N., Orlov, A., ... & Sillmann, J. (2022). Perspectives on tipping points in integrated models of the natural and human Earth system: cascading effects and telecoupling. Environmental Research Letters, 17(1), 015004.

Helbing, D. (2013). Globally networked risks and how to respond. Nature, 497(7447), 51-59.

HM Government (2025) National Risk Register 2025. London: Cabinet Office.

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

IPCC, 2018: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. In Press.

Jones, R. N. (2001). An environmental risk assessment/management framework for climate change impact assessments. Natural hazards, 23(2), 197-230.

King, D., Schrag, D., Dadi, Z., Ye, Q. and Ghosh, A. (2015) Climate change: a risk assessment. London: UK Foreign & Commonwealth Office.

Klose, A. K., Wunderling, N., Winkelmann, R., and Donges, J. F. (2021). What do we mean,'tipping cascade'?. Environmental Research Letters, 16(12), 125011.

Kriegler, E., Hall, J. W., Held, H., Dawson, R., and Schellnhuber, H. J. (2009). Imprecise probability assessment of tipping points in the climate system. Proceedings of the National Academy of Sciences, 106(13), 5041-5046.

Lenton, T.M., McKay, D.I.A., Loriani, S., Abrams, J.F., Lade, S.J., Donges, J.F., Buxton, J.E., Milkoreit, M., Powell, T., Smith, S.R. and Constantino, S. (2023). The global tipping points report 2023 (University of Exeter).

Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., & Schellnhuber, H. J. (2019). Climate tipping points—too risky to bet against. Nature, 575(7784), 592-595.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., and Schellnhuber, H. J. (2008). Tipping elements in the Earth's climate system. Proceedings of the National Academy of Sciences, 105(6), 1786-1793.

Pescaroli, G., and Alexander, D. (2018). Understanding compound, interconnected, interacting, and cascading risks: A holistic framework. International Journal of Disaster Risk Reduction, 30, 315-327.

Renn, O., Lucas, K., Haas, A., and Jaeger, C. (2019). Things are different today: the challenge of global systemic risks. Journal of Risk Research, 22(4), 401-415.

Roberts F, De Meyer K and Hubble-Rose L (2021) Communicating climate risk: a handbook, Climate Action Unit, University College London. London, United Kingdom. DOI: 10.14324/000.rp.10137325

Rocha, J. C., Peterson, G., Bodin, Ö.,and Levin, S. (2018). Cascading regime shifts within and across scales. Science, 362(6421), 1379-1383.

Ruane, A.C., Vautard, R., Ranasinghe, R., Sillmann, J., Coppola, E., Arnell, N., Cruz, F.A., Dessai, S., Iles, C.E., Islam, A.S. and Jones, R.G. (2022). The climatic impact-driver framework for assessment of risk-relevant climate information. Earth's Future, 10(11), p.e2022EF002803.

Schaumann, F., and Alastrué de Asenjo, E. (2025). Weakening AMOC reduces ocean carbon uptake and increases the social cost of carbon. Proceedings of the National Academy of Sciences, 122(9), e2419543122.

Sillmann, J., Christensen, I., Hochrainer-Stigler, S. , Huang-Lachmann, J., Juhola, S., Kornhuber, K., Mahecha, M., Mechler, R. , Reichstein, M., Ruane, A.C., Schweizer, P.-J., and Wiliiams, S. (2022). ISC-UNDRR-RISK KAN Briefing note on systemic risk. International Science Council , Paris, France. 10.24948/2022.01.

Sillmann, J., Raupach, T.H., Findell, K.L., Donat, M., Alves, L.M., Alexander, L., Borchert, L., De Amorim, P.B., Buontempo, C., Fischer, E.M. and Franzke, C.L. (2024). Climate extremes and risks: links between climate science and decision-making. Frontiers in Climate, 6, p.1499765.

Simpson, N.P., Mach, K.J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R.J., Muccione, V., Mackey, B. and New, M.G. (2021). A framework for complex climate change risk assessment. One Earth, 4(4), pp.489-501.

Spaiser, V., Juhola, S., Constantino, S.M., Guo, W., Watson, T., Sillmann, J., Craparo, A., Basel, A., Bruun, J.T., Krishnamurthy, K. and Scheffran, J. (2024). Negative social tipping dynamics resulting from and reinforcing Earth system destabilization. Earth System Dynamics, 15(5), pp.1179-1206.

Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D., Summerhayes, C.P., Barnosky, A.D., Cornell, S.E., Crucifix, M. and Donges, J.F. (2018). Trajectories of the Earth System in the Anthropocene. Proceedings of the National Academy of Sciences, 115(33), pp.8252-8259.

United Nations (1992) Rio Declaration on Environment and Development. United Nations. Available at: https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_CONF.151_26_Vol.I_Declaration.pdf (Accessed: 4 September 2025).

Wang, S., Foster, A., Lenz, E.A., Kessler, J.D., Stroeve, J.C., Anderson, L.O., Turetsky, M., Betts, R., Zou, S., Liu, W. and Boos, W.R. (2023). Mechanisms and impacts of Earth system tipping elements. Reviews of Geophysics, 61(1), p.e2021RG000757.

Wood, R.A., Crucifix, M., Lenton, T.M., Mach, K.J., Moore, C., New, M., Sharpe, S., Stocker, T.F. and Sutton, R.T. (2023). A climate science toolkit for high impact-low likelihood climate risks. Earth's Future, 11(4), p.e2022EF003369.

Wunderling, N., Krönke, J., Wohlfarth, V., Kohler, J., Heitzig, J., Staal, A., Willner, S., Winkelmann, R. and Donges, J.F. (2021). Modelling nonlinear dynamics of interacting tipping elements on complex networks: the PyCascades package. The European Physical Journal Special Topics, 230(14), pp.3163-3176.

Wunderling, N., von der Heydt, A.S., Aksenov, Y., Barker, S., Bastiaansen, R., Brovkin, V., Brunetti, M., Couplet, V., Kleinen, T., Lear, C.H. and Lohmann, J. (2024). Climate tipping point interactions and cascades: a review. Earth System Dynamics, 15(1), pp.41-74.

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

Zscheischler, J., Westra, S., Van Den Hurk, B.J., Seneviratne, S.I., Ward, P.J., Pitman, A., AghaKouchak, A., Bresch, D.N., Leonard, M., Wahl, T. and Zhang, X. (2018). Future climate risk from compound events. Nature climate change, 8(6), pp.469-477.

References 2.2

Abernathey, R.P., Cerovecki, I., Holland, P.R., Newsom, E., Mazloff, M. and Talley, L.D. (2016) 'Water-mass transformation by sea ice in the upper branch of the Southern Ocean overturning', Nature Geoscience, 9(8), pp. 596–601. Available at: https://doi.org/10.1038/ngeo2749.

Abis, B. and Brovkin, V. (2017) 'Environmental conditions for alternative tree-cover states in high latitudes', Biogeosciences, 14(3), pp. 511–527. Available at: https://doi.org/10.5194/bg-14-511-2017.

Abolt, C.J., Atchley, A.L., Harp, D.R., Jorgenson, M.T., Witharana, C., Bolton, W.R., Schwenk, J., Rettelbach, T., Grosse, G., Boike, J., Nitze, I., Liljedahl, A.K., Rumpca, C.T., Wilson, C.J. and Bennett, K.E. (2024) 'Topography Controls Variability in Circumpolar Permafrost Thaw Pond Expansion', Journal of Geophysical Research: Earth Surface, 129(9), p. e2024JF007675. Available at: https://doi.org/10.1029/2024JF007675.

Abram, N.J., Purich, A., England, M.H., McCormack, F.S., Strugnell, J.M., Bergstrom, D.M., Vance, T.R., Stål, T., Wienecke, B., Heil, P., Doddridge, E.W., Sallée, J.-B., Williams, T.J., Reading, A.M., Mackintosh, A., Reese, R., Winkelmann, R., Klose, A.K., Boyd, P.W., Chown, S.L. and Robinson, S.A. (2025) 'Emerging evidence of abrupt changes in the Antarctic environment', Nature, 644(8077), pp. 621–633. Available at: https://doi.org/10.1038/s41586-025-09349-5.

Aguirre-Gutiérrez, J., Rifai, S.W., Deng, X., ter Steege, H., Thomson, E., Corral-Rivas, J.J., Guimaraes, A.F., Muller, S., Klipel, J., Fauset, S., Resende, A.F., Wallin, G., Joly, C.A., Abernethy, K., Adu-Bredu, S., Alexandre Silva, C., de Oliveira, E.A., Almeida, D.R.A., Alvarez-Davila, E., Asner, G.P., Baker, T.R., Benchimol, M., Bentley, L.P., Berenguer, E., Blanc, L., Bonal, D., Bordin, K., Borges de Lima, R., Both, S., Cabezas Duarte, J., Cardoso, D., de Lima, H.C., Cavalheiro, L., Cernusak, L.A., dos Santos Prestes, N.C.C., da Silva Zanzini, A.C., da Silva, R.J., dos Santos Alves da Silva, R., de Andrade Iguatemy, M., De Sousa Oliveira, T.C., Dechant, B., Derroire, G., Dexter, K.G., Rodrigues, D.J., Espírito-Santo, M., Silva, L.F., Domingues, T.F., Ferreira, J., Simon, M.F., Girardin, C.A.J., Hérault, B., Jeffery, K.J., Kalpuzha Ashtamoorthy, S., Kavidapadinjattathil Sivadasan, A., Klitgaard, B., Laurance, W.F., Dan, M.L., Magnusson, W.E., Campos-Filho, E.M., Manoel dos Santos, R., Manzatto, A.G., Silveira, M., Marimon-Junior, B.H., Martin, R.E., Vieira, D.L.M., Metzker, T., Milliken, W., Moonlight, P., Moraes de Seixas, M.M., Morandi, P.S., Muscarella, R., Nava-Miranda, M.G., Nyirambangutse, B., Silva, J.O., Oliveras Menor, I., Francisco Pena Rodrigues, P.J., Pereira de Oliveira, C., Pereira Zanzini, L., Peres, C.A., Punjayil, V., Quesada, C.A., Réjou-Méchain, M., Riutta, T., Rivas-Torres, G., Rosa, C., Salinas, N., Bergamin, R.S., Marimon, B.S., Shenkin, A., Silva Rodrigues, P.M., Figueiredo, A.E.S., Garcia, Q.S., Spósito, T., Storck-Tonon, D., Sullivan, M.J.P., Svátek, M., Vieira Santiago, W.T., Arn Teh, Y., Theruvil Parambil Sivan, P., Nascimento, M.T., Veenendaal, E., Zo-Bi, I.C., Dago, M.R., Traoré, S., Patacca, M., Badouard, V., de Padua Chaves e Carvalho, S., White, L.J.T., Zhang-Zheng, H., Zibera, E., Zwerts, J.A., Burslem, D.F.R.P., Silman, M., Chave, J., Enquist, B.J., Barlow, J., Phillips, O.L., Coomes, D.A. and Malhi, Y. (2025) 'Canopy functional trait variation across Earth's tropical forests', Nature, 641(8061), pp. 129–136. Available at: https://doi.org/10.1038/s41586-025-08663-2.

Akabane, T.K., Chiessi, C.M., Hirota, M., Bouimetarhan, I., Prange, M., Mulitza, S., Bertassoli Jr, D.J., Häggi, C., Staal, A., Lohmann, G., Boers, N., Daniau, A.L., Oliveira, R.S., Campos, M.C., Shi, X. and De Oliveira, P.E. (2024) 'Weaker Atlantic overturning circulation increases the vulnerability of northern Amazon forests', Nature Geoscience, 17(12), pp. 1284–1290. Available at: https://doi.org/10.1038/s41561-024-01578-z.

van den Akker, T., Lipscomb, W.H., Leguy, G.R., Bernales, J., Berends, C.J., van de Berg, W.J. and van de Wal, R.S.W. (2025) 'Present-day mass loss rates are a precursor for West Antarctic Ice Sheet collapse', The Cryosphere, 19(1), pp. 283–301. Available at: https://doi.org/10.5194/tc-19-283-2025.

Albert, J.S., Carnaval, A.C., Flantua, S.G.A., Lohmann, L.G., Ribas, C.C., Riff, D., Carrillo, J.D., Fan, Y., Figueiredo, J.J.P., Guayasamin, J.M., Hoorn, C., de Melo, G.H., Nascimento, N., Quesada, C.A., Ulloa Ulloa, C., Val, P., Arieira, J., Encalada, A.C. and Nobre, C.A. (2023) 'Human impacts outpace natural processes in the Amazon', Science, 379(6630), p. eabo5003. Available at: https://doi.org/10.1126/science.abo5003.

Aleman, J.C., Fayolle, A., Favier, C., Staver, A.C., Dexter, K.G., Ryan, C.M., Azihou, A.F., Bauman, D., te Beest, M., Chidumayo, E.N., Comiskey, J.A., Cromsigt, J.P.G.M., Dessard, H., Doucet, J.-L., Finckh, M., Gillet, J.-F., Gourlet-Fleury, S., Hempson, G.P., Holdo, R.M., Kirunda, B., Kouame, F.N., Mahy, G., Gonçalves, F.M.P., McNicol, I., Quintano, P.N., Plumptre, A.J., Pritchard, R.C., Revermann, R., Schmitt, C.B., Swemmer, A.M., Talila, H., Woollen, E. and Swaine, M.D. (2020) 'Floristic evidence for alternative biome states in tropical Africa', Proceedings of the National Academy of Sciences, 117(45), pp. 28183–28190. Available at: https://doi.org/10.1073/pnas.2011515117.

Alevropoulos-Borrill, A., Golledge, N.R., Cornford, S.L., Lowry, D.P. and Krapp, M. (2024) 'Sustained ocean cooling insufficient to reverse sea level rise from Antarctica', Communications Earth & Environment, 5(1), p. 150. Available at: https://doi.org/10.1038/s43247-024-01297-8.

Alfaro-Sánchez, R., Richardson, A.D., Smith, S.L., Johnstone, J.F., Turetsky, M.R., Cumming, S.G., Le Moine, J.M. and Baltzer, J.L. (2024) 'Permafrost instability negates the positive impact of warming temperatures on boreal radial growth', Proceedings of the National Academy of Sciences, 121(50), p. e2411721121. Available at: https://doi.org/10.1073/pnas.2411721121.

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H. (Ted), Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S.W., Semerci, A. and Cobb, N. (2010) 'A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests', Forest Ecology and Management, 259(4), pp. 660–684. Available at: https://doi.org/10.1016/j.foreco.2009.09.001.

Alley, R.B., Andrews, J.T., Brigham-Grette, J., Clarke, G.K.C., Cuffey, K.M., Fitzpatrick, J.J., Funder, S., Marshall, S.J., Miller, G.H., Mitrovica, J.X., Muhs, D.R., Otto-Bliesner, B.L., Polyak, L. and White, J.W.C. (2010) 'History of the Greenland Ice Sheet: paleoclimatic insights', Quaternary Science Reviews, 29(15), pp. 1728–1756. Available at: https://doi.org/10.1016/j.quascirev.2010.02.007.

Amaral, C., Poulter, B., Lagomasino, D., Fatoyinbo, T., Taillie, P., Lizcano, G., Canty, S., Silveira, J.A.H., Teutli-Hernández, C., Cifuentes-Jara, M., Charles, S.P., Moreno, C.S., González-Trujillo, J.D. and Roman-Cuesta, R.M. (2023) 'Drivers of mangrove vulnerability and resilience to tropical cyclones in the North Atlantic Basin', Science of The Total Environment, 898, p. 165413. Available at: https://doi.org/10.1016/j.scitotenv.2023.165413.

do Amaral Camara Lima, M., Bergamo, T.F., Ward, R.D. and Joyce, C.B. (2023) 'A review of seagrass ecosystem services: providing nature-based solutions for a changing world', Hydrobiologia, 850(12), pp. 2655–2670. Available at: https://doi.org/10.1007/s10750-023-05244-0.

Amir, H. (2022) 'Status and trends of hard coral cover derived from long-term monitoring sites in the Maldives: 1998-2021'. Available at: http://mrc.gov.mv/dv/publications/show/status-and-trends-of-hard-coral-cover-derived-from-long-term-monitoring-sites-in-the-maldives-1998-2 (Accessed: 2 September 2025).

An, S.-I., Moon, J.-Y., Dijkstra, H.A., Yang, Y.-M. and Song, H. (2024) 'Antarctic meltwater reduces the Atlantic meridional overturning circulation through oceanic freshwater transport and atmospheric teleconnections', Communications Earth & Environment, 5(1), p. 490. Available at: https://doi.org/10.1038/s43247-024-01670-7.

Andela, N., Morton, D.C., Giglio, L., Chen, Y., van der Werf, G.R., Kasibhatla, P.S., DeFries, R.S., Collatz, G.J., Hantson, S., Kloster, S., Bachelet, D., Forrest, M., Lasslop, G., Li, F., Mangeon, S., Melton, J.R., Yue, C. and Randerson, J.T. (2017) 'A human-driven decline in global burned area', Science, 356(6345), pp. 1356–1362. Available at: https://doi.org/10.1126/science.aal4108.

Anderson, N.J., Heathcote, A.J., Engstrom, D.R., and Globocarb data contributors (2020) 'Anthropogenic alteration of nutrient supply increases the global freshwater carbon sink', Science Advances, 6(16), p. eaaw2145. Available at: https://doi.org/10.1126/sciadv.aaw2145.

Angevaare, J.R. and Drijfhout, S.S. (2025) 'Catalogue of Strong Nonlinear Surprises in ocean, sea-ice, and atmospheric variables in CMIP6', EGUsphere, pp. 1–40. Available at: https://doi.org/10.5194/egusphere-2025-2039.

Anthony, K.M.W., Zimov, S.A., Grosse, G., Jones, M.C., Anthony, P.M., Iii, F.S.C., Finlay, J.C., Mack, M.C., Davydov, S., Frenzel, P. and Frolking, S. (2014) 'A shift of thermokarst lakes from carbon sources to sinks during the Holocene epoch', Nature, 511(7510), pp. 452–456. Available at: https://doi.org/10.1038/nature13560.

Arellano-Nava, B., Lenton, T. M., Boulton, C. A., Holmes, S., Scourse, J., Butler, P. G., Reynolds, D. J., Trofimova, T., Poitevin, P., Román-González, A., & Halloran, P. R. (2025). Recent and early twentieth century destabilization of the subpolar North Atlantic recorded in bivalves. Science Advances, 11(40), eadw3468. https://doi.org/10.1126/sciadv.adw3468"

Arellano-Nava, B., Lenton, T.M., Boulton, C.A., Holmes, S., Scourse, J., Butler, P.G., Reynolds, D.J., Trofimova, T., Poitevin, P., Román-González, A. and Halloran, P.R. (in press) 'Recent and early twentieth century destabilization of the subpolar North Atlantic recorded in bivalves'. Science Advances

Arias, P.A., Bellouin, N., Coppola, E., Jones, R.G., Krinner, G., Marotzke, J., Naik, V., Palmer, M.D., Plattner, G.-K., Rogelj, J., Rojas, M., Sillmann, J., Storelvmo, T., Thorne, P.W. and Trewin, B. (2021) 'Technical summary', in Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,: Cambridge University Press, p. 33–144. Available at: doi.org/10.1017/9781009157896.002.

Armstrong McKay, D.I., Cornell, S.E., Richardson, K. and Rockström, J. (2021) 'Resolving ecological feedbacks on the ocean carbon sink in Earth system models', Earth System Dynamics, 12(3), pp. 797–818. Available at: https://doi.org/10.5194/esd-12-797-2021.

Armstrong McKay, D.I., Sakschewski, B., Roman-Cuesta, R.M., Dakos, V., Flores, B.M., Hessen, D.O., Hirota, M., Kéfi, S., Obura, D., Reyer, C.P.O., Staver, C., Thom, D., Abis, B., Amaral, C., Andersen, T., Bathiany, S., Beaugrand, G., Blenckner, T., Brovkin, V., Berdugo, M., Delgado-Baquerizo, M., Dexter, K.G., Drüke, M., Duke, N.C., Friess, D., Herrera Silveira, J.A., Bill-Weilandt, A., Guirado, E., Holmgren, M., Kosten, S., Lovelock, C., Mayor, A.G., Mayor, D.J., McField, M., Meerhoff, M., Castillo, I.M., Niiranen, S., Paton, S., Pearce-Kelly, P., Estaún, Y.P., Rocha, J., Romagnoni, G., Sanabria-Fernandez, J.A., Sguotti, C., Spears, B.M., Staal, A., Stevens, N. and Tarling, G.A. (2023) 'Chapter 1.3: Tipping points in the biosphere', in Global Tipping Points Report 2023. Exeter, UK: University of Exeter. Available at: https://report-2023.global-tipping-points.org/section1/1-earth-system-tipping-points/1-3-tipping-points-in-the-biosphere/ (Accessed: 25 September 2024).

Armstrong McKay, D.I., Staal, A., Abrams, J.F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S.E., Rockström, J. and Lenton, T.M. (2022) 'Exceeding 1.5°C global warming could trigger multiple climate tipping points', Science, 377(6611), p. eabn7950. Available at: https://doi.org/10.1126/science.abn7950.

Arnheim, J.B., Peings, Y. and Magnusdottir, G. (2025) 'Contrasting Arctic Amplification Response in the Community Earth System Model Large Ensembles and Implications for the North Atlantic Region', Journal of Geophysical Research: Atmospheres, 130(6), p. e2024JD042490. Available at: https://doi.org/10.1029/2024JD042490.

Arthern, R.J. and Williams, C.R. (2017) 'The sensitivity of West Antarctica to the submarine melting feedback', Geophysical Research Letters, 44(5), pp. 2352–2359. Available at: https://doi.org/10.1002/2017GL072514.

Arumí-Planas, C., Dong, S., Perez, R., Harrison, M.J., Farneti, R. and Hernández-Guerra, A. (2024) 'A Multi-Data Set Analysis of the Freshwater Transport by the Atlantic Meridional Overturning Circulation at Nominally 34.5°S', Journal of Geophysical Research: Oceans, 129(6), p. e2023JC020558. Available at: https://doi.org/10.1029/2023JC020558.

Asbridge, E., Krause, C., Lucas, R., Owers, C.J., Rogers, K., Lymburner, L., Mueller, N., Ai, E. and Wong, S. (2025) 'Characterising the short- and long-term impacts of tropical cyclones on mangroves using the Landsat archive', Cambridge Prisms: Coastal Futures, 3, p. e4. Available at: https://doi.org/10.1017/cft.2024.19.

Asbridge, E.F., Bartolo, R., Finlayson, C.M., Lucas, R.M., Rogers, K. and Woodroffe, C.D. (2019) 'Assessing the distribution and drivers of mangrove dieback in Kakadu National Park, northern Australia', Estuarine, Coastal and Shelf Science, 228, p. 106353. Available at: https://doi.org/10.1016/j.ecss.2019.106353.

Aschwanden, A., Fahnestock, M.A., Truffer, M., Brinkerhoff, D.J., Hock, R., Khroulev, C., Mottram, R. and Khan, S.A. (2019) 'Contribution of the Greenland Ice Sheet to sea level over the next millennium', Science Advances, 5(6), p. eaav9396. Available at: https://doi.org/10.1126/sciadv.aav9396.

Athanase, M., Köhler, R., Heuzé, C., Lévine, X. and Williams, R. (2025) 'The Arctic Beaufort Gyre in CMIP6 Models: Present and Future', Journal of Geophysical Research: Oceans, 130(4), p. e2024JC021873. Available at: https://doi.org/10.1029/2024JC021873.

Baker, J.A., Bell, M.J., Jackson, L.C., Vallis, G.K., Watson, A.J. and Wood, R.A. (2025) 'Continued Atlantic overturning circulation even under climate extremes', Nature, 638(8052), pp. 987–994. Available at: https://doi.org/10.1038/s41586-024-08544-0.

Ban, S.S., Graham, N.A.J. and Connolly, S.R. (2014) 'Evidence for multiple stressor interactions and effects on coral reefs', Global Change Biology, 20(3), pp. 681–697. Available at: https://doi.org/10.1111/gcb.12453.

Ban, Z., Hu, X. and Li, J. (2022) 'Tipping points of marine phytoplankton to multiple environmental stressors', Nature Climate Change, 12(11), pp. 1045–1051. Available at: https://doi.org/10.1038/s41558-022-01489-0.

Banderier, H., Tuel, A., Woollings, T. and Martius, O. (2025) 'Seasonal to decadal variability and persistence properties of the Euro-Atlantic jet streams characterized by complementary approaches', Weather and Climate Dynamics, 6(2), pp. 715–739. Available at: https://doi.org/10.5194/wcd-6-715-2025.

Barriopedro, D., Fischer, E.M., Luterbacher, J., Trigo, R.M. and García-Herrera, R. (2011) 'The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe', Science, 332(6026), pp. 220–224. Available at: https://doi.org/10.1126/science.1201224.

Bartenfelder, A., Kenworthy, W.J., Puckett, B., Deaton, C. and Jarvis, J.C. (2022) 'The Abundance and Persistence of Temperate and Tropical Seagrasses at Their Edge-of-Range in the Western Atlantic Ocean', Frontiers in Marine Science, 9. Available at: https://doi.org/10.3389/fmars.2022.917237.

Batelaan, T.J., Weijenborg, C., Steeneveld, G.J., van Heerwaarden, C.C. and Sinclair, V.A. (2024) 'The Influence of Large-Scale Spatial Warming on Jet Stream Extreme Waviness on an Aquaplanet', Geophysical Research Letters, 51(18), p. e2024GL108470. Available at: https://doi.org/10.1029/2024GL108470.

Bayr, T., Lübbecke, J.F. and Fiedler, S. (2024) 'Is El Niño-Southern Oscillation a Tipping Element in the Climate System?', Geophysical Research Letters, 51(13), p. e2023GL107848. Available at: https://doi.org/10.1029/2023GL107848.

Beaugrand, G., Balembois, A., Kléparski, L. and Kirby, R.R. (2022) 'Addressing the dichotomy of fishing and climate in fishery management with the FishClim model', Communications Biology, 5(1), p. 1146. Available at: https://doi.org/10.1038/s42003-022-04100-6.

Beaugrand, G., Conversi, A., Atkinson, A., Cloern, J., Chiba, S., Fonda-Umani, S., Kirby, R.R., Greene, C.H., Goberville, E., Otto, S.A., Reid, P.C., Stemmann, L. and Edwards, M. (2019) 'Prediction of unprecedented biological shifts in the global ocean', Nature Climate Change, 9(3), pp. 237–243. Available at: https://doi.org/10.1038/s41558-019-0420-1.

Bellomo, K., Clement, A., Mauritsen, T., Rädel, G. and Stevens, B. (2014) 'Simulating the Role of Subtropical Stratocumulus Clouds in Driving Pacific Climate Variability'. Available at: https://doi.org/10.1175/JCLI-D-13-00548.1.

Bellomo, K., Meccia, V.L., D'Agostino, R., Fabiano, F., Larson, S.M., von Hardenberg, J. and Corti, S. (2023) 'Impacts of a weakened AMOC on precipitation over the Euro-Atlantic region in the EC-Earth3 climate model', Climate Dynamics, 61(7), pp. 3397–3416. Available at: https://doi.org/10.1007/s00382-023-06754-2.

Ben-Yami, M., Good, P., Jackson, L.C., Crucifix, M., Hu, A., Saenko, O., Swingedouw, D. and Boers, N. (2024) 'Impacts of AMOC Collapse on Monsoon Rainfall: A Multi-Model Comparison', Earth's Future, 12(9), p. e2023EF003959. Available at: https://doi.org/10.1029/2023EF003959.

Ben-Yami, Maya, Morr, A., Bathiany, S. and Boers, N. (2024) 'Uncertainties too large to predict tipping times of major Earth system components from historical data', Science Advances, 10(31), p. eadl4841. Available at: https://doi.org/10.1126/sciadv.adl4841.

Benyon, R.G., Inbar, A., Sheridan, G.J. and Lane, P.N.J. (2023) 'Critical climate thresholds for fire in wet, temperate forests', Forest Ecology and Management, 537, p. 120911. Available at: https://doi.org/10.1016/j.foreco.2023.120911.

Berdugo, M., Delgado-Baquerizo, M., Soliveres, S., Hernández-Clemente, R., Zhao, Y., Gaitán, J.J., Gross, N., Saiz, H., Maire, V., Lehmann, A., Rillig, M.C., Solé, R.V. and Maestre, F.T. (2020) 'Global ecosystem thresholds driven by aridity', Science, 367(6479), pp. 787–790. Available at: https://doi.org/10.1126/science.aay5958.

Berdugo, M., Gaitán, J.J., Delgado-Baquerizo, M., Crowther, T.W. and Dakos, V. (2022) 'Prevalence and drivers of abrupt vegetation shifts in global drylands', Proceedings of the National Academy of Sciences, 119(43), p. e2123393119. Available at: https://doi.org/10.1073/pnas.2123393119.

Berdugo, M., Kéfi, S., Soliveres, S. and Maestre, F.T. (2017) 'Plant spatial patterns identify alternative ecosystem multifunctionality states in global drylands', Nature Ecology & Evolution, 1(2), p. 0003. Available at: https://doi.org/10.1038/s41559-016-0003.

Bergstrom, D.M., Wienecke, B.C., van den Hoff, J., Hughes, L., Lindenmayer, D.B., Ainsworth, T.D., Baker, C.M., Bland, L., Bowman, D.M.J.S., Brooks, S.T., Canadell, J.G., Constable, A.J., Dafforn, K.A., Depledge, M.H., Dickson, C.R., Duke, N.C., Helmstedt, K.J., Holz, A., Johnson, C.R., McGeoch, M.A., Melbourne-Thomas, J., Morgain, R., Nicholson, E., Prober, S.M., Raymond, B., Ritchie, E.G., Robinson, S.A., Ruthrof, K.X., Setterfield, S.A., Sgrò, C.M., Stark, J.S., Travers, T., Trebilco, R., Ward, D.F.L., Wardle, G.M., Williams, K.J., Zylstra, P.J. and Shaw, J.D. (2021) 'Combating ecosystem collapse from the tropics to the Antarctic', Global Change Biology, 27(9), pp. 1692–1703. Available at: https://doi.org/10.1111/gcb.15539.

Bernardino, P.N., De Keersmaecker, W., Horion, S., Oehmcke, S., Gieseke, F., Fensholt, R., Van De Kerchove, R., Lhermitte, S., Abel, C., Van Meerbeek, K., Verbesselt, J. and Somers, B. (2025) 'Predictability of abrupt shifts in dryland ecosystem functioning', Nature Climate Change, 15(1), pp. 86–91. Available at: https://doi.org/10.1038/s41558-024-02201-0.

Bett, D.T., Bradley, A.T., Williams, C.R., Holland, P.R., Arthern, R.J. and Goldberg, D.N. (2024) 'Coupled ice–ocean interactions during future retreat of West Antarctic ice streams in the Amundsen Sea sector', The Cryosphere, 18(6), pp. 2653–2675. Available at: https://doi.org/10.5194/tc-18-2653-2024.

Blackport, R. and Screen, J.A. (2020) 'Insignificant effect of Arctic amplification on the amplitude of midlatitude atmospheric waves', Science Advances, 6(8), p. eaay2880. Available at: https://doi.org/10.1126/sciadv.aay2880.

Bland, L.M., Rowland, J.A., Regan, T.J., Keith, D.A., Murray, N.J., Lester, R.E., Linn, M., Rodríguez, J.P. and Nicholson, E. (2018) 'Developing a standardized definition of ecosystem collapse for risk assessment', Frontiers in Ecology and the Environment, 16(1), pp. 29–36. Available at: https://doi.org/10.1002/fee.1747.

Blaschke, L.L., Nian, D., Bathiany, S., Ben-Yami, M., Smith, T., Boulton, C.A. and Boers, N. (2024) 'Spatial Correlation Increase in Single-Sensor Satellite Data Reveals Loss of Amazon Rainforest Resilience', Earth's Future, 12(7), p. e2023EF004040. Available at: https://doi.org/10.1029/2023EF004040.

Blasco, J., Tabone, I., Moreno-Parada, D., Robinson, A., Alvarez-Solas, J., Pattyn, F. and Montoya, M. (2024) 'Antarctic tipping points triggered by the mid-Pliocene warm climate', Climate of the Past, 20(9), pp. 1919–1938. Available at: https://doi.org/10.5194/cp-20-1919-2024.

Bloch-Johnson, J., Pierrehumbert, R.T. and Abbot, D.S. (2015) 'Feedback temperature dependence determines the risk of high warming', Geophysical Research Letters, 42(12), pp. 4973–4980. Available at: https://doi.org/10.1002/2015GL064240.

Bochow, N. and Boers, N. (2023) 'The South American monsoon approaches a critical transition in response to deforestation', Science Advances, 9(40), p. eadd9973. Available at: https://doi.org/10.1126/sciadv.add9973.

Boers, N., Ghil, M. and Stocker, T.F. (2022) 'Theoretical and paleoclimatic evidence for abrupt transitions in the Earth system', Environmental Research Letters, 17(9), p. 093006. Available at: https://doi.org/10.1088/1748-9326/ac8944.

Boers, N. and Rypdal, M. (2021) 'Critical slowing down suggests that the western Greenland Ice Sheet is close to a tipping point', Proceedings of the National Academy of Sciences, 118(21), p. e2024192118. Available at: https://doi.org/10.1073/pnas.2024192118.

Bolibar, J., Rabatel, A., Gouttevin, I., Zekollari, H. and Galiez, C. (2022) 'Nonlinear sensitivity of glacier mass balance to future climate change unveiled by deep learning', Nature Communications, 13(1), p. 409. Available at: https://doi.org/10.1038/s41467-022-28033-0.

Bonan, D.B., Thompson, A.F., Schneider, T., Zanna, L., Armour, K.C. and Sun, S. (2025) 'Observational constraints imply limited future Atlantic meridional overturning circulation weakening', Nature Geoscience, 18(6), pp. 479–487. Available at: https://doi.org/10.1038/s41561-025-01709-0.

Bond, W.J. (2008) 'What Limits Trees in C4 Grasslands and Savannas?', Annual Review of Ecology, Evolution, and Systematics, 39(Volume 39, 2008), pp. 641–659. Available at: https://doi.org/10.1146/annurev.ecolsys.39.110707.173411.

Bonsoms, J., Oliva, M., López-Moreno, J.I. and Fettweis, X. (2024) 'Rising Extreme Meltwater Trends in Greenland Ice Sheet (1950–2022): Surface Energy Balance and Large-Scale Circulation Changes'. Available at: https://doi.org/10.1175/JCLI-D-23-0396.1.

Boos, W.R. and Storelvmo, T. (2016) 'Near-linear response of mean monsoon strength to a broad range of radiative forcings', Proceedings of the National Academy of Sciences, 113(6), pp. 1510–1515. Available at: https://doi.org/10.1073/pnas.1517143113.

Born, A. and Stocker, T.F. (2014) 'Two Stable Equilibria of the Atlantic Subpolar Gyre'. Available at: https://doi.org/10.1175/JPO-D-13-073.1.

Börner, R., Mehling, O., Hardenberg, J. von and Lucarini, V. (2025) 'Boundary crisis and long transients of the Atlantic overturning circulation mediated by an edge state'. arXiv. Available at: https://doi.org/10.48550/arXiv.2504.20002.

Boulton, C.A., Good, P. and Lenton, T.M. (2013) 'Early warning signals of simulated Amazon rainforest dieback', Theoretical Ecology, 6(3), pp. 373–384. Available at: https://doi.org/10.1007/s12080-013-0191-7.

Boulton, C.A., Lenton, T.M. and Boers, N. (2022) 'Pronounced loss of Amazon rainforest resilience since the early 2000s', Nature Climate Change, 12(3), pp. 271–278. Available at: https://doi.org/10.1038/s41558-022-01287-8.

Box, J.E., Hubbard, A., Bahr, D.B., Colgan, W.T., Fettweis, X., Mankoff, K.D., Wehrlé, A., Noël, B., van den Broeke, M.R., Wouters, B., Bjørk, A.A. and Fausto, R.S. (2022) 'Greenland ice sheet climate disequilibrium and committed sea-level rise', Nature Climate Change, 12(9), pp. 808–813. Available at: https://doi.org/10.1038/s41558-022-01441-2.

Bradley, A.T. and Hewitt, I.J. (2024) 'Tipping point in ice-sheet grounding-zone melting due to ocean water intrusion', Nature Geoscience, 17(7), pp. 631–637. Available at: https://doi.org/10.1038/s41561-024-01465-7.

Breitburg, D., Levin, L.A., Oschlies, A., Grégoire, M., Chavez, F.P., Conley, D.J., Garçon, V., Gilbert, D., Gutiérrez, D., Isensee, K., Jacinto, G.S., Limburg, K.E., Montes, I., Naqvi, S.W.A., Pitcher, G.C., Rabalais, N.N., Roman, M.R., Rose, K.A., Seibel, B.A., Telszewski, M., Yasuhara, M. and Zhang, J. (2018) 'Declining oxygen in the global ocean and coastal waters', Science, 359(6371), p. eaam7240. Available at: https://doi.org/10.1126/science.aam7240.

Brovkin, V., Bartsch, A., Hugelius, G., Calamita, E., Lever, J.J., Goo, E., Kim, H., Stacke, T. and de Vrese, P. (2025) 'Permafrost and Freshwater Systems in the Arctic as Tipping Elements of the Climate System', Surveys in Geophysics, 46(2), pp. 303–326. Available at: https://doi.org/10.1007/s10712-025-09885-9.

Brown, J.R., Brierley, C.M., An, S.-I., Guarino, M.-V., Stevenson, S., Williams, C.J.R., Zhang, Q., Zhao, A., Abe-Ouchi, A., Braconnot, P., Brady, E.C., Chandan, D., D'Agostino, R., Guo, C., LeGrande, A.N., Lohmann, G., Morozova, P.A., Ohgaito, R., O'ishi, R., Otto-Bliesner, B.L., Peltier, W.R., Shi, X., Sime, L., Volodin, E.M., Zhang, Z. and Zheng, W. (2020) 'Comparison of past and future simulations of ENSO in CMIP5/PMIP3 and CMIP6/PMIP4 models', Climate of the Past, 16(5), pp. 1777–1805. Available at: https://doi.org/10.5194/cp-16-1777-2020.

Buckley, M.W. and Marshall, J. (2016) 'Observations, inferences, and mechanisms of the Atlantic Meridional Overturning Circulation: A review', Reviews of Geophysics, 54(1), pp. 5–63. Available at: https://doi.org/10.1002/2015RG000493.

Buras, A., Rammig, A. and Zang, C.S. (2020) 'Quantifying impacts of the 2018 drought on European ecosystems in comparison to 2003', Biogeosciences, 17(6), pp. 1655–1672. Available at: https://doi.org/10.5194/bg-17-1655-2020.

Byrne, M., Waller, A., Clements, M., Kelly, A.S., Kingsford, M.J., Liu, B., Reymond, C.E., Vila-Concejo, A., Webb, M., Whitton, K. and Foo, S.A. (2025) 'Catastrophic bleaching in protected reefs of the Southern Great Barrier Reef', Limnology and Oceanography Letters, 10(3), pp. 340–348. Available at: https://doi.org/10.1002/lol2.10456.

Caballero, R. and Carlson, H. (2018) 'Surface Superrotation'. Available at: https://doi.org/10.1175/JAS-D-18-0076.1.

Caballero, R. and Huber, M. (2010) 'Spontaneous transition to superrotation in warm climates simulated by CAM3', Geophysical Research Letters, 37(11). Available at: https://doi.org/10.1029/2010GL043468.

Caballero, R. and Huber, M. (2013) 'State-dependent climate sensitivity in past warm climates and its implications for future climate projections', Proceedings of the National Academy of Sciences, 110(35), pp. 14162–14167. Available at: https://doi.org/10.1073/pnas.1303365110.

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G. and Saba, V. (2018) 'Observed fingerprint of a weakening Atlantic Ocean overturning circulation', Nature, 556(7700), pp. 191–196. Available at: https://doi.org/10.1038/s41586-018-0006-5.

Cai, W., Ng, B., Wang, G., Santoso, A., Wu, L. and Yang, K. (2022) 'Increased ENSO sea surface temperature variability under four IPCC emission scenarios', Nature Climate Change, 12(3), pp. 228–231. Available at: https://doi.org/10.1038/s41558-022-01282-z.

Cai, W., Wang, G., Dewitte, B., Wu, L., Santoso, A., Takahashi, K., Yang, Y., Carréric, A. and McPhaden, M.J. (2018) 'Increased variability of eastern Pacific El Niño under greenhouse warming', Nature, 564(7735), pp. 201–206. Available at: https://doi.org/10.1038/s41586-018-0776-9.

Cai, W., Wang, G., Santoso, A., McPhaden, M.J., Wu, L., Jin, F.-F., Timmermann, A., Collins, M., Vecchi, G., Lengaigne, M., England, M.H., Dommenget, D., Takahashi, K. and Guilyardi, E. (2015) 'Increased frequency of extreme La Niña events under greenhouse warming', Nature Climate Change, 5(2), pp. 132–137. Available at: https://doi.org/10.1038/nclimate2492.

Callahan, C.W. and Mankin, J.S. (2023) 'Persistent effect of El Niño on global economic growth', Science, 380(6649), pp. 1064–1069. Available at: https://doi.org/10.1126/science.adf2983.

Cano, A.V., Jensen, O.P. and Dakos, V. (2025) 'Identifying fish populations prone to abrupt shifts via dynamical footprint analysis', Proceedings of the National Academy of Sciences, 122(34), p. e2505461122. Available at: https://doi.org/10.1073/pnas.2505461122.

Capistrant-Fossa, K.A. and Dunton, K.H. (2024) 'Rapid sea level rise causes loss of seagrass meadows', Communications Earth & Environment, 5(1), p. 87. Available at: https://doi.org/10.1038/s43247-024-01236-7.

Capotondi, A., Wittenberg, A.T., Newman, M., Lorenzo, E.D., Yu, J.-Y., Braconnot, P., Cole, J., Dewitte, B., Giese, B., Guilyardi, E., Jin, F.-F., Karnauskas, K., Kirtman, B., Lee, T., Schneider, N., Xue, Y. and Yeh, S.-W. (2015) 'Understanding ENSO Diversity'. Available at: https://doi.org/10.1175/BAMS-D-13-00117.1.

Carnicer, J., Vives-Ingla, M., Blanquer, L., Méndez-Camps, X., Rosell, C., Sabaté, S., Gutiérrez, E., Sauras, T., Peñuelas, J. and Barbeta, A. (2021) 'Forest resilience to global warming is strongly modulated by local-scale topographic, microclimatic and biotic conditions', Journal of Ecology, 109(9), pp. 3322–3339. Available at: https://doi.org/10.1111/1365-2745.13752.

Cecapolli, E., Romagnoni, G., Blöcker, A.M., Möllmann, C. and Sguotti, C. (2025) 'Unmasking contrasting regime shift dynamics across three substocks of Atlantic cod in the North Sea', ICES Journal of Marine Science, 82(3), p. fsaf021. Available at: https://doi.org/10.1093/icesjms/fsaf021.

Chandler, D.M., Langebroek, P.M., Reese, R., Albrecht, T., Garbe, J. and Winkelmann, R. (2025) 'Antarctic Ice Sheet tipping in the last 800,000 years warns of future ice loss', Communications Earth & Environment, 6(1), p. 420. Available at: https://doi.org/10.1038/s43247-025-02366-2.

Chapman, R.R., Ashwin, P., Baker, J. and Wood, R.A. (2024) 'Quantifying risk of a noise-induced AMOC collapse from northern and tropical Atlantic Ocean variability', Environmental Research Communications, 6(11), p. 111003. Available at: https://doi.org/10.1088/2515-7620/ad8f98.

Charney, J.G. (1975) 'Dynamics of deserts and drought in the Sahel', Quarterly Journal of the Royal Meteorological Society, 101(428), pp. 193–202. Available at: https://doi.org/10.1002/qj.49710142802.

Chemke, R. and Coumou, D. (2024) 'Human influence on the recent weakening of storm tracks in boreal summer', npj Climate and Atmospheric Science, 7(1), p. 86. Available at: https://doi.org/10.1038/s41612-024-00640-2.

Christ, A.J., Bierman, P.R., Schaefer, J.M., Dahl-Jensen, D., Steffensen, J.P., Corbett, L.B., Peteet, D.M., Thomas, E.K., Steig, E.J., Rittenour, T.M., Tison, J.-L., Blard, P.-H., Perdrial, N., Dethier, D.P., Lini, A., Hidy, A.J., Caffee, M.W. and Southon, J. (2021) 'A multimillion-year-old record of Greenland vegetation and glacial history preserved in sediment beneath 1.4 km of ice at Camp Century', Proceedings of the National Academy of Sciences, 118(13), p. e2021442118. Available at: https://doi.org/10.1073/pnas.2021442118.

Chudley, T.R., Howat, I.M., King, M.D. and MacKie, E.J. (2025) 'Increased crevassing across accelerating Greenland Ice Sheet margins', Nature Geoscience, 18(2), pp. 148–153. Available at: https://doi.org/10.1038/s41561-024-01636-6.

Chung, C.T.Y., Hope, P., Hutley, L.B., Brown, J. and Duke, N.C. (2023) 'Future climate change will increase risk to mangrove health in Northern Australia', Communications Earth & Environment, 4(1), p. 192. Available at: https://doi.org/10.1038/s43247-023-00852-z.

Clark, P.U., Shakun, J.D., Marcott, S.A., Mix, A.C., Eby, M., Kulp, S., Levermann, A., Milne, G.A., Pfister, P.L., Santer, B.D., Schrag, D.P., Solomon, S., Stocker, T.F., Strauss, B.H., Weaver, A.J., Winkelmann, R., Archer, D., Bard, E., Goldner, A., Lambeck, K., Pierrehumbert, R.T. and Plattner, G.-K. (2016) 'Consequences of twenty-first-century policy for multi-millennial climate and sea-level change', Nature Climate Change, 6(4), pp. 360–369. Available at: https://doi.org/10.1038/nclimate2923.

CMIP (2022) 'CMIP - Coupled Model Intercomparison Project', 30 October. Available at: https://wcrp-cmip.org/ (Accessed: 26 August 2025).

Cochrane, M.A., Alencar, A., Schulze, M.D., Souza, C.M., Nepstad, D.C., Lefebvre, P. and Davidson, E.A. (1999) 'Positive Feedbacks in the Fire Dynamic of Closed Canopy Tropical Forests', Science, 284(5421), pp. 1832–1835. Available at: https://doi.org/10.1126/science.284.5421.1832.

Conversi, A., Dakos, V., Gårdmark, A., Ling, S., Folke, C., Mumby, P.J., Greene, C., Edwards, M., Blenckner, T., Casini, M., Pershing, A. and Möllmann, C. (2015) 'A holistic view of marine regime shifts', Philosophical Transactions of the Royal Society B: Biological Sciences, 370(1659), p. 20130279. Available at: https://doi.org/10.1098/rstb.2013.0279.

Cornwall, C.E., Comeau, S. and Harvey, B.P. (2024) 'Are physiological and ecosystem-level tipping points caused by ocean acidification? A critical evaluation', Earth System Dynamics, 15(3), pp. 671–687. Available at: https://doi.org/10.5194/esd-15-671-2024.

Coulon, V., Klose, A.K., Kittel, C., Edwards, T., Turner, F., Winkelmann, R. and Pattyn, F. (2024) 'Disentangling the drivers of future Antarctic ice loss with a historically calibrated ice-sheet model', The Cryosphere, 18(2), pp. 653–681. Available at: https://doi.org/10.5194/tc-18-653-2024.

Coumou, D., Di Capua, G., Vavrus, S., Wang, L. and Wang, S. (2018) 'The influence of Arctic amplification on mid-latitude summer circulation', Nature Communications, 9(1), p. 2959. Available at: https://doi.org/10.1038/s41467-018-05256-8.

Cramer, K.L., Jackson, J.B.C., Donovan, M.K., Greenstein, B.J., Korpanty, C.A., Cook, G.M. and Pandolfi, J.M. (2020) 'Widespread loss of Caribbean acroporid corals was underway before coral bleaching and disease outbreaks', Science Advances, 6(17), p. eaax9395. Available at: https://doi.org/10.1126/sciadv.aax9395.

Creed, I.F., Bergström, A.-K., Trick, C.G., Grimm, N.B., Hessen, D.O., Karlsson, J., Kidd, K.A., Kritzberg, E., McKnight, D.M., Freeman, E.C., Senar, O.E., Andersson, A., Ask, J., Berggren, M., Cherif, M., Giesler, R., Hotchkiss, E.R., Kortelainen, P., Palta, M.M., Vrede, T. and Weyhenmeyer, G.A. (2018) 'Global change-driven effects on dissolved organic matter composition: Implications for food webs of northern lakes', Global Change Biology, 24(8), pp. 3692–3714. Available at: https://doi.org/10.1111/gcb.14129.

Crezee, B., Dargie, G.C., Ewango, C.E.N., Mitchard, E.T.A., Emba B., O., Kanyama T., J., Bola, P., Ndjango, J.-B.N., Girkin, N.T., Bocko, Y.E., Ifo, S.A., Hubau, W., Seidensticker, D., Batumike, R., Imani, G., Cuní-Sanchez, A., Kiahtipes, C.A., Lebamba, J., Wotzka, H.-P., Bean, H., Baker, T.R., Baird, A.J., Boom, A., Morris, P.J., Page, S.E., Lawson, I.T. and Lewis, S.L. (2022) 'Mapping peat thickness and carbon stocks of the central Congo Basin using field data', Nature Geoscience, 15(8), pp. 639–644. Available at: https://doi.org/10.1038/s41561-022-00966-7.

Cunillera-Montcusí, D., Beklioğlu, M., Cañedo-Argüelles, M., Jeppesen, E., Ptacnik, R., Amorim, C.A., Arnott, S.E., Berger, S.A., Brucet, S., Dugan, H.A., Gerhard, M., Horváth, Z., Langenheder, S., Nejstgaard, J.C., Reinikainen, M., Striebel, M., Urrutia-Cordero, P., Vad, C.F., Zadereev, E. and Matias, M. (2022) 'Freshwater salinisation: a research agenda for a saltier world', Trends in Ecology & Evolution, 37(5), pp. 440–453. Available at: https://doi.org/10.1016/j.tree.2021.12.005.

Da Silveira Lobo Sternberg, L. (2001) 'Savanna–forest hysteresis in the tropics', Global Ecology and Biogeography, 10(4), pp. 369–378. Available at: https://doi.org/10.1046/j.1466-822X.2001.00243.x.

Dakos, V., Le Vilain, A., Thebault, E., Alcoverro, T., Boada, J., Infantes, E., Krause-Jensen, D., Marbà, N., Serrano, O., Vizzini, S. and Apostolaki, E.T. (2025) 'Carbon storage of seagrass ecosystems may experience tipping points in response to anthropogenic stress - a modeling perspective', Frontiers in Complex Systems, 3. Available at: https://doi.org/10.3389/fcpxs.2025.1534330.

Darling, E.S., McClanahan, T.R., Maina, J., Gurney, G.G., Graham, N.A.J., Januchowski-Hartley, F., Cinner, J.E., Mora, C., Hicks, C.C., Maire, E., Puotinen, M., Skirving, W.J., Adjeroud, M., Ahmadia, G., Arthur, R., Bauman, A.G., Beger, M., Berumen, M.L., Bigot, L., Bouwmeester, J., Brenier, A., Bridge, T.C.L., Brown, E., Campbell, S.J., Cannon, S., Cauvin, B., Chen, C.A., Claudet, J., Denis, V., Donner, S., Estradivari, Fadli, N., Feary, D.A., Fenner, D., Fox, H., Franklin, E.C., Friedlander, A., Gilmour, J., Goiran, C., Guest, J., Hobbs, J.-P.A., Hoey, A.S., Houk, P., Johnson, S., Jupiter, S.D., Kayal, M., Kuo, C., Lamb, J., Lee, M.A.C., Low, J., Muthiga, N., Muttaqin, E., Nand, Y., Nash, K.L., Nedlic, O., Pandolfi, J.M., Pardede, S., Patankar, V., Penin, L., Ribas-Deulofeu, L., Richards, Z., Roberts, T.E., Rodgers, K.S., Safuan, C.D.M., Sala, E., Shedrawi, G., Sin, T.M., Smallhorn-West, P., Smith, J.E., Sommer, B., Steinberg, P.D., Sutthacheep, M., Tan, C.H.J., Williams, G.J., Wilson, S., Yeemin, T., Bruno, J.F., Fortin, M.-J., Krkosek, M. and Mouillot, D. (2019) 'Social–environmental drivers inform strategic management of coral reefs in the Anthropocene', Nature Ecology & Evolution, 3(9), pp. 1341–1350. Available at: https://doi.org/10.1038/s41559-019-0953-8.

Davidson, T.A., Sayer, C.D., Jeppesen, E., Søndergaard, M., Lauridsen, T.L., Johansson, L.S., Baker, A. and Graeber, D. (2023) 'Bimodality and alternative equilibria do not help explain long-term patterns in shallow lake chlorophyll-a', Nature Communications, 14(1), p. 398. Available at: https://doi.org/10.1038/s41467-023-36043-9.

Davies, B., Bendle, J., Carrivick, J., McNabb, R., McNeil, C., Pelto, M., Campbell, S., Holt, T., Ely, J. and Markle, B. (2022) 'Topographic controls on ice flow and recession for Juneau Icefield (Alaska/British Columbia)', Earth Surface Processes and Landforms, 47(9), pp. 2357–2390. Available at: https://doi.org/10.1002/esp.5383.

Davies, B., McNabb, R., Bendle, J., Carrivick, J., Ely, J., Holt, T., Markle, B., McNeil, C., Nicholson, L. and Pelto, M. (2024) 'Accelerating glacier volume loss on Juneau Icefield driven by hypsometry and melt-accelerating feedbacks', Nature Communications, 15(1), p. 5099. Available at: https://doi.org/10.1038/s41467-024-49269-y.

DeConto, R.M. and Pollard, D. (2016) 'Contribution of Antarctica to past and future sea-level rise', Nature, 531(7596), pp. 591–597. Available at: https://doi.org/10.1038/nature17145.

DeConto, R.M., Pollard, D., Alley, R.B., Velicogna, I., Gasson, E., Gomez, N., Sadai, S., Condron, A., Gilford, D.M., Ashe, E.L., Kopp, R.E., Li, D. and Dutton, A. (2021) 'The Paris Climate Agreement and future sea-level rise from Antarctica', Nature, 593(7857), pp. 83–89. Available at: https://doi.org/10.1038/s41586-021-03427-0.

Dial, R.J., Maher, C.T., Hewitt, R.E. and Sullivan, P.F. (2022) 'Sufficient conditions for rapid range expansion of a boreal conifer', Nature, 608(7923), pp. 546–551. Available at: https://doi.org/10.1038/s41586-022-05093-2.

Diaz, R.J. and Rosenberg, R. (2008) 'Spreading Dead Zones and Consequences for Marine Ecosystems', Science, 321(5891), pp. 926–929. Available at: https://doi.org/10.1126/science.1156401.

Dima, M., Lohmann, G., Nichita, D.-R., Knorr, G. and Scholz, P. (2025) 'Structural stability changes of the Atlantic Meridional Overturning Circulation', npj Climate and Atmospheric Science, 8(1), p. 73. Available at: https://doi.org/10.1038/s41612-025-00960-x.

Dinerstein, E., Olson, D., Joshi, A., Vynne, C., Burgess, N.D., Wikramanayake, E., Hahn, N., Palminteri, S., Hedao, P., Noss, R., Hansen, M., Locke, H., Ellis, E.C., Jones, B., Barber, C.V., Hayes, R., Kormos, C., Martin, V., Crist, E., Sechrest, W., Price, L., Baillie, J.E.M., Weeden, D., Suckling, K., Davis, C., Sizer, N., Moore, R., Thau, D., Birch, T., Potapov, P., Turubanova, S., Tyukavina, A., de Souza, N., Pintea, L., Brito, J.C., Llewellyn, O.A., Miller, A.G., Patzelt, A., Ghazanfar, S.A., Timberlake, J., Klöser, H., Shennan-Farpón, Y., Kindt, R., Lillesø, J.-P.B., van Breugel, P., Graudal, L., Voge, M., Al-Shammari, K.F. and Saleem, M. (2017) 'An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm', BioScience, 67(6), pp. 534–545. Available at: https://doi.org/10.1093/biosci/bix014.

Ding, B., Yang, K., Qin, J., Wang, L., Chen, Y. and He, X. (2014) 'The dependence of precipitation types on surface elevation and meteorological conditions and its parameterization', Journal of Hydrology, 513, pp. 154–163. Available at: https://doi.org/10.1016/j.jhydrol.2014.03.038.

Ding, J. and Eldridge, D.J. (2024) 'Woody encroachment: social–ecological impacts and sustainable management', Biological Reviews, 99(6), pp. 1909–1926. Available at: https://doi.org/10.1111/brv.13104.

Ditlevsen, P. and Ditlevsen, S. (2023) 'Warning of a forthcoming collapse of the Atlantic meridional overturning circulation', Nature Communications, 14(1), p. 4254. Available at: https://doi.org/10.1038/s41467-023-39810-w.

Dixon, A.M., Forster, P.M., Heron, S.F., Stoner, A.M.K. and Beger, M. (2022) 'Future loss of local-scale thermal refugia in coral reef ecosystems', PLOS Climate, 1(2), p. e0000004. Available at: https://doi.org/10.1371/journal.pclm.0000004.

D'Odorico, P., Bhattachan, A., Davis, K.F., Ravi, S. and Runyan, C.W. (2013) 'Global desertification: Drivers and feedbacks', Advances in Water Resources, 51, pp. 326–344. Available at: https://doi.org/10.1016/j.advwatres.2012.01.013.

Domínguez-Tuda, M. and Gutiérrez-Jurado, H.A. (2024) 'Global analysis of forest tipping points leading to changing water cycle dynamics', Journal of Hydrology X, 25, p. 100187. Available at: https://doi.org/10.1016/j.hydroa.2024.100187.

D'Onofrio, D., Sweeney, L., von Hardenberg, J. and Baudena, M. (2019) 'Grass and tree cover responses to intra-seasonal rainfall variability vary along a rainfall gradient in African tropical grassy biomes', Scientific Reports, 9(1), p. 2334. Available at: https://doi.org/10.1038/s41598-019-38933-9.

Drijfhout, S., Angevaare, J.R., Mecking, J., van Westen, R.M. and Rahmstorf, S. (2025) 'Shutdown of northern Atlantic overturning after 2100 following deep mixing collapse in CMIP6 projections', Environmental Research Letters, 20(9), p. 094062. Available at: https://doi.org/10.1088/1748-9326/adfa3b.

Drijfhout, S., Bathiany, S., Beaulieu, C., Brovkin, V., Claussen, M., Huntingford, C., Scheffer, M., Sgubin, G. and Swingedouw, D. (2015) 'Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models', Proceedings of the National Academy of Sciences, 112(43), pp. E5777–E5786. Available at: https://doi.org/10.1073/pnas.1511451112.

Drijfhout, S., Gleeson, E., Dijkstra, H.A. and Livina, V. (2013) 'Spontaneous abrupt climate change due to an atmospheric blocking–sea-ice–ocean feedback in an unforced climate model simulation', Proceedings of the National Academy of Sciences, 110(49), pp. 19713–19718. Available at: https://doi.org/10.1073/pnas.1304912110.

Duarte, B., Martins, I., Rosa, R., Matos, A.R., Roleda, M.Y., Reusch, T.B.H., Engelen, A.H., Serrão, E.A., Pearson, G.A., Marques, J.C., Caçador, I., Duarte, C.M. and Jueterbock, A. (2018) 'Climate Change Impacts on Seagrass Meadows and Macroalgal Forests: An Integrative Perspective on Acclimation and Adaptation Potential', Frontiers in Marine Science, 5. Available at: https://doi.org/10.3389/fmars.2018.00190.

Duke, N.C., Canning, A.D. and Mackenzie, J.R. (2024) 'More Intense Severe Tropical Cyclones in Recent Decades Cause Greater Impacts on Mangroves Bordering Australia's Great Barrier Reef', in Oceanographic Processes of Coral Reefs. 2nd edn. CRC Press.

Duke, N.C., Field, C., Mackenzie, J.R., Meynecke, J.-O. and Wood, A.L. (2019) 'Rainfall and its possible hysteresis effect on the proportional cover of tropical tidal-wetland mangroves and saltmarsh–saltpans', Marine and Freshwater Research, 70(8), pp. 1047–1055. Available at: https://doi.org/10.1071/MF18321.

Duke, N.C., Hutley, L.B., Mackenzie, J.R. and Burrows, D. (2021) 'Processes and Factors Driving Change in Mangrove Forests: An Evaluation Based on the Mass Dieback Event in Australia's Gulf of Carpentaria', in J.G. Canadell and R.B. Jackson (eds) Ecosystem Collapse and Climate Change. Cham: Springer International Publishing, pp. 221–264. Available at: https://doi.org/10.1007/978-3-030-71330-0_9.

Duke, N.C., Kovacs, J.M., Griffiths, A.D., Preece, L., Hill, D.J.E., Oosterzee, P. van, Mackenzie, J., Morning, H.S. and Burrows, D. (2017) 'Large-scale dieback of mangroves in Australia's Gulf of Carpentaria: a severe ecosystem response, coincidental with an unusually extreme weather event', Marine and Freshwater Research, 68(10), pp. 1816–1829. Available at: https://doi.org/10.1071/MF16322.

Duke, N.C., Mackenzie, J.R., Canning, A.D., Hutley, L.B., Bourke, A.J., Kovacs, J.M., Cormier, R., Staben, G., Lymburner, L. and Ai, E. (2022) 'ENSO-driven extreme oscillations in mean sea level destabilise critical shoreline mangroves—An emerging threat', PLOS Climate, 1(8), p. e0000037. Available at: https://doi.org/10.1371/journal.pclm.0000037.

Dunic, J.C., Brown, C.J., Connolly, R.M., Turschwell, M.P. and Côté, I.M. (2021) 'Long-term declines and recovery of meadow area across the world's seagrass bioregions', Global Change Biology, 27(17), pp. 4096–4109. Available at: https://doi.org/10.1111/gcb.15684.

Durigan, G. and Ratter, J.A. (2016) 'The need for a consistent fire policy for Cerrado conservation', Journal of Applied Ecology, 53(1), pp. 11–15. Available at: https://doi.org/10.1111/1365-2664.12559.

Edmunds, P.J. and Gray, S.C. (2014) 'The effects of storms, heavy rain, and sedimentation on the shallow coral reefs of St. John, US Virgin Islands', Hydrobiologia, 734(1), pp. 143–158. Available at: https://doi.org/10.1007/s10750-014-1876-7.

Edwards, T.L., Brandon, M.A., Durand, G., Edwards, N.R., Golledge, N.R., Holden, P.B., Nias, I.J., Payne, A.J., Ritz, C. and Wernecke, A. (2019) 'Revisiting Antarctic ice loss due to marine ice-cliff instability', Nature, 566(7742), pp. 58–64. Available at: https://doi.org/10.1038/s41586-019-0901-4.

Eldridge, D.J., Ding, J., Dorrough, J., Delgado-Baquerizo, M., Sala, O., Gross, N., Le Bagousse-Pinguet, Y., Mallen-Cooper, M., Saiz, H., Asensio, S., Ochoa, V., Gozalo, B., Guirado, E., García-Gómez, M., Valencia, E., Martínez-Valderrama, J., Plaza, C., Abedi, M., Ahmadian, N., Ahumada, R.J., Alcántara, J.M., Amghar, F., Azevedo, L., Ben Salem, F., Berdugo, M., Blaum, N., Boldgiv, B., Bowker, M., Bran, D., Bu, C., Canessa, R., Castillo-Monroy, A.P., Castro, I., Castro-Quezada, P., Cesarz, S., Chibani, R., Conceição, A.A., Darrouzet-Nardi, A., Davila, Y.C., Deák, B., Díaz-Martínez, P., Donoso, D.A., Dougill, A.D., Durán, J., Eisenhauer, N., Ejtehadi, H., Espinosa, C.I., Fajardo, A., Farzam, M., Foronda, A., Franzese, J., Fraser, L.H., Gaitán, J., Geissler, K., Gonzalez, S.L., Gusman-Montalvan, E., Hernández, R.M., Hölzel, N., Hughes, F.M., Jadan, O., Jentsch, A., Ju, M., Kaseke, K.F., Köbel, M., Lehmann, A., Liancourt, P., Linstädter, A., Louw, M.A., Ma, Q., Mabaso, M., Maggs-Kölling, G., Makhalanyane, T.P., Issa, O.M., Marais, E., McClaran, M., Mendoza, B., Mokoka, V., Mora, J.P., Moreno, G., Munson, S., Nunes, A., Oliva, G., Oñatibia, G.R., Osborne, B., Peter, G., Pierre, M., Pueyo, Y., Emiliano Quiroga, R., Reed, S., Rey, A., Rey, P., Gómez, V.M.R., Rolo, V., Rillig, M.C., le Roux, P.C., Ruppert, J.C., Salah, A., Sebei, P.J., Sharkhuu, A., Stavi, I., Stephens, C., Teixido, A.L., Thomas, A.D., Tielbörger, K., Robles, S.T., Travers, S., Valkó, O., van den Brink, L., Velbert, F., von Heßberg, A., Wamiti, W., Wang, D., Wang, L., Wardle, G.M., Yahdjian, L., Zaady, E., Zhang, Y., Zhou, X. and Maestre, F.T. (2024) 'Hotspots of biogeochemical activity linked to aridity and plant traits across global drylands', Nature Plants, 10(5), pp. 760–770. Available at: https://doi.org/10.1038/s41477-024-01670-7.

Environment, U.N. (2021) Status of Coral Reefs of the World 2020 | UNEP - UN Environment Programme. Available at: https://www.unep.org/resources/status-coral-reefs-world-2020

Espinosa, Z.I., Blanchard-Wrigglesworth, E. and Bitz, C.M. (2024) 'Understanding the drivers and predictability of record low Antarctic sea ice in austral winter 2023', Communications Earth & Environment, 5(1), p. 723. Available at: https://doi.org/10.1038/s43247-024-01772-2.

Falkena, S.K.J., Dijkstra, H.A. and Heydt, A.S. von der (2025) 'Causal Mechanisms of Subpolar Gyre Variability in CMIP6 Models'. arXiv. Available at: https://doi.org/10.48550/arXiv.2408.16541.

Fedorov, A.V., Brierley, C.M., Lawrence, K.T., Liu, Z., Dekens, P.S. and Ravelo, A.C. (2013) 'Patterns and mechanisms of early Pliocene warmth', Nature, 496(7443), pp. 43–49. Available at: https://doi.org/10.1038/nature12003.

Fedorov, A.V., Burls, N.J., Lawrence, K.T. and Peterson, L.C. (2015) 'Tightly linked zonal and meridional sea surface temperature gradients over the past five million years', Nature Geoscience, 8(12), pp. 975–980. Available at: https://doi.org/10.1038/ngeo2577.

Fedorov, A.V., Dekens, P.S., McCarthy, M., Ravelo, A.C., deMenocal, P.B., Barreiro, M., Pacanowski, R.C. and Philander, S.G. (2006) 'The Pliocene Paradox (Mechanisms for a Permanent El Niño)', Science, 312(5779), pp. 1485–1489. Available at: https://doi.org/10.1126/science.1122666.

Fedorov, A.V., Hu, S., Wittenberg, A.T., Levine, A.F.Z. and Deser, C. (2020) 'ENSO Low-Frequency Modulation and Mean State Interactions', in El Niño Southern Oscillation in a Changing Climate. American Geophysical Union (AGU), pp. 173–198. Available at: https://doi.org/10.1002/9781119548164.ch8.

Feldmann, J. and Levermann, A. (2015) 'Collapse of the West Antarctic Ice Sheet after local destabilization of the Amundsen Basin', Proceedings of the National Academy of Sciences, 112(46), pp. 14191–14196. Available at: https://doi.org/10.1073/pnas.1512482112.

Feller, I.C., Friess, D.A., Krauss, K.W. and Lewis, R.R. (2017) 'The state of the world's mangroves in the 21st century under climate change', Hydrobiologia, 803(1), pp. 1–12. Available at: https://doi.org/10.1007/s10750-017-3331-z.

Ferreira, A.C., Ashton, E.C., Ward, R.D., Hendy, I. and Lacerda, L.D. (2024) 'Mangrove Biodiversity and Conservation: Setting Key Functional Groups and Risks of Climate-Induced Functional Disruption', Diversity, 16(7), p. 423. Available at: https://doi.org/10.3390/d16070423.

Filbee-Dexter, K. and Wernberg, T. (2018) 'Rise of Turfs: A New Battlefront for Globally Declining Kelp Forests', BioScience, 68(2), pp. 64–76. Available at: https://doi.org/10.1093/biosci/bix147.

Filbee-Dexter, K., Wernberg, T., Grace, S.P., Thormar, J., Fredriksen, S., Narvaez, C.N., Feehan, C.J. and Norderhaug, K.M. (2020) 'Marine heatwaves and the collapse of marginal North Atlantic kelp forests', Scientific Reports, 10(1), p. 13388. Available at: https://doi.org/10.1038/s41598-020-70273-x.

Flores, B.M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R.A., Levis, C., Lapola, D.M., Esquível-Muelbert, A., Jakovac, C., Nobre, C.A., Oliveira, R.S., Borma, L.S., Nian, D., Boers, N., Hecht, S.B., ter Steege, H., Arieira, J., Lucas, I.L., Berenguer, E., Marengo, J.A., Gatti, L.V., Mattos, C.R.C. and Hirota, M. (2024) 'Critical transitions in the Amazon forest system', Nature, 626(7999), pp. 555–564. Available at: https://doi.org/10.1038/s41586-023-06970-0.

Flores, B.M. and Staal, A. (2022) 'Feedback in tropical forests of the Anthropocene', Global Change Biology, 28(17), pp. 5041–5061. Available at: https://doi.org/10.1111/gcb.16293.

Forster, P., T. Storelvmo, K. Armour, W. Collins, J.-L. Dufresne, D. Frame, D.J. Lunt, T. Mauritsen, M.D. Palmer, M. Watanabe, M. Wild, and H. Zhang, (2021): The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054, doi: 10.1017/9781009157896.009.

Forzieri, G., Dakos, V., McDowell, N.G., Ramdane, A. and Cescatti, A. (2022) 'Emerging signals of declining forest resilience under climate change', Nature, 608(7923), pp. 534–539. Available at: https://doi.org/10.1038/s41586-022-04959-9.

Fox-Kemper, B., Hewitt, H.T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S.S., Edwards, T.L., Golledge, N.R., Hemer, M., Kopp, R.E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I.S., Ruiz, L., Sallée, J.-B., Slangen, A.B.A. and Yu, Y. (2021) 'Chapter 9: Ocean, Cryosphere and Sea Level Change', in V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Franco, M.A., Rizzo, L.V., Teixeira, M.J., Artaxo, P., Azevedo, T., Lelieveld, J., Nobre, C.A., Pöhlker, C., Pöschl, U., Shimbo, J., Xu, X. and Machado, L.A.T. (2025) 'How climate change and deforestation interact in the transformation of the Amazon rainforest', Nature Communications, 16(1), p. 7944. Available at: https://doi.org/10.1038/s41467-025-63156-0.

Freitas, N.L., Walter Anthony, K., Lenz, J., Porras, R.C. and Torn, M.S. (2025) 'Substantial and overlooked greenhouse gas emissions from deep Arctic lake sediment', Nature Geoscience, 18(1), pp. 65–71. Available at: https://doi.org/10.1038/s41561-024-01614-y.

Freund, M.B., Henley, B.J., Karoly, D.J., McGregor, H.V., Abram, N.J. and Dommenget, D. (2019) 'Higher frequency of Central Pacific El Niño events in recent decades relative to past centuries', Nature Geoscience, 12(6), pp. 450–455. Available at: https://doi.org/10.1038/s41561-019-0353-3.

Fricker, H.A., Galton-Fenzi, B.K., Walker, C.C., Freer, B.I.D., Padman, L. and DeConto, R. (2025) 'Antarctica in 2025: Drivers of deep uncertainty in projected ice loss', Science, 387(6734), pp. 601–609. Available at: https://doi.org/10.1126/science.adt9619.

Fried, N., Biló, T.C., Johns, W.E., Katsman, C.A., Fogaren, K.E., Yoder, M., Palevsky, H.I., Straneo, F. and de Jong, M.F. (2024) 'Recent Freshening of the Subpolar North Atlantic Increased the Transport of Lighter Waters of the Irminger Current From 2014 to 2022', Journal of Geophysical Research: Oceans, 129(11), p. e2024JC021184. Available at: https://doi.org/10.1029/2024JC021184.

Frieler, K., Meinshausen, M., Golly, A., Mengel, M., Lebek, K., Donner, S.D. and Hoegh-Guldberg, O. (2013) 'Limiting global warming to 2 °C is unlikely to save most coral reefs', Nature Climate Change, 3(2), pp. 165–170. Available at: https://doi.org/10.1038/nclimate1674.

Friess, D.A., Rogers, K., Lovelock, C.E., Krauss, K.W., Hamilton, S.E., Lee, S.Y., Lucas, R., Primavera, J., Rajkaran, A. and Shi, S. (2019) 'The State of the World's Mangrove Forests: Past, Present, and Future', Annual Review of Environment and Resources, 44(Volume 44, 2019), pp. 89–115. Available at: https://doi.org/10.1146/annurev-environ-101718-033302.

Fu, X., Li, Z., Ma, J., Zhou, M., Chen, L. and Peng, J. (2025) 'Ecosystem resilience response to forest fragmentation in China: Thresholds identification', Journal of Environmental Management, 380, p. 125180. Available at: https://doi.org/10.1016/j.jenvman.2025.125180.

Garbe, J., Albrecht, T., Levermann, A., Donges, J.F. and Winkelmann, R. (2020) 'The hysteresis of the Antarctic Ice Sheet', Nature, 585(7826), pp. 538–544. Available at: https://doi.org/10.1038/s41586-020-2727-5.

Garcin, Y., Schefuß, E., Dargie, G.C., Hawthorne, D., Lawson, I.T., Sebag, D., Biddulph, G.E., Crezee, B., Bocko, Y.E., Ifo, S.A., Mampouya Wenina, Y.E., Mbemba, M., Ewango, C.E.N., Emba, O., Bola, P., Kanyama Tabu, J., Tyrrell, G., Young, D.M., Gassier, G., Girkin, N.T., Vane, C.H., Adatte, T., Baird, A.J., Boom, A., Gulliver, P., Morris, P.J., Page, S.E., Sjögersten, S. and Lewis, S.L. (2022) 'Hydroclimatic vulnerability of peat carbon in the central Congo Basin', Nature, 612(7939), pp. 277–282. Available at: https://doi.org/10.1038/s41586-022-05389-3.

Geen, R., Bordoni, S., Battisti, D.S. and Hui, K. (2020) 'Monsoons, ITCZs, and the Concept of the Global Monsoon', Reviews of Geophysics, 58(4), p. e2020RG000700. Available at: https://doi.org/10.1029/2020RG000700.

Georgievski, G., Kleinen, T., de Vrese, P., Brovkin, V., Silvy, Y. and Frölicher, T.L. (2025) 'Permafrost Thaw Impact on Remaining Carbon Budgets and Emissions Pathways in 2°C and 3°C Global Warming Scenarios', Earth's Future, 13(7), p. e2024EF005153. Available at: https://doi.org/10.1029/2024EF005153.

Gerber, L., Lippold, J., Süfke, F., Valk, O., Testorf, P., Ehnis, M., Tautenhahn, S., Max, L., Chiessi, C.M., Regelous, M., Szidat, S., Friedrich, O. and Pöppelmeier, F. (2025) 'Low variability of the Atlantic Meridional Overturning Circulation throughout the Holocene', Nature Communications, 16(1), p. 6748. Available at: https://doi.org/10.1038/s41467-025-61793-z.

Gilarranz, L.J., Narwani, A., Odermatt, D., Siber, R. and Dakos, V. (2022) 'Regime shifts, trends, and variability of lake productivity at a global scale', Proceedings of the National Academy of Sciences, 119(35), p. e2116413119. Available at: https://doi.org/10.1073/pnas.2116413119.

Gilbert, A., Leinss, S., Kargel, J., Kääb, A., Gascoin, S., Leonard, G., Berthier, E., Karki, A. and Yao, T. (2018) 'Mechanisms leading to the 2016 giant twin glacier collapses, Aru Range, Tibet', The Cryosphere, 12(9), pp. 2883–2900. Available at: https://doi.org/10.5194/tc-12-2883-2018.

Glasby, T.M., Gibson, P.T., Laird, R., Swadling, D.S. and West, G. (2023) 'Black summer bushfires caused extensive damage to estuarine wetlands in New South Wales, Australia', Ecological Management & Restoration, 24(1), pp. 27–35. Available at: https://doi.org/10.1111/emr.12572.

Golledge, N.R., Clark, P.U., He, F., Dutton, A., Turney, C.S.M., Fogwill, C.J., Naish, T.R., Levy, R.H., McKay, R.M., Lowry, D.P., Bertler, N. a. N., Dunbar, G.B. and Carlson, A.E. (2021) 'Retreat of the Antarctic Ice Sheet During the Last Interglaciation and Implications for Future Change', Geophysical Research Letters, 48(17), p. e2021GL094513. Available at: https://doi.org/10.1029/2021GL094513.

Gottschalk, J., Skinner, L.C., Lippold, J., Vogel, H., Frank, N., Jaccard, S.L. and Waelbroeck, C. (2016) 'Biological and physical controls in the Southern Ocean on past millennial-scale atmospheric CO_2 changes', Nature Communications, 7(1), p. 11539. Available at: https://doi.org/10.1038/ncomms11539.

Gou, R., Lohmann, G. and Wu, L. (2024) 'Atlantic Meridional Overturning Circulation Decline: Tipping Small Scales under Global Warming', Physical Review Letters, 133(3), p. 034201. Available at: https://doi.org/10.1103/PhysRevLett.133.034201.

Grant, G.R., Naish, T.R., Dunbar, G.B., Stocchi, P., Kominz, M.A., Kamp, P.J.J., Tapia, C.A., McKay, R.M., Levy, R.H. and Patterson, M.O. (2019) 'The amplitude and origin of sea-level variability during the Pliocene epoch', Nature, 574(7777), pp. 237–241. Available at: https://doi.org/10.1038/s41586-019-1619-z.

Greene, C.A., Gardner, A.S., Wood, M. and Cuzzone, J.K. (2024) 'Ubiquitous acceleration in Greenland Ice Sheet calving from 1985 to 2022', Nature, 625(7995), pp. 523–528. Available at: https://doi.org/10.1038/s41586-023-06863-2.

Gregory, J.M., Stott, P.A., Cresswell, D.J., Rayner, N.A., Gordon, C. and Sexton, D.M.H. (2002) 'Recent and future changes in Arctic sea ice simulated by the HadCM3 AOGCM', Geophysical Research Letters, 29(24), pp. 28-1-28–4. Available at: https://doi.org/10.1029/2001GL014575.

Grodofzig, R., Renoult, M. and Mauritsen, T. (2024) 'Observation-inferred resilience loss of the Amazon rainforest possibly due to internal climate variability', Earth System Dynamics, 15(4), pp. 913–927. Available at: https://doi.org/10.5194/esd-15-913-2024.

Grothe, P.R., Cobb, K.M., Liguori, G., Di Lorenzo, E., Capotondi, A., Lu, Y., Cheng, H., Edwards, R.L., Southon, J.R., Santos, G.M., Deocampo, D.M., Lynch-Stieglitz, J., Chen, T., Sayani, H.R., Thompson, D.M., Conroy, J.L., Moore, A.L., Townsend, K., Hagos, M., O'Connor, G. and Toth, L.T. (2020) 'Enhanced El Niño–Southern Oscillation Variability in Recent Decades', Geophysical Research Letters, 47(7), p. e2019GL083906. Available at: https://doi.org/10.1029/2019GL083906.

Gu, Q., Gervais, M., Danabasoglu, G., Kim, W.M., Castruccio, F., Maroon, E. and Xie, S.-P. (2024) 'Wide range of possible trajectories of North Atlantic climate in a warming world', Nature Communications, 15(1), p. 4221. Available at: https://doi.org/10.1038/s41467-024-48401-2.

Guimarães, S.O., Mann, M.E., Rahmstorf, S., Petri, S., Steinman, B.A., Brouillette, D.J., Christiansen, S. and Li, X. (2024) 'Increased projected changes in quasi-resonant amplification and persistent summer weather extremes in the latest multimodel climate projections', Scientific Reports, 14(1), p. 21991. Available at: https://doi.org/10.1038/s41598-024-72787-0.

Gunn, K., Rintoul, S. and England, M. (In Review) 'Persistent warming and reduced freshening of the abyssal Southern Ocean'. Available at: https://doi.org/10.5281/zenodo.17067349.

Gunn, K.L., Rintoul, S.R., England, M.H. and Bowen, M.M. (2023) 'Recent reduced abyssal overturning and ventilation in the Australian Antarctic Basin', Nature Climate Change, 13(6), pp. 537–544. Available at: https://doi.org/10.1038/s41558-023-01667-8.

Hagger, V., Worthington, T.A., Lovelock, C.E., Adame, M.F., Amano, T., Brown, B.M., Friess, D.A., Landis, E., Mumby, P.J., Morrison, T.H., O'Brien, K.R., Wilson, K.A., Zganjar, C. and Saunders, M.I. (2022) 'Drivers of global mangrove loss and gain in social-ecological systems', Nature Communications, 13(1), p. 6373. Available at: https://doi.org/10.1038/s41467-022-33962-x.

Hajdu, L.H., Meesters, A.G.C.A., Dolman, A.J. and Friend, A.D. (2025) 'Deforestation Could Push Amazonia Close to a Tipping Point Under Future Climate Change', Geophysical Research Letters, 52(15), p. e2024GL108304. Available at: https://doi.org/10.1029/2024GL108304.

Hankel, C. (2025) 'The effect of CO^2 ramping rate on the transient weakening of the Atlantic Meridional Overturning Circulation', Proceedings of the National Academy of Sciences, 122(1), p. e2411357121. Available at: https://doi.org/10.1073/pnas.2411357121.

Hankel, C. and Tziperman, E. (2023) 'An approach for projecting the timing of abrupt winter Arctic sea ice loss', Nonlinear Processes in Geophysics, 30(3), pp. 299–309. Available at: https://doi.org/10.5194/npg-30-299-2023.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. and Townshend, J.R.G. (2013) 'High-Resolution Global Maps of 21st-Century Forest Cover Change', Science, 342(6160), pp. 850–853. Available at: https://doi.org/10.1126/science.1244693.

Harris, S.A., French, H.M., Heginbottom, J.A., Johnston, G.H., Ladanyi, B., Sego, D.C., van Everdingen, R.O., and Permafrost Subcommittee, Associate Committee on Geotechnical Research, National Research Council of Canada (eds) (1988) Glossary of permafrost and related ground-ice terms. Ottawa,Ontario,Canada (Technical Memorandum / National Research Council, Canada, 142). Available at: https://www.permafrost.org/publication/glossary-of-permafrost-and-related-ground-ice-terms/.

Hayes, C.T., Martínez-García, A., Hasenfratz, A.P., Jaccard, S.L., Hodell, D.A., Sigman, D.M., Haug, G.H. and Anderson, R.F. (2014) 'A stagnation event in the deep South Atlantic during the last interglacial period', Science, 346(6216), pp. 1514–1517. Available at: https://doi.org/10.1126/science.1256620.

Heede, U.K. and Fedorov, A.V. (2023a) 'Colder Eastern Equatorial Pacific and Stronger Walker Circulation in the Early 21st Century: Separating the Forced Response to Global Warming From Natural Variability', Geophysical Research Letters, 50(3), p. e2022GL101020. Available at: https://doi.org/10.1029/2022GL101020.

Heede, U.K. and Fedorov, A.V. (2023b) 'Towards understanding the robust strengthening of ENSO and more frequent extreme El Niño events in CMIP6 global warming simulations', Climate Dynamics, 61(5), pp. 3047–3060. Available at: https://doi.org/10.1007/s00382-023-06856-x.

Heinze, C., Blenckner, T., Martins, H., Rusiecka, D., Döscher, R., Gehlen, M., Gruber, N., Holland, E., Hov, Ø., Joos, F., Matthews, J.B.R., Rødven, R. and Wilson, S. (2021) 'The quiet crossing of ocean tipping points', Proceedings of the National Academy of Sciences, 118(9), p. e2008478118. Available at: https://doi.org/10.1073/pnas.2008478118.

Hellmer, H.H., Kauker, F., Timmermann, R., Determann, J. and Rae, J. (2012) 'Twenty-first-century warming of a large Antarctic ice-shelf cavity by a redirected coastal current', Nature, 485(7397), pp. 225–228. Available at: https://doi.org/10.1038/nature11064.

Hellmer, H.H., Kauker, F., Timmermann, R. and Hattermann, T. (2017) 'The Fate of the Southern Weddell Sea Continental Shelf in a Warming Climate'. Available at: https://doi.org/10.1175/JCLI-D-16-0420.1.

Henley, B.J., McGregor, H.V., King, A.D., Hoegh-Guldberg, O., Arzey, A.K., Karoly, D.J., Lough, J.M., DeCarlo, T.M. and Linsley, B.K. (2024) 'Highest ocean heat in four centuries places Great Barrier Reef in danger', Nature, 632(8024), pp. 320–326. Available at: https://doi.org/10.1038/s41586-024-07672-x.

Hessen, D.O., Andersen, T., Armstrong McKay, D., Kosten, S., Meerhoff, M., Pickard, A. and Spears, B.M. (2024) 'Lake ecosystem tipping points and climate feedbacks', Earth System Dynamics, 15(3), pp. 653–669. Available at: https://doi.org/10.5194/esd-15-653-2024.

Hesterberg, S.G., Jackson, K. and Bell, S.S. (2022) 'Climate drives coupled regime shifts across subtropical estuarine ecosystems', Proceedings of the National Academy of Sciences, 119(33), p. e2121654119. Available at: https://doi.org/10.1073/pnas.2121654119.

Heuzé, C. (2021) 'Antarctic Bottom Water and North Atlantic Deep Water in CMIP6 models', Ocean Science, 17(1), pp. 59–90. Available at: https://doi.org/10.5194/os-17-59-2021.

Heuzé, C. and Jahn, A. (2024) 'The first ice-free day in the Arctic Ocean could occur before 2030', Nature Communications, 15(1), p. 10101. Available at: https://doi.org/10.1038/s41467-024-54508-3.

Higgins, S.I., Banerjee, S., Baudena, M., Bowman, D.M.J.S., Conradi, T., Couteron, P., Kruger, L.M., O'Hara, R.B. and Williamson, G.J. (2024) 'Reassessing the alternative ecosystem states proposition in the African savanna-forest domain', New Phytologist, 243(5), pp. 1660–1669. Available at: https://doi.org/10.1111/nph.19911.

Hill, E.A., Gudmundsson, G.H. and Chandler, D.M. (2024) 'Ocean warming as a trigger for irreversible retreat of the Antarctic ice sheet', Nature Climate Change, 14(11), pp. 1165–1171. Available at: https://doi.org/10.1038/s41558-024-02134-8.

Hill, E.A., Urruty, B., Reese, R., Garbe, J., Gagliardini, O., Durand, G., Gillet-Chaulet, F., Gudmundsson, G.H., Winkelmann, R., Chekki, M., Chandler, D. and Langebroek, P.M. (2023) 'The stability of present-day Antarctic grounding lines – Part 1: No indication of marine ice sheet instability in the current geometry', The Cryosphere, 17(9), pp. 3739–3759. Available at: https://doi.org/10.5194/tc-17-3739-2023.

Hirota, M., Holmgren, M., Van Nes, E.H. and Scheffer, M. (2011) 'Global Resilience of Tropical Forest and Savanna to Critical Transitions', Science, 334(6053), pp. 232–235. Available at: https://doi.org/10.1126/science.1210657.

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S. and Kutuzov, S. (2019) 'Chapter 2: High Mountain Areas', in The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change. Cambridge: H.-O. Pörtner, DC Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E ..., pp. 131–202. Available at: https://doi.org/10.1017/9781009157964.004.

Hoffman, M.J., Branecky Begeman, C., Asay-Davis, X.S., Comeau, D., Barthel, A., Price, S.F. and Wolfe, J.D. (2024) 'Ice-shelf freshwater triggers for the Filchner–Ronne Ice Shelf melt tipping point in a global ocean–sea-ice model', The Cryosphere, 18(6), pp. 2917–2937. Available at: https://doi.org/10.5194/tc-18-2917-2024.

Högner, A., Capua, G.D., Donges, J.F., Donner, R.V., Feulner, G. and Wunderling, N. (2025) 'Causal pathway from AMOC to Southern Amazon rainforest indicates stabilising interaction between two climate tipping elements', Environmental Research Letters, 20(7), p. 074026. Available at: https://doi.org/10.1088/1748-9326/addb62.

Holbrook, N.J., Claar, D.C., Hobday, A.J., McInnes, K.L., Oliver, E.C.J., Gupta, A.S., Widlansky, M.J. and Zhang, X. (2020) 'ENSO-Driven Ocean Extremes and Their Ecosystem Impacts', in El Niño Southern Oscillation in a Changing Climate. American Geophysical Union (AGU), pp. 409–428. Available at: https://doi.org/10.1002/9781119548164.ch18.

Holland, P.R. and Kwok, R. (2012) 'Wind-driven trends in Antarctic sea-ice drift', Nature Geoscience, 5(12), pp. 872–875. Available at: https://doi.org/10.1038/ngeo1627.

Holliday, N.P., Bersch, M., Berx, B., Chafik, L., Cunningham, S., Florindo-López, C., Hátún, H., Johns, W., Josey, S.A., Larsen, K.M.H., Mulet, S., Oltmanns, M., Reverdin, G., Rossby, T., Thierry, V., Valdimarsson, H. and Yashayaev, I. (2020) 'Ocean circulation causes the largest freshening event for 120 years in eastern subpolar North Atlantic', Nature Communications, 11(1), p. 585. Available at: https://doi.org/10.1038/s41467-020-14474-y.

Holling, C.S. (1973) 'Resilience and Stability of Ecological Systems', Annual Review of Ecology and Systematics, 4, pp. 1–23.

Höning, D., Willeit, M. and Ganopolski, A. (2024) 'Reversibility of Greenland ice sheet mass loss under artificial carbon dioxide removal scenarios', Environmental Research Letters, 19(2), p. 024038. Available at: https://doi.org/10.1088/1748-9326/ad2129.

Houk, P., Yalon, A., Maxin, S., Starsinic, C., McInnis, A., Gouezo, M., Golbuu, Y. and van Woesik, R. (2020) 'Predicting coral-reef futures from El Niño and Pacific Decadal Oscillation events', Scientific Reports, 10(1), p. 7735. Available at: https://doi.org/10.1038/s41598-020-64411-8.

Hsu, P., Li, T., Luo, J.-J., Murakami, H., Kitoh, A. and Zhao, M. (2012) 'Increase of global monsoon area and precipitation under global warming: A robust signal?', Geophysical Research Letters, 39(6). Available at: https://doi.org/10.1029/2012GL051037.

Huang, H., Gutjahr, M., Eisenhauer, A. and Kuhn, G. (2020) 'No detectable Weddell Sea Antarctic Bottom Water export during the Last and Penultimate Glacial Maximum', Nature Communications, 11(1), p. 424. Available at: https://doi.org/10.1038/s41467-020-14302-3.

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J.W., Schuur, E. a. G., Ping, C.-L., Schirrmeister, L., Grosse, G., Michaelson, G.J., Koven, C.D., O'Donnell, J.A., Elberling, B., Mishra, U., Camill, P., Yu, Z., Palmtag, J. and Kuhry, P. (2014) 'Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps', Biogeosciences, 11(23), pp. 6573–6593. Available at: https://doi.org/10.5194/bg-11-6573-2014.

Hughes, T.P., Anderson, K.D., Connolly, S.R., Heron, S.F., Kerry, J.T., Lough, J.M., Baird, A.H., Baum, J.K., Berumen, M.L., Bridge, T.C., Claar, D.C., Eakin, C.M., Gilmour, J.P., Graham, N.A.J., Harrison, H., Hobbs, J.-P.A., Hoey, A.S., Hoogenboom, M., Lowe, R.J., McCulloch, M.T., Pandolfi, J.M., Pratchett, M., Schoepf, V., Torda, G. and Wilson, S.K. (2018) 'Spatial and temporal patterns of mass bleaching of corals in the Anthropocene', Science, 359(6371), pp. 80–83. Available at: https://doi.org/10.1126/science.aan8048.

Hughes, T.P., Kerry, J.T., Álvarez-Noriega, M., Álvarez-Romero, J.G., Anderson, K.D., Baird, A.H., Babcock, R.C., Beger, M., Bellwood, D.R., Berkelmans, R., Bridge, T.C., Butler, I.R., Byrne, M., Cantin, N.E., Comeau, S., Connolly, S.R., Cumming, G.S., Dalton, S.J., Diaz-Pulido, G., Eakin, C.M., Figueira, W.F., Gilmour, J.P., Harrison, H.B., Heron, S.F., Hoey, A.S., Hobbs, J.-P.A., Hoogenboom, M.O., Kennedy, E.V., Kuo, C., Lough, J.M., Lowe, R.J., Liu, G., McCulloch, M.T., Malcolm, H.A., McWilliam, M.J., Pandolfi, J.M., Pears, R.J., Pratchett, M.S., Schoepf, V., Simpson, T., Skirving, W.J., Sommer, B., Torda, G., Wachenfeld, D.R., Willis, B.L. and Wilson, S.K. (2017) 'Global warming and recurrent mass bleaching of corals', Nature, 543(7645), pp. 373–377. Available at: https://doi.org/10.1038/nature21707.

Hughes, T.P., Kerry, J.T., Baird, A.H., Connolly, S.R., Dietzel, A., Eakin, C.M., Heron, S.F., Hoey, A.S., Hoogenboom, M.O., Liu, G., McWilliam, M.J., Pears, R.J., Pratchett, M.S., Skirving, W.J., Stella, J.S. and Torda, G. (2018) 'Global warming transforms coral reef assemblages', Nature, 556(7702), pp. 492–496. Available at: https://doi.org/10.1038/s41586-018-0041-2.

Hülsen, S., Dee, L.E., Kropf, C.M., Meiler, S. and Bresch, D.N. (2025) 'Mangroves and their services are at risk from tropical cyclones and sea level rise under climate change', Communications Earth & Environment, 6(1), p. 262. Available at: https://doi.org/10.1038/s43247-025-02242-z.

IPCC, 2018: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 616 pp. https://doi.org/ 10.1017/9781009157940.

Jaccard, S.L., Galbraith, E.D., Martínez-García, A. and Anderson, R.F. (2016) 'Covariation of deep Southern Ocean oxygenation and atmospheric CO_2 through the last ice age', Nature, 530(7589), pp. 207–210. Available at: https://doi.org/10.1038/nature16514.

Jackson, L.C., Kahana, R., Graham, T., Ringer, M.A., Woollings, T., Mecking, J.V. and Wood, R.A. (2015) 'Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM', Climate Dynamics, 45(11), pp. 3299–3316. Available at: https://doi.org/10.1007/s00382-015-2540-2.

James, R.K., Keyzer, L.M., van de Velde, S.J., Herman, P.M.J., van Katwijk, M.M. and Bouma, T.J. (2023) 'Climate change mitigation by coral reefs and seagrass beds at risk: How global change compromises coastal ecosystem services', Science of The Total Environment, 857, p. 159576. Available at: https://doi.org/10.1016/j.scitotenv.2022.159576.

Janse, J.H., De Senerpont Domis, L.N., Scheffer, M., Lijklema, L., Van Liere, L., Klinge, M. and Mooij, W.M. (2008) 'Critical phosphorus loading of different types of shallow lakes and the consequences for management estimated with the ecosystem model PCLake', Limnologica, 38(3), pp. 203–219. Available at: https://doi.org/10.1016/j.limno.2008.06.001.

Jeppesen, E. (1991) 'Recovery resilience following a reduction in external phosphorus loading of shallow, eutrophic Danish lakes: duration, regulating factors and methods for overcoming resilience'. Available at: https://www.academia.edu/12937212/Recovery_resilience_following_a_reduction_in_external_phosphorus_loading_of_shallow_eutrophic_Danish_lakes_duration_regulating_factors_and_methods_for_overcoming_resilience (Accessed: 1 September 2025).

Ji, D., Cui, M., Chen, Y. and Dai, Y. (2025) 'Permafrost Response in Northern High-Latitude Regions to 1.5°C Warming and Overshoot Scenarios Achieved via Solar Radiation Modification', Journal of Geophysical Research: Atmospheres, 130(2), p. e2024JD041772. Available at: https://doi.org/10.1029/2024JD041772.

Jiang, J., He, S. and Fan, K. (2025) 'Recent impact of reduced arctic sea-ice on the winter North Atlantic jet stream and its quantitative contributions compared to pre-industrial level', Atmospheric Research, 313, p. 107778. Available at: https://doi.org/10.1016/j.atmosres.2024.107778.

Jiang, N., Zhu, C., Hu, Z.-Z., McPhaden, M.J., Lian, T., Zhou, C., Qian, W. and Chen, D. (2025) 'El Niño and Sea Surface Temperature Pattern Effects Lead to Historically High Global Mean Surface Temperatures in 2023', Geophysical Research Letters, 52(2), p. e2024GL113733. Available at: https://doi.org/10.1029/2024GL113733.

Jiménez, J.C., Miranda, V., Trigo, I., Libonati, R., Albuquerque, R., Peres, L.F., Espinoza, J.-C. and Marengo, J.A. (2024) 'Vegetation Warming and Greenness Decline across Amazonia during the Extreme Drought of 2023', Remote Sensing, 16(14), p. 2519. Available at: https://doi.org/10.3390/rs16142519.

Jónasdóttir, S.H., Visser, A.W., Richardson, K. and Heath, M.R. (2015) 'Seasonal copepod lipid pump promotes carbon sequestration in the deep North Atlantic', Proceedings of the National Academy of Sciences, 112(39), pp. 12122–12126. Available at: https://doi.org/10.1073/pnas.1512110112.

Joos, F., Prentice, I.C., Sitch, S., Meyer, R., Hooss, G., Plattner, G.-K., Gerber, S. and Hasselmann, K. (2001) 'Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) Emission Scenarios', Global Biogeochemical Cycles, 15(4), pp. 891–907. Available at: https://doi.org/10.1029/2000GB001375.

Josey, S.A., Meijers, A.J.S., Blaker, A.T., Grist, J.P., Mecking, J. and Ayres, H.C. (2024) 'Record-low Antarctic sea ice in 2023 increased ocean heat loss and storms', Nature, 636(8043), pp. 635–639. Available at: https://doi.org/10.1038/s41586-024-08368-y.

Jouffray, J.-B., Blasiak, R., Norström, A.V., Österblom, H. and Nyström, M. (2020) 'The Blue Acceleration: The Trajectory of Human Expansion into the Ocean', One Earth, 2(1), pp. 43–54. Available at: https://doi.org/10.1016/j.oneear.2019.12.016.

Jury, C.P. and Toonen, R.J. (2024) 'Widespread scope for coral adaptation under combined ocean warming and acidification', Proceedings of the Royal Society B: Biological Sciences, 291(2031), p. 20241161. Available at: https://doi.org/10.1098/rspb.2024.1161.

Karp, A.T., Uno, K.T., Berke, M.A., Russell, J.M., Scholz, C.A., Marlon, J.R., Faith, J.T. and Staver, A.C. (2023) 'Nonlinear rainfall effects on savanna fire activity across the African Humid Period', Quaternary Science Reviews, 304, p. 107994. Available at: https://doi.org/10.1016/j.quascirev.2023.107994.

Katzenberger, A. and Levermann, A. (2024) 'Consistent increase in East Asian Summer Monsoon rainfall and its variability under climate change over China in CMIP6', Earth System Dynamics, 15(4), pp. 1137–1151. Available at: https://doi.org/10.5194/esd-15-1137-2024.

Katzenberger, A. and Levermann, A. (2025) 'Monsoon hysteresis reveals atmospheric memory', Proceedings of the National Academy of Sciences, 122(19), p. e2418093122. Available at: https://doi.org/10.1073/pnas.2418093122.

Kautz, L.-A., Martius, O., Pfahl, S., Pinto, J.G., Ramos, A.M., Sousa, P.M. and Woollings, T. (2022) 'Atmospheric blocking and weather extremes over the Euro-Atlantic sector – a review', Weather and Climate Dynamics, 3(1), pp. 305–336. Available at: https://doi.org/10.5194/wcd-3-305-2022.

Kéfi, S., Génin, A., Garcia-Mayor, A., Guirado, E., Cabral, J.S., Berdugo, M., Guerber, J., Solé, R. and Maestre, F.T. (2024) 'Self-organization as a mechanism of resilience in dryland ecosystems', Proceedings of the National Academy of Sciences, 121(6), p. e2305153121. Available at: https://doi.org/10.1073/pnas.2305153121.

Keith, D.A., Ferrer-Paris, J.R., Nicholson, E., Bishop, M.J., Polidoro, B.A., Ramirez-Llodra, E., Tozer, M.G., Nel, J.L., Mac Nally, R., Gregr, E.J., Watermeyer, K.E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C.E.R., Etter, A., Roux, D.J., Stark, J.S., Rowland, J.A., Brummitt, N.A., Fernandez-Arcaya, U.C., Suthers, I.M., Wiser, S.K., Donohue, I., Jackson, L.J., Pennington, R.T., Iliffe, T.M., Gerovasileiou, V., Giller, P., Robson, B.J., Pettorelli, N., Andrade, A., Lindgaard, A., Tahvanainen, T., Terauds, A., Chadwick, M.A., Murray, N.J., Moat, J., Pliscoff, P., Zager, I. and Kingsford, R.T. (2022) 'A function-based typology for Earth's ecosystems', Nature, 610(7932), pp. 513–518. Available at: https://doi.org/10.1038/s41586-022-05318-4.

Kendrick, G.A., Nowicki, R.J., Olsen, Y.S., Strydom, S., Fraser, M.W., Sinclair, E.A., Statton, J., Hovey, R.K., Thomson, J.A., Burkholder, D.A., McMahon, K.M., Kilminster, K., Hetzel, Y., Fourqurean, J.W., Heithaus, M.R. and Orth, R.J. (2019) 'A Systematic Review of How Multiple Stressors From an Extreme Event Drove Ecosystem-Wide Loss of Resilience in an Iconic Seagrass Community', Frontiers in Marine Science, 6. Available at: https://doi.org/10.3389/fmars.2019.00455.

Kim, I.-W., Timmermann, A., Kim, J.-E., Rodgers, K.B., Lee, S.-S., Lee, H. and Wieder, W.R. (2024) 'Abrupt increase in Arctic-Subarctic wildfires caused by future permafrost thaw', Nature Communications, 15(1), p. 7868. Available at: https://doi.org/10.1038/s41467-024-51471-x.

Kim, Y.-H., Min, S.-K., Gillett, N.P., Notz, D. and Malinina, E. (2023) 'Observationally-constrained projections of an ice-free Arctic even under a low emission scenario', Nature Communications, 14(1), p. 3139. Available at: https://doi.org/10.1038/s41467-023-38511-8.

Klages, J.P., Hillenbrand, C.-D., Bohaty, S.M., Salzmann, U., Bickert, T., Lohmann, G., Knahl, H.S., Gierz, P., Niu, L., Titschack, J., Kuhn, G., Frederichs, T., Müller, J., Bauersachs, T., Larter, R.D., Hochmuth, K., Ehrmann, W., Nehrke, G., Rodríguez-Tovar, F.J., Schmiedl, G., Spezzaferri, S., Läufer, A., Lisker, F., van de Flierdt, T., Eisenhauer, A., Uenzelmann-Neben, G., Esper, O., Smith, J.A., Pälike, H., Spiegel, C., Dziadek, R., Ronge, T.A., Freudenthal, T. and Gohl, K. (2024) 'Ice sheet–free West Antarctica during peak early Oligocene glaciation', Science, 385(6706), pp. 322–327. Available at: https://doi.org/10.1126/science.adj3931.

Klein, S.G., Roch, C. and Duarte, C.M. (2024) 'Systematic review of the uncertainty of coral reef futures under climate change', Nature Communications, 15(1), p. 2224. Available at: https://doi.org/10.1038/s41467-024-46255-2.

Klose, A.K., Donges, J.F., Feudel, U. and Winkelmann, R. (2024) 'Rate-induced tipping cascades arising from interactions between the Greenland Ice Sheet and the Atlantic Meridional Overturning Circulation', Earth System Dynamics, 15(3), pp. 635–652. Available at: https://doi.org/10.5194/esd-15-635-2024.

Knight, J. and Condron, A. (2025) 'Freshwater from Antarctica mitigates the risk of an AMOC slowdown'. Research Square. Available at: https://doi.org/10.21203/rs.3.rs-5369100/v1.

Kolbe, M., Torres Alavez, J.A., Mottram, R., Bintanja, R., van der Linden, E.C. and Stendel, M. (2025) 'Model performance and surface impacts of atmospheric river events in Antarctica', Discover Atmosphere, 3(1), p. 4. Available at: https://doi.org/10.1007/s44292-025-00026-w.

Koppa, A., Keune, J., Schumacher, D.L., Michaelides, K., Singer, M., Seneviratne, S.I. and Miralles, D.G. (2024) 'Dryland self-expansion enabled by land–atmosphere feedbacks', Science, 385(6712), pp. 967–972. Available at: https://doi.org/10.1126/science.adn6833.

Kornhuber, K. and Tamarin-Brodsky, T. (2021) 'Future Changes in Northern Hemisphere Summer Weather Persistence Linked to Projected Arctic Warming', Geophysical Research Letters, 48(4), p. e2020GL091603. Available at: https://doi.org/10.1029/2020GL091603.

Kriegler, E., Hall, J.W., Held, H., Dawson, R. and Schellnhuber, H.J. (2009) 'Imprecise probability assessment of tipping points in the climate system', Proceedings of the National Academy of Sciences, 106(13), pp. 5041–5046. Available at: https://doi.org/10.1073/pnas.0809117106.

Kump, L.R., Kasting, J.F. and Crane, R.G. (1999) The Earth System. 1st Ed. San Francisco ; London : Prentice Hall.

Kuuluvainen, T. and Gauthier, S. (2018) 'Young and old forest in the boreal: critical stages of ecosystem dynamics and management under global change', Forest Ecosystems, 5(1), p. 26. Available at: https://doi.org/10.1186/s40663-018-0142-2.

Kwiatkowski, L., Planchat, A., Pyolle, M., Torres, O., Bouttes, N., Comte, A. and Bopp, L. (2025) 'Declining coral calcification to enhance twenty-first-century ocean carbon uptake by gigatonnes', Proceedings of the National Academy of Sciences, 122(23), p. e2501562122. Available at: https://doi.org/10.1073/pnas.2501562122.

Lago, V. and England, M.H. (2019) 'Projected Slowdown of Antarctic Bottom Water Formation in Response to Amplified Meltwater Contributions'. Available at: https://doi.org/10.1175/JCLI-D-18-0622.1.

Lamentowicz, M., Ga□ka, M., Marcisz, K., S□owi□ski, M., Kajuka□o-Drygalska, K., Dayras, M.D. and Jassey, V.E.J. (2019) 'Unveiling tipping points in long-term ecological records from Sphagnum-dominated peatlands', Biology Letters, 15(4), p. 20190043. Available at: https://doi.org/10.1098/rsbl.2019.0043.

Lapola, D.M., Pinho, P., Barlow, J., Aragão, L.E.O.C., Berenguer, E., Carmenta, R., Liddy, H.M., Seixas, H., Silva, C.V.J., Silva-Junior, C.H.L., Alencar, A.A.C., Anderson, L.O., Armenteras, D., Brovkin, V., Calders, K., Chambers, J., Chini, L., Costa, M.H., Faria, B.L., Fearnside, P.M., Ferreira, J., Gatti, L., Gutierrez-Velez, V.H., Han, Z., Hibbard, K., Koven, C., Lawrence, P., Pongratz, J., Portela, B.T.T., Rounsevell, M., Ruane, A.C., Schaldach, R., da Silva, S.S., von Randow, C. and Walker, W.S. (2023) 'The drivers and impacts of Amazon forest degradation', Science, 379(6630), p. eabp8622. Available at: https://doi.org/10.1126/science.abp8622.

Latif, M., Sun, J., Visbeck, M. and Hadi Bordbar, M. (2022) 'Natural variability has dominated Atlantic Meridional Overturning Circulation since 1900', Nature Climate Change, 12(5), pp. 455–460. Available at: https://doi.org/10.1038/s41558-022-01342-4.

Lawman, A.E., Di Nezio, P.N., Partin, J.W., Dee, S.G., Thirumalai, K. and Quinn, T.M. (2022) 'Unraveling forced responses of extreme El Niño variability over the Holocene', Science Advances, 8(9), p. eabm4313. Available at: https://doi.org/10.1126/sciadv.abm4313.

Lawrence, D.M., Slater, A.G., Tomas, R.A., Holland, M.M. and Deser, C. (2008) 'Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss', Geophysical Research Letters, 35(11). Available at: https://doi.org/10.1029/2008GL033985.

Le Nohaïc, M., Ross, C.L., Cornwall, C.E., Comeau, S., Lowe, R., McCulloch, M.T. and Schoepf, V. (2017) 'Marine heatwave causes unprecedented regional mass bleaching of thermally resistant corals in northwestern Australia', Scientific Reports, 7(1), p. 14999. Available at: https://doi.org/10.1038/s41598-017-14794-y.

Leathers, T., King, N.G., Foggo, A. and Smale, D.A. (2024) 'Marine heatwave duration and intensity interact to reduce physiological tipping points of kelp species with contrasting thermal affinities', Annals of Botany, 133(1), pp. 51–60. Available at: https://doi.org/10.1093/aob/mcad172.

Leloup, G., Quiquet, A., Roche, D.M., Dumas, C. and Paillard, D. (2025) 'Hysteresis of the Antarctic Ice Sheet With a Coupled Climate-Ice-Sheet Model', Geophysical Research Letters, 52(5), p. e2024GL111492. Available at: https://doi.org/10.1029/2024GL111492.

Lenton, T. (2016) Earth System Science: A Very Short Introduction. Oxford University Press. Available at: https://doi.org/10.1093/actrade/9780198718871.001.0001.

Lenton, T.M., Abrams, J.F., Bartsch, A., Bathiany, S., Boulton, C.A., Buxton, J.E., Conversi, A., Cunliffe, A.M., Hebden, S., Lavergne, T., Poulter, B., Shepherd, A., Smith, T., Swingedouw, D., Winkelmann, R. and Boers, N. (2024) 'Remotely sensing potential climate change tipping points across scales', Nature Communications, 15(1), p. 343. Available at: https://doi.org/10.1038/s41467-023-44609-w.

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S. and Schellnhuber, H.J. (2008) 'Tipping elements in the Earth's climate system', Proceedings of the National Academy of Sciences, 105(6), pp. 1786–1793. Available at: https://doi.org/10.1073/pnas.0705414105.

Lenton, T.M., McKay, D.I.A., Loriani, S., Abrams, J.F., Lade, S.J., Donges, J.F., Milkoreit, M., Powell, T., Smith, S.R., Zimm, C., Buxton, J.E., Bailey, E., Laybourn, L., Ghadiali, A. and Dyke, J.G. (2023) The Global Tipping Points Report 2023. Exeter, UK: University of Exeter.

Levermann, A., Schewe, J., Petoukhov, V. and Held, H. (2009) 'Basic mechanism for abrupt monsoon transitions', Proceedings of the National Academy of Sciences, 106(49), pp. 20572–20577. Available at: https://doi.org/10.1073/pnas.0901414106.

Levermann, A., Winkelmann, R., Albrecht, T., Goelzer, H., Golledge, N.R., Greve, R., Huybrechts, P., Jordan, J., Leguy, G., Martin, D., Morlighem, M., Pattyn, F., Pollard, D., Quiquet, A., Rodehacke, C., Seroussi, H., Sutter, J., Zhang, T., Van Breedam, J., Calov, R., DeConto, R., Dumas, C., Garbe, J., Gudmundsson, G.H., Hoffman, M.J., Humbert, A., Kleiner, T., Lipscomb, W.H., Meinshausen, M., Ng, E., Nowicki, S.M.J., Perego, M., Price, S.F., Saito, F., Schlegel, N.-J., Sun, S. and van de Wal, R.S.W. (2020) 'Projecting Antarctica's contribution to future sea level rise from basal ice shelf melt using linear response functions of 16 ice sheet models (LARMIP-2)', Earth System Dynamics, 11(1), pp. 35–76. Available at: https://doi.org/10.5194/esd-11-35-2020.

Li, C. and Born, A. (2019) 'Coupled atmosphere-ice-ocean dynamics in Dansgaard-Oeschger events', Quaternary Science Reviews, 203, pp. 1–20. Available at: https://doi.org/10.1016/j.quascirev.2018.10.031.

Li, C., Fu, B., Wang, S., Stringer, L.C., Zhou, W., Ren, Z., Hu, M., Zhang, Y., Rodriguez-Caballero, E., Weber, B. and Maestre, F.T. (2023) 'Climate-driven ecological thresholds in China's drylands modulated by grazing', Nature Sustainability, 6(11), pp. 1363–1372. Available at: https://doi.org/10.1038/s41893-023-01187-5.

Li, K.-Y. and Liu, W. (2025) 'Weakened Atlantic Meridional Overturning Circulation causes the historical North Atlantic Warming Hole', Communications Earth & Environment, 6(1), p. 416. Available at: https://doi.org/10.1038/s43247-025-02403-0.

Li, Q., England, M.H., Hogg, A.M., Rintoul, S.R. and Morrison, A.K. (2023) 'Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater', Nature, 615(7954), pp. 841–847. Available at: https://doi.org/10.1038/s41586-023-05762-w.

Li, W., Manzanedo, R.D., Jiang, Y., Ma, W., Du, E., Zhao, S., Rademacher, T., Dong, M., Xu, H., Kang, X., Wang, J., Wu, F., Cui, X. and Pederson, N. (2023) 'Reassessment of growth-climate relations indicates the potential for decline across Eurasian boreal larch forests', Nature Communications, 14(1), p. 3358. Available at: https://doi.org/10.1038/s41467-023-39057-5.

Li, X., Mann, M.E., Wehner, M.F. and Christiansen, S. (2025) 'Increased frequency of planetary wave resonance events over the past half-century', Proceedings of the National Academy of Sciences, 122(25), p. e2504482122. Available at: https://doi.org/10.1073/pnas.2504482122.

Lin, P., Pickart, R.S., Heorton, H., Tsamados, M., Itoh, M. and Kikuchi, T. (2023) 'Recent state transition of the Arctic Ocean's Beaufort Gyre', Nature Geoscience, 16(6), pp. 485–491. Available at: https://doi.org/10.1038/s41561-023-01184-5.

Ling, S.D. and Keane, J.P. (2024) 'Climate-driven invasion and incipient warnings of kelp ecosystem collapse', Nature Communications, 15(1), p. 400. Available at: https://doi.org/10.1038/s41467-023-44543-x.

Ling, S.D., Scheibling, R.E., Rassweiler, A., Johnson, C.R., Shears, N., Connell, S.D., Salomon, A.K., Norderhaug, K.M., Pérez-Matus, A., Hernández, J.C., Clemente, S., Blamey, L.K., Hereu, B., Ballesteros, E., Sala, E., Garrabou, J., Cebrian, E., Zabala, M., Fujita, D. and Johnson, L.E. (2015) 'Global regime shift dynamics of catastrophic sea urchin overgrazing', Philosophical Transactions of the Royal Society B: Biological Sciences, 370(1659), p. 20130269. Available at: https://doi.org/10.1098/rstb.2013.0269.

Liu, A., Cheng, X., Wang, C. and Chen, Y. (2024) 'Evidence of Ecosystem Tipping Point on St. Lawrence Island: Widespread Lake Drainage Events After 2018', Geophysical Research Letters, 51(15), p. e2024GL110161. Available at: https://doi.org/10.1029/2024GL110161.

Liu, W., Xie, S.-P., Liu, Z. and Zhu, J. (2017) 'Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate', Science Advances, 3(1), p. e1601666. Available at: https://doi.org/10.1126/sciadv.1601666.

Liu, Y., Moore, J.K., Primeau, F. and Wang, W.L. (2023) 'Reduced CO_2 uptake and growing nutrient sequestration from slowing overturning circulation', Nature Climate Change, 13(1), pp. 83–90. Available at: https://doi.org/10.1038/s41558-022-01555-7.

Loft, T., Cardoso, A., Bond, W.J., Gonçalves, F.M.P., Machado, M., Oliveras Menor, I., Staver, C. and Stevens, N. (2024) 'Central Africa's mesic savannas should be conserved, not afforested', Global Change Biology, 30(6), p. e17369. Available at: https://doi.org/10.1111/gcb.17369.

Lohmann, J., Dijkstra, H.A., Jochum, M., Lucarini, V. and Ditlevsen, P.D. (2024) 'Multistability and intermediate tipping of the Atlantic Ocean circulation', Science Advances, 10(12), p. eadi4253. Available at: https://doi.org/10.1126/sciadv.adi4253.

Lohmann, J. and Lucarini, V. (2024) 'Melancholia states of the Atlantic Meridional Overturning Circulation', Physical Review Fluids, 9(12), p. 123801. Available at: https://doi.org/10.1103/PhysRevFluids.9.123801.

Loisel, J. and Bunsen, M. (2020) 'Abrupt Fen-Bog Transition Across Southern Patagonia: Timing, Causes, and Impacts on Carbon Sequestration', Frontiers in Ecology and Evolution, 8. Available at: https://doi.org/10.3389/fevo.2020.00273.

Loriani, S., Aksenov, Y., Armstrong McKay, D. I., Bala, G., Born, A., Chiessi, C. M., Dijkstra, H. A., Donges, J. F., Drijfhout, S., England, M. H., Fedorov, A. V., Jackson, L. C., Kornhuber, K., Messori, G., Pausata, F. S. R., Rynders, S., Sallée, J.-B., Sinha, B., Sherwood, S. C., Swingedouw, D., and Tharammal, T.: Tipping points in ocean and atmosphere circulations, Earth System Dynamics, 16, 1611–1653, https://doi.org/10.5194/esd-16-1611-2025, 2025.

Loriani, S., Aksenov, Y., Dijkstra, H., England, M., Fedorov, A., Messori, G., Pausata, F., Sallée, JB., Sinha, B., Sherwood, S., Tharammal, T., Armstrong McKay, D.I., Bala, G., Born, A., Drijfhout, S., Jackson, L., Kornhuber, K., Chiessi, C.M., Rynders, S. and Swingedouw, D. (2023) 'Chapter 1.4 Tipping points in ocean and atmosphere circulations', in Global Tipping Points Report 2023. Exeter, UK: University of Exeter.

Lovejoy, T.E. and Nobre, C. (2018) 'Amazon Tipping Point', Science Advances, 4(2), p. eaat2340. Available at: https://doi.org/10.1126/sciadv.aat2340.

Lu, F., Lu, H., Gu, Y., Lin, P., Lu, Z., Zhang, Q., Zhang, H., Yang, F., Dong, X., Yi, S., Chen, D., Pausata, F.S.R., Ben-Yami, M. and Mecking, J.V. (2025) 'Tipping point-induced abrupt shifts in East Asian hydroclimate since the Last Glacial Maximum', Nature Communications, 16(1), p. 477. Available at: https://doi.org/10.1038/s41467-025-55888-w.

Lucarini, V., Melinda Galfi, V., Riboldi, J. and Messori, G. (2023) 'Typicality of the 2021 Western North America summer heatwave', Environmental Research Letters, 18(1), p. 015004. Available at: https://doi.org/10.1088/1748-9326/acab77.

Lucht, W., Schaphoff, S., Erbrecht, T., Heyder, U. and Cramer, W. (2006) 'Terrestrial vegetation redistribution and carbon balance under climate change', Carbon Balance and Management, 1(1), p. 6. Available at: https://doi.org/10.1186/1750-0680-1-6.

Lunde, L.F., Birkemoe, T., Sverdrup-Thygeson, A., Asplund, J., Halvorsen, R., Kjønaas, O.J., Nordén, J., Maurice, S., Skrede, I., Nybakken, L. and Kauserud, H. (2025) 'Towards repeated clear-cutting of boreal forests – a tipping point for biodiversity?', Biological Reviews, 100(3), pp. 1181–1205. Available at: https://doi.org/10.1111/brv.13180.

Luo, B., Xiao, C., Luo, D., Fu, Q., Chen, D., Zhang, Q., Ge, Y. and Diao, Y. (2025) 'Atmospheric and oceanic drivers behind the 2023 Canadian wildfires', Communications Earth & Environment, 6(1), p. 446. Available at: https://doi.org/10.1038/s43247-025-02387-x.

Ma, S. and Zhou, T. (2016) 'Robust Strengthening and Westward Shift of the Tropical Pacific Walker Circulation during 1979–2012: A Comparison of 7 Sets of Reanalysis Data and 26 CMIP5 Models'. Available at: https://doi.org/10.1175/JCLI-D-15-0398.1.

Machava-António, V.C.E., Mabilana, H., Macamo, C., Fernando, A., Santos, R., Bandeira, S. and Paula, J. (2024) 'Massive mangrove dieback due to extreme weather impact - case of Maputo River Estuary, Mozambique', Regional Studies in Marine Science, 78, p. 103770. Available at: https://doi.org/10.1016/j.rsma.2024.103770.

MacLeod, K., Koch, M.S., Johnson, C.R. and Madden, C.J. (2023) 'Resilience of recruiting seagrass (Thalassia testudinum) to porewater H2S in Florida Bay', Aquatic Botany, 187, p. 103650. Available at: https://doi.org/10.1016/j.aquabot.2023.103650.

Maestre, F.T., Eldridge, D.J., Soliveres, S., Kéfi, S., Delgado-Baquerizo, M., Bowker, M.A., García-Palacios, P., Gaitán, J., Gallardo, A., Lázaro, R. and Berdugo, M. (2016) 'Structure and Functioning of Dryland Ecosystems in a Changing World', Annual Review of Ecology, Evolution, and Systematics, 47(Volume 47, 2016), pp. 215–237. Available at: https://doi.org/10.1146/annurev-ecolsys-121415-032311.

Mahlstein, I. and Knutti, R. (2012) 'September Arctic sea ice predicted to disappear near 2°C global warming above present', Journal of Geophysical Research: Atmospheres, 117(D6). Available at: https://doi.org/10.1029/2011JD016709.

Marbà, N., Jordà, G., Bennett, S. and Duarte, C.M. (2022) 'Seagrass Thermal Limits and Vulnerability to Future Warming', Frontiers in Marine Science, 9. Available at: https://doi.org/10.3389/fmars.2022.860826.

Marshall, S.J. (2021) 'Regime Shifts in Glacier and Ice Sheet Response to Climate Change: Examples From the Northern Hemisphere', Frontiers in Climate, 3. Available at: https://doi.org/10.3389/fclim.2021.702585.

Martinez, M., Ardón, M. and Gray, J. (2024) 'Detecting Trajectories of Regime Shifts and Loss of Resilience in Coastal Wetlands using Remote Sensing', Ecosystems, 27(8), pp. 1060–1075. Available at: https://doi.org/10.1007/s10021-024-00938-5.

Marzeion, B., Kaser, G., Maussion, F. and Champollion, N. (2018) 'Limited influence of climate change mitigation on short-term glacier mass loss', Nature Climate Change, 8(4), pp. 305–308. Available at: https://doi.org/10.1038/s41558-018-0093-1.

Mastrandrea, M.D., Field, C.B., Stocker, T.F., Ottmar Edenhofer, K.L., Eldridge, D.J., Held, H., Kriegler, E., Mach, K.J., Matschoss, P.R., Plattner, G.-K., Yohe, G.W. and Zwiers, F.W. (2010) 'Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties', Intergovernmental Panel on Climate Change (IPCC) [Preprint]. Available at: https://www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf.

Mathes, T., Seidel, D. and Annighöfer, P. (2023) 'Response to extreme events: do morphological differences affect the ability of beech (Fagus sylvatica L.) to resist drought stress?', Forestry: An International Journal of Forest Research, 96(3), pp. 355–371. Available at: https://doi.org/10.1093/forestry/cpac056.

Mathias, J.-D., Deffuant, G. and Brias, A. (2024) 'From tipping point to tipping set: Extending the concept of regime shift to uncertain dynamics for real-world applications', Ecological Modelling, 496, p. 110801. Available at: https://doi.org/10.1016/j.ecolmodel.2024.110801.

Mauritsen, T. and Stevens, B. (2015) 'Missing iris effect as a possible cause of muted hydrological change and high climate sensitivity in models', Nature Geoscience, 8(5), pp. 346–351. Available at: https://doi.org/10.1038/ngeo2414.

Maxwell, P.S., Eklöf, J.S., van Katwijk, M.M., O'Brien, K.R., de la Torre-Castro, M., Boström, C., Bouma, T.J., Krause-Jensen, D., Unsworth, R.K.F., van Tussenbroek, B.I. and van der Heide, T. (2017) 'The fundamental role of ecological feedback mechanisms for the adaptive management of seagrass ecosystems – a review', Biological Reviews, 92(3), pp. 1521–1538. Available at: https://doi.org/10.1111/brv.12294.

McPhaden, M.J. (ed.) (2020) El Niño southern oscillation in a changing climate. First edition. Hoboken, NJ: Wiley-American Geophysical Union (Geophysical monograph series).

McWhorter, J.K., Halloran, P.R., Roff, G., Skirving, W.J., Perry, C.T. and Mumby, P.J. (2022) 'The importance of 1.5°C warming for the Great Barrier Reef', Global Change Biology, 28(4), pp. 1332–1341. Available at: https://doi.org/10.1111/gcb.15994.

Melnikova, I., Hajima, T., Shiogama, H., Hayashi, M., Ito, A., Nishina, K., Tachiiri, K. and Yokohata, T. (2025) 'Amazon dieback beyond the 21st century under high-emission scenarios by Earth System models', Communications Earth & Environment, 6(1), p. 670. Available at: https://doi.org/10.1038/s43247-025-02606-5.

Menary, M.B., Jackson, L.C., Wood, R.A. and Betts, R.A. (2025) 'Abrupt Changes in the Subpolar North Atlantic and Their Impact on the Climate of the British Isles', Geophysical Research Letters, 52(9), p. e2024GL113871. Available at: https://doi.org/10.1029/2024GL113871.

Menéndez, P., Losada, I.J., Torres-Ortega, S., Narayan, S. and Beck, M.W. (2020) 'The Global Flood Protection Benefits of Mangroves', Scientific Reports, 10(1), p. 4404. Available at: https://doi.org/10.1038/s41598-020-61136-6.

Mengel, M. and Levermann, A. (2014) 'Ice plug prevents irreversible discharge from East Antarctica', Nature Climate Change, 4(6), pp. 451–455. Available at: https://doi.org/10.1038/nclimate2226.

Meredith, M.P., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A.A., Hollowed, A.B., Kofinas, G., Mackintosh, A.N., Muelbert, Mônica Mathias Costa, Melbourne-Thomas, J., Muelbert, M. M. C., Otterson, G., Pritchard, H. and Schuur, E.A.G. (2019) 'Chapter 3: Polar regions', in IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge University Press, pp. 203–320. Available at: https://doi.org/10.1017/9781009157964.005.

Michel, S.L.L., Dijkstra, H.A., Guardamagna, F., Jacques-Dumas, V., van Westen, R.M. and von der Heydt, A.S. (2025) 'Deep learning based reconstructions of the Atlantic meridional overturning circulation confirm twenty-first century decline', Environmental Research Letters, 20(6), p. 064036. Available at: https://doi.org/10.1088/1748-9326/add7f0.

Milner, A.M., Baird, A.J., Green, S.M., Swindles, G.T., Young, D.M., Sanderson, N.K., Timmins, M.S.I. and Ga□ka, M. (2021) 'A regime shift from erosion to carbon accumulation in a temperate northern peatland', Journal of Ecology, 109(1), pp. 125–138. Available at: https://doi.org/10.1111/1365-2745.13453.

Milner, A.M., Brown, L.E. and Hannah, D.M. (2009) 'Hydroecological response of river systems to shrinking glaciers', Hydrological Processes, 23(1), pp. 62–77. Available at: https://doi.org/10.1002/hyp.7197.

Möllmann, C., Cormon, X., Funk, S., Otto, S.A., Schmidt, J.O., Schwermer, H., Sguotti, C., Voss, R. and Quaas, M. (2021) 'Tipping point realized in cod fishery', Scientific Reports, 11(1), p. 14259. Available at: https://doi.org/10.1038/s41598-021-93843-z.

Molnar, P., Boos, W.R. and Battisti, D.S. (2010) 'Orographic Controls on Climate and Paleoclimate of Asia: Thermal and Mechanical Roles for the Tibetan Plateau', Annual Review of Earth and Planetary Sciences, 38(Volume 38, 2010), pp. 77–102. Available at: https://doi.org/10.1146/annurev-earth-040809-152456.

Montesano, P.M., Frost, M., Li, J., Carroll, M., Neigh, C.S.R., Macander, M.J., Sexton, J.O. and Frost, G.V. (2024) 'A shift in transitional forests of the North American boreal will persist through 2100', Communications Earth & Environment, 5(1), p. 290. Available at: https://doi.org/10.1038/s43247-024-01454-z.

Moon, T.A., Druckenmiller, M.L. and Thoman, R.L. (2024) 'NOAA Arctic Report Card 2024 : Executive Summary'. Available at: https://doi.org/10.25923/B7C7-6431.

Morlighem, M., Goldberg, D., Barnes, J.M., Bassis, J.N., Benn, D.I., Crawford, A.J., Gudmundsson, G.H. and Seroussi, H. (2024) 'The West Antarctic Ice Sheet may not be vulnerable to marine ice cliff instability during the 21st century', Science Advances, 10(34), p. eado7794. Available at: https://doi.org/10.1126/sciadv.ado7794.

Morlighem, M., Rignot, E., Binder, T., Blankenship, D., Drews, R., Eagles, G., Eisen, O., Ferraccioli, F., Forsberg, R., Fretwell, P., Goel, V., Greenbaum, J.S., Gudmundsson, H., Guo, J., Helm, V., Hofstede, C., Howat, I., Humbert, A., Jokat, W., Karlsson, N.B., Lee, W.S., Matsuoka, K., Millan, R., Mouginot, J., Paden, J., Pattyn, F., Roberts, J., Rosier, S., Ruppel, A., Seroussi, H., Smith, E.C., Steinhage, D., Sun, B., Broeke, M.R. van den, Ommen, T.D. van, Wessem, M. van and Young, D.A. (2020) 'Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet', Nature Geoscience, 13(2), pp. 132–137. Available at: https://doi.org/10.1038/s41561-019-0510-8.

Muñiz-Castillo, A.I., Rivera-Sosa, A., Chollett, I., Eakin, C.M., Andrade-Gómez, L., McField, M. and Arias-González, J.E. (2019) 'Three decades of heat stress exposure in Caribbean coral reefs: a new regional delineation to enhance conservation', Scientific Reports, 9(1), p. 11013. Available at: https://doi.org/10.1038/s41598-019-47307-0.

Myers, T.A., Mechoso, C.R., Cesana, G.V., DeFlorio, M.J. and Waliser, D.E. (2018) 'Cloud Feedback Key to Marine Heatwave off Baja California', Geophysical Research Letters, 45(9), pp. 4345–4352. Available at: https://doi.org/10.1029/2018GL078242.

Myers-Smith, I.H., Forbes, B.C., Wilmking, M., Hallinger, M., Lantz, T., Blok, D., Tape, K.D., Macias-Fauria, M., Sass-Klaassen, U., Lévesque, E., Boudreau, S., Ropars, P., Hermanutz, L., Trant, A., Collier, L.S., Weijers, S., Rozema, J., Rayback, S.A., Schmidt, N.M., Schaepman-Strub, G., Wipf, S., Rixen, C., Ménard, C.B., Venn, S., Goetz, S., Andreu-Hayles, L., Elmendorf, S., Ravolainen, V., Welker, J., Grogan, P., Epstein, H.E. and Hik, D.S. (2011) 'Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities', Environmental Research Letters, 6(4), p. 045509. Available at: https://doi.org/10.1088/1748-9326/6/4/045509.

Naish, T., Powell, R., Levy, R., Wilson, G., Scherer, R., Talarico, F., Krissek, L., Niessen, F., Pompilio, M., Wilson, T., Carter, L., DeConto, R., Huybers, P., McKay, R., Pollard, D., Ross, J., Winter, D., Barrett, P., Browne, G., Cody, R., Cowan, E., Crampton, J., Dunbar, G., Dunbar, N., Florindo, F., Gebhardt, C., Graham, I., Hannah, M., Hansaraj, D., Harwood, D., Helling, D., Henrys, S., Hinnov, L., Kuhn, G., Kyle, P., Läufer, A., Maffioli, P., Magens, D., Mandernack, K., McIntosh, W., Millan, C., Morin, R., Ohneiser, C., Paulsen, T., Persico, D., Raine, I., Reed, J., Riesselman, C., Sagnotti, L., Schmitt, D., Sjunneskog, C., Strong, P., Taviani, M., Vogel, S., Wilch, T. and Williams, T. (2009) 'Obliquity-paced Pliocene West Antarctic ice sheet oscillations', Nature, 458(7236), pp. 322–328. Available at: https://doi.org/10.1038/nature07867.

Nath, D., Nath, R. and Chen, W. (2024) 'Faster dieback of rainforests altering tropical carbon sinks under climate change', npj Climate and Atmospheric Science, 7(1), p. 235. Available at: https://doi.org/10.1038/s41612-024-00793-0.

Naughten, K.A., Holland, P.R. and De Rydt, J. (2023) 'Unavoidable future increase in West Antarctic ice-shelf melting over the twenty-first century', Nature Climate Change, 13(11), pp. 1222–1228. Available at: https://doi.org/10.1038/s41558-023-01818-x.

Needell, C., Walker, C. and Bassis, J. (2025) 'Empirical constraints on ice-cliff calving'. Research Square. Available at: https://doi.org/10.21203/rs.3.rs-7133627/v1.

Neff, A., Keane, A., Dijkstra, H.A. and Krauskopf, B. (2023) 'Bifurcation analysis of a North Atlantic Ocean box model with two deep-water formation sites', Physica D: Nonlinear Phenomena, 456, p. 133907. Available at: https://doi.org/10.1016/j.physd.2023.133907.

Nerlekar, A.N. and Veldman, J.W. (2020) 'High plant diversity and slow assembly of old-growth grasslands', Proceedings of the National Academy of Sciences, 117(31), pp. 18550–18556. Available at: https://doi.org/10.1073/pnas.1922266117.

Nian, D., Bathiany, S., Ben-Yami, M., Blaschke, L.L., Hirota, M., Rodrigues, R.R. and Boers, N. (2023) 'A potential collapse of the Atlantic Meridional Overturning Circulation may stabilise eastern Amazonian rainforests', Communications Earth & Environment, 4(1), p. 470. Available at: https://doi.org/10.1038/s43247-023-01123-7.

Nielsen, D.M., Chegini, F., Maerz, J., Brune, S., Mathis, M., Dobrynin, M., Baehr, J., Brovkin, V. and Ilyina, T. (2024) 'Reduced Arctic Ocean CO_2 uptake due to coastal permafrost erosion', Nature Climate Change, 14(9), pp. 968–975. Available at: https://doi.org/10.1038/s41558-024-02074-3.

Nitzbon, J., Schneider von Deimling, T., Aliyeva, M., Chadburn, S.E., Grosse, G., Laboor, S., Lee, H., Lohmann, G., Steinert, N.J., Stuenzi, S.M., Werner, M., Westermann, S. and Langer, M. (2024) 'No respite from permafrost-thaw impacts in the absence of a global tipping point', Nature Climate Change, 14(6), pp. 573–585. Available at: https://doi.org/10.1038/s41558-024-02011-4.

Nitzbon, J., Westermann, S., Langer, M., Martin, L.C.P., Strauss, J., Laboor, S. and Boike, J. (2020) 'Fast response of cold ice-rich permafrost in northeast Siberia to a warming climate', Nature Communications, 11(1), p. 2201. Available at: https://doi.org/10.1038/s41467-020-15725-8.

NOAA (2024) NOAA Coral Reef Watch Current Global Bleaching: Status Update & Data Submission. Available at: https://coralreefwatch.noaa.gov/satellite/research/coral_bleaching_report.php (Accessed: 2 September 2025).

Nordlund, L.M., Koch, E.W., Barbier, E.B. and Creed, J.C. (2016) 'Seagrass Ecosystem Services and Their Variability across Genera and Geographical Regions', PLOS ONE, 11(10), p. e0163091. Available at: https://doi.org/10.1371/journal.pone.0163091.

Notz, D. (2009) 'The future of ice sheets and sea ice: Between reversible retreat and unstoppable loss', Proceedings of the National Academy of Sciences, 106(49), pp. 20590–20595. Available at: https://doi.org/10.1073/pnas.0902356106.

Obu, J. (2021) 'How Much of the Earth's Surface is Underlain by Permafrost?', Journal of Geophysical Research: Earth Surface, 126(5), p. e2021JF006123. Available at: https://doi.org/10.1029/2021JF006123.

Obura, D., Gudka, M., Samoilys, M., Osuka, K., Mbugua, J., Keith, D.A., Porter, S., Roche, R., van Hooidonk, R., Ahamada, S., Araman, A., Karisa, J., Komakoma, J., Madi, M., Ravinia, I., Razafindrainibe, H., Yahya, S. and Zivane, F. (2022) 'Vulnerability to collapse of coral reef ecosystems in the Western Indian Ocean', Nature Sustainability, 5(2), pp. 104–113. Available at: https://doi.org/10.1038/s41893-021-00817-0.

Ometto, J.P., Kalaba, K., Anshari, G.Z., Chacón, N., Farrell, A., Halim, S.A., Neufeldt, H. and Sukumar, R. (2023) 'Cross Chapter Paper 7: Tropical Forests', in Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, pp. 2369–2410. Available at: https://doi.org/10.1017/9781009325844.024.

Onarheim, I.H., Årthun, M., Teigen, S.H., Eik, K.J. and Steele, M. (2024) 'Recent Thickening of the Barents Sea Ice Cover', Geophysical Research Letters, 51(10), p. e2024GL108225. Available at: https://doi.org/10.1029/2024GL108225.

Orihuela-Pinto, B., England, M.H. and Taschetto, A.S. (2022) 'Interbasin and interhemispheric impacts of a collapsed Atlantic Overturning Circulation', Nature Climate Change, 12(6), pp. 558–565. Available at: https://doi.org/10.1038/s41558-022-01380-y.

Otosaka, I.N., Shepherd, A., Ivins, E.R., Schlegel, N.-J., Amory, C., van den Broeke, M.R., Horwath, M., Joughin, I., King, M.D., Krinner, G., Nowicki, S., Payne, A.J., Rignot, E., Scambos, T., Simon, K.M., Smith, B.E., Sørensen, L.S., Velicogna, I., Whitehouse, P.L., A, G., Agosta, C., Ahlstrøm, A.P., Blazquez, A., Colgan, W., Engdahl, M.E., Fettweis, X., Forsberg, R., Gallée, H., Gardner, A., Gilbert, L., Gourmelen, N., Groh, A., Gunter, B.C., Harig, C., Helm, V., Khan, S.A., Kittel, C., Konrad, H., Langen, P.L., Lecavalier, B.S., Liang, C.-C., Loomis, B.D., McMillan, M., Melini, D., Mernild, S.H., Mottram, R., Mouginot, J., Nilsson, J., Noël, B., Pattle, M.E., Peltier, W.R., Pie, N., Roca, M., Sasgen, I., Save, H.V., Seo, K.-W., Scheuchl, B., Schrama, E.J.O., Schröder, L., Simonsen, S.B., Slater, T., Spada, G., Sutterley, T.C., Vishwakarma, B.D., van Wessem, J.M., Wiese, D., van der Wal, W. and Wouters, B. (2023) 'Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020', Earth System Science Data, 15(4), pp. 1597–1616. Available at: https://doi.org/10.5194/essd-15-1597-2023.

Oudar, T., Cattiaux, J. and Douville, H. (2020) 'Drivers of the Northern Extratropical Eddy-Driven Jet Change in CMIP5 and CMIP6 Models', Geophysical Research Letters, 47(8), p. e2019GL086695. Available at: https://doi.org/10.1029/2019GL086695.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S. and Hayes, D. (2011) 'A Large and Persistent Carbon Sink in the World's Forests', Science, 333(6045), pp. 988–993. Available at: https://doi.org/10.1126/science.1201609.

Park, H., Watanabe, E., Kim, Y., Polyakov, I., Oshima, K., Zhang, X., Kimball, J.S. and Yang, D. (2020) 'Increasing riverine heat influx triggers Arctic sea ice decline and oceanic and atmospheric warming', Science Advances, 6(45), p. eabc4699. Available at: https://doi.org/10.1126/sciadv.abc4699.

Park, S.-W., Mun, J.-H., Lee, H., Steinert, N.J., An, S.-I., Shin, J. and Kug, J.-S. (2025) 'Continued permafrost ecosystem carbon loss under net-zero and negative emissions', Science Advances, 11(7), p. eadn8819. Available at: https://doi.org/10.1126/sciadv.adn8819.

Parr, C.L., Te Beest, M. and Stevens, N. (2024) 'Conflation of reforestation with restoration is widespread', Science, 383(6684), pp. 698–701. Available at: https://doi.org/10.1126/science.adj0899.

Pearce-Kelly, P., Altieri, A.H., Bruno, J.F., Cornwall, C.E., McField, M., Muñiz-Castillo, A.I., Rocha, J., Setter, R.O., Sheppard, C., Roman-Cuesta, R.M. and Yesson, C. (2025) 'Considerations for determining warm-water coral reef tipping points', Earth System Dynamics, 16(1), pp. 275–292. Available at: https://doi.org/10.5194/esd-16-275-2025.

Pelle, T., Greenbaum, J.S., Ehrenfeucht, S., Dow, C.F. and McCormack, F.S. (2024) 'Subglacial Discharge Accelerates Dynamic Retreat of Aurora Subglacial Basin Outlet Glaciers, East Antarctica, Over the 21st Century', Journal of Geophysical Research: Earth Surface, 129(7), p. e2023JF007513. Available at: https://doi.org/10.1029/2023JF007513.

Perry, C.T., Murphy, G.N., Kench, P.S., Smithers, S.G., Edinger, E.N., Steneck, R.S. and Mumby, P.J. (2013) 'Caribbean-wide decline in carbonate production threatens coral reef growth', Nature Communications, 4(1), p. 1402. Available at: https://doi.org/10.1038/ncomms2409.

Petrini, M., Scherrenberg, M.D.W., Muntjewerf, L., Vizcaino, M., Sellevold, R., Leguy, G.R., Lipscomb, W.H. and Goelzer, H. (2025) 'A topographically controlled tipping point for complete Greenland ice sheet melt', The Cryosphere, 19(1), pp. 63–81. Available at: https://doi.org/10.5194/tc-19-63-2025.

Pillay, R., Venter, M., Aragon-Osejo, J., González-del-Pliego, P., Hansen, A.J., Watson, J.E. and Venter, O. (2022) 'Tropical forests are home to over half of the world's vertebrate species', Frontiers in Ecology and the Environment, 20(1), pp. 10–15. Available at: https://doi.org/10.1002/fee.2420.

Pörtner, H.-O., Roberts, D.C., Tignor, M.M.B., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A. and Rama, B. (eds) (2022) Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Potapov, P., Hansen, M.C., Laestadius, L., Turubanova, S., Yaroshenko, A., Thies, C., Smith, W., Zhuravleva, I., Komarova, A., Minnemeyer, S. and Esipova, E. (2017) 'The last frontiers of wilderness: Tracking loss of intact forest landscapes from 2000 to 2013', Science Advances, 3(1), p. e1600821. Available at: https://doi.org/10.1126/sciadv.1600821.

Pritchard, H.D., Fretwell, P.T., Fremand, A.C., Bodart, J.A., Kirkham, J.D., Aitken, A., Bamber, J., Bell, R., Bianchi, C., Bingham, R.G., Blankenship, D.D., Casassa, G., Christianson, K., Conway, H., Corr, H.F.J., Cui, X., Damaske, D., Damm, V., Dorschel, B., Drews, R., Eagles, G., Eisen, O., Eisermann, H., Ferraccioli, F., Field, E., Forsberg, R., Franke, S., Goel, V., Gogineni, S.P., Greenbaum, J., Hills, B., Hindmarsh, R.C.A., Hoffman, A.O., Holschuh, N., Holt, J.W., Humbert, A., Jacobel, R.W., Jansen, D., Jenkins, A., Jokat, W., Jong, L., Jordan, T.A., King, E.C., Kohler, J., Krabill, W., Maton, J., Gillespie, M.K., Langley, K., Lee, J., Leitchenkov, G., Leuschen, C., Luyendyk, B., MacGregor, J.A., MacKie, E., Moholdt, G., Matsuoka, K., Morlighem, M., Mouginot, J., Nitsche, F.O., Nost, O.A., Paden, J., Pattyn, F., Popov, S., Rignot, E., Rippin, D.M., Rivera, A., Roberts, J.L., Ross, N., Ruppel, A., Schroeder, D.M., Siegert, M.J., Smith, A.M., Steinhage, D., Studinger, M., Sun, B., Tabacco, I., Tinto, K.J., Urbini, S., Vaughan, D.G., Wilson, D.S., Young, D.A. and Zirizzotti, A. (2025) 'Bedmap3 updated ice bed, surface and thickness gridded datasets for Antarctica', Scientific Data, 12(1), p. 414. Available at: https://doi.org/10.1038/s41597-025-04672-y.

Purich, A. and England, M.H. (2023) 'Projected Impacts of Antarctic Meltwater Anomalies over the Twenty-First Century'. Available at: https://doi.org/10.1175/JCLI-D-22-0457.1.

Qin, Y., Wang, D., Ziegler, A.D., Fu, B. and Zeng, Z. (2025) 'Impact of Amazonian deforestation on precipitation reverses between seasons', Nature, 639(8053), pp. 102–108. Available at: https://doi.org/10.1038/s41586-024-08570-y.

Rachmayani, R., Prange, M., Lunt, D.J., Stone, E.J. and Schulz, M. (2017) 'Sensitivity of the Greenland Ice Sheet to Interglacial Climate Forcing: MIS 5e Versus MIS 11', Paleoceanography, 32(11), pp. 1089–1101. Available at: https://doi.org/10.1002/2017PA003149.

Raghuraman, S.P., Soden, B., Clement, A., Vecchi, G., Menemenlis, S. and Yang, W. (2024) 'The 2023 global warming spike was driven by the El Niño–Southern Oscillation', Atmospheric Chemistry and Physics, 24(19), pp. 11275–11283. Available at: https://doi.org/10.5194/acp-24-11275-2024.

Rahmstorf, S. (1995) 'Bifurcations of the Atlantic thermohaline circulation in response to changes in the hydrological cycle', Nature, 378(6553), pp. 145–149. Available at: https://doi.org/10.1038/378145a0.

Rahmstorf, S. (2024) 'Is the Atlantic Overturning Circulation Approaching a Tipping Point?', Oceanography, 37(3), pp. 16–29. Available at: https://doi.org/10.5670/oceanog.2024.501.

Raphael, M.N., Maierhofer, T.J., Fogt, R.L., Hobbs, W.R. and Handcock, M.S. (2025) 'A twenty-first century structural change in Antarctica's sea ice system', Communications Earth & Environment, 6(1), p. 131. Available at: https://doi.org/10.1038/s43247-025-02107-5.

Ravinder, N., Shepherd, A., Otosaka, I., Slater, T., Muir, A. and Gilbert, L. (2024) 'Greenland Ice Sheet Elevation Change From CryoSat-2 and ICESat-2', Geophysical Research Letters, 51(24), p. e2024GL110822. Available at: https://doi.org/10.1029/2024GL110822.

Recchia, L.G. and Lucarini, V. (2023) 'Modelling the effect of aerosol and greenhouse gas forcing on the South Asian and East Asian monsoons with an intermediate-complexity climate model', Earth System Dynamics, 14(3), pp. 697–722. Available at: https://doi.org/10.5194/esd-14-697-2023.

Reese, R., Garbe, J., Hill, E.A., Urruty, B., Naughten, K.A., Gagliardini, O., Durand, G., Gillet-Chaulet, F., Gudmundsson, G.H., Chandler, D., Langebroek, P.M. and Winkelmann, R. (2023) 'The stability of present-day Antarctic grounding lines – Part 2: Onset of irreversible retreat of Amundsen Sea glaciers under current climate on centennial timescales cannot be excluded', The Cryosphere, 17(9), pp. 3761–3783. Available at: https://doi.org/10.5194/tc-17-3761-2023.

Riboldi, J., Lott, F., D'Andrea, F. and Rivière, G. (2020) 'On the Linkage Between Rossby Wave Phase Speed, Atmospheric Blocking, and Arctic Amplification', Geophysical Research Letters, 47(19), p. e2020GL087796. Available at: https://doi.org/10.1029/2020GL087796.

Rignot, E., Ciracì, E., Scheuchl, B., Tolpekin, V., Wollersheim, M. and Dow, C. (2024) 'Widespread seawater intrusions beneath the grounded ice of Thwaites Glacier, West Antarctica', Proceedings of the National Academy of Sciences, 121(22), p. e2404766121. Available at: https://doi.org/10.1073/pnas.2404766121.

Robinson, A., Alvarez-Solas, J., Calov, R., Ganopolski, A. and Montoya, M. (2017) 'MIS-11 duration key to disappearance of the Greenland ice sheet', Nature Communications, 8(1), p. 16008. Available at: https://doi.org/10.1038/ncomms16008.

Rodrigues, R.R., Gonçalves Neto, A.H., Vieira, E.A. and Longo, G.O. (2025) 'The severe 2020 coral bleaching event in the tropical Atlantic linked to marine heatwaves', Communications Earth & Environment, 6(1), p. 208. Available at: https://doi.org/10.1038/s43247-025-02195-3.

Romanou, A., Rind, D., Jonas, J., Miller, R., Kelley, M., Russell, G., Orbe, C., Nazarenko, L., Latto, R. and Schmidt, G.A. (2023) 'Stochastic Bifurcation of the North Atlantic Circulation under a Midrange Future Climate Scenario with the NASA-GISS ModelE', Journal of Climate, 36(18), pp. 6141–6161. Available at: https://doi.org/10.1175/JCLI-D-22-0536.1.

Rosan, T.M., Aragão, L.E.O.C., Oliveras, I., Phillips, O.L., Malhi, Y., Gloor, E. and Wagner, F.H. (2019) 'Extensive 21st-Century Woody Encroachment in South America's Savanna', Geophysical Research Letters, 46(12), pp. 6594–6603. Available at: https://doi.org/10.1029/2019GL082327.

Rosentreter, J.A., Borges, A.V., Deemer, B.R., Holgerson, M.A., Liu, S., Song, C., Melack, J., Raymond, P.A., Duarte, C.M., Allen, G.H., Olefeldt, D., Poulter, B., Battin, T.I. and Eyre, B.D. (2021) 'Half of global methane emissions come from highly variable aquatic ecosystem sources', Nature Geoscience, 14(4), pp. 225–230. Available at: https://doi.org/10.1038/s41561-021-00715-2.

Rosser, J.P., Meijers, A., Haynes, P. and Webb, M.J. (no date) 'Shutdown of Southern Ocean Convective Centennial Variability under Global Warming and Implications for Climate Projections'. Available at: https://www.authorea.com/users/946271/articles/1316085-shutdown-of-southern-ocean-convective-centennial-variability-under-global-warming-and-implications-for-climate-projections (Accessed: 1 September 2025).

Rotbarth, R., van Nes, E.H., Scheffer, M. and Holmgren, M. (2025) 'Boreal forests are heading for an open state', Proceedings of the National Academy of Sciences, 122(2), p. e2404391121. Available at: https://doi.org/10.1073/pnas.2404391121.

Rotbarth, R., Van Nes, E.H., Scheffer, M., Jepsen, J.U., Vindstad, O.P.L., Xu, C. and Holmgren, M. (2023) 'Northern expansion is not compensating for southern declines in North American boreal forests', Nature Communications, 14(1), p. 3373. Available at: https://doi.org/10.1038/s41467-023-39092-2.

Rounce, D.R., Hock, R., Maussion, F., Hugonnet, R., Kochtitzky, W., Huss, M., Berthier, E., Brinkerhoff, D., Compagno, L., Copland, L., Farinotti, D., Menounos, B. and McNabb, R.W. (2023) 'Global glacier change in the 21st century: Every increase in temperature matters', Science, 379(6627), pp. 78–83. Available at: https://doi.org/10.1126/science.abo1324.

Sabatini, F.M., Keeton, W.S., Lindner, M., Svoboda, M., Verkerk, P.J., Bauhus, J., Bruelheide, H., Burrascano, S., Debaive, N., Duarte, I., Garbarino, M., Grigoriadis, N., Lombardi, F., Mikoláš, M., Meyer, P., Motta, R., Mozgeris, G., Nunes, L., Ódor, P., Panayotov, M., Ruete, A., Simovski, B., Stillhard, J., Svensson, J., Szwagrzyk, J., Tikkanen, O.-P., Vandekerkhove, K., Volosyanchuk, R., Vrska, T., Zlatanov, T. and Kuemmerle, T. (2020) 'Protection gaps and restoration opportunities for primary forests in Europe', Diversity and Distributions, 26(12), pp. 1646–1662. Available at: https://doi.org/10.1111/ddi.13158.

Saintilan, N., Horton, B., Törnqvist, T.E., Ashe, E.L., Khan, N.S., Schuerch, M., Perry, C., Kopp, R.E., Garner, G.G., Murray, N., Rogers, K., Albert, S., Kelleway, J., Shaw, T.A., Woodroffe, C.D., Lovelock, C.E., Goddard, M.M., Hutley, L.B., Kovalenko, K., Feher, L. and Guntenspergen, G. (2023) 'Widespread retreat of coastal habitat is likely at warming levels above 1.5 °C', Nature, 621(7977), pp. 112–119. Available at: https://doi.org/10.1038/s41586-023-06448-z.

Saintilan, N., Khan, N.S., Ashe, E., Kelleway, J.J., Rogers, K., Woodroffe, C.D. and Horton, B.P. (2020) 'Thresholds of mangrove survival under rapid sea level rise', Science, 368(6495), pp. 1118–1121. Available at: https://doi.org/10.1126/science.aba2656.

Saintilan, N., Kovalenko, K.E., Guntenspergen, G., Rogers, K., Lynch, J.C., Cahoon, D.R., Lovelock, C.E., Friess, D.A., Ashe, E., Krauss, K.W., Cormier, N., Spencer, T., Adams, J., Raw, J., Ibanez, C., Scarton, F., Temmerman, S., Meire, P., Maris, T., Thorne, K., Brazner, J., Chmura, G.L., Bowron, T., Gamage, V.P., Cressman, K., Endris, C., Marconi, C., Marcum, P., St. Laurent, K., Reay, W., Raposa, K.B., Garwood, J.A. and Khan, N. (2022) 'Constraints on the adjustment of tidal marshes to accelerating sea level rise', Science, 377(6605), pp. 523–527. Available at: https://doi.org/10.1126/science.abo7872.

Saros, J.E., Hazuková, V., Northington, R.M., Huston, G.P., Lamb, A., Birkel, S., Pereira, R., Bourdin, G., Jiang, B. and McGowan, S. (2025) 'Abrupt transformation of West Greenland lakes following compound climate extremes associated with atmospheric rivers', Proceedings of the National Academy of Sciences, 122(4), p. e2413855122. Available at: https://doi.org/10.1073/pnas.2413855122.

Saunders, M.I., Leon, J.X., Callaghan, D.P., Roelfsema, C.M., Hamylton, S., Brown, C.J., Baldock, T., Golshani, A., Phinn, S.R., Lovelock, C.E., Hoegh-Guldberg, O., Woodroffe, C.D. and Mumby, P.J. (2014) 'Interdependency of tropical marine ecosystems in response to climate change', Nature Climate Change, 4(8), pp. 724–729. Available at: https://doi.org/10.1038/nclimate2274.

Schaefer, J.M., Finkel, R.C., Balco, G., Alley, R.B., Caffee, M.W., Briner, J.P., Young, N.E., Gow, A.J. and Schwartz, R. (2016) 'Greenland was nearly ice-free for extended periods during the Pleistocene', Nature, 540(7632), pp. 252–255. Available at: https://doi.org/10.1038/nature20146.

Scheffer, M., Carpenter, S., Foley, J.A., Folke, C. and Walker, B. (2001) 'Catastrophic shifts in ecosystems', Nature, 413(6856), pp. 591–596. Available at: https://doi.org/10.1038/35098000.

Scheffer, M., Hosper, S.H., Meijer, M.-L., Moss, B. and Jeppesen, E. (1993) 'Alternative equilibria in shallow lakes', Trends in Ecology & Evolution, 8(8), pp. 275–279. Available at: https://doi.org/10.1016/0169-5347(93)90254-M.

Scheffer, M. and van Nes, E.H. (2007) 'Shallow lakes theory revisited: various alternative regimes driven by climate, nutrients, depth and lake size', Hydrobiologia, 584(1), pp. 455–466. Available at: https://doi.org/10.1007/s10750-007-0616-7.

Schewe, J., Levermann, A. and Cheng, H. (2012) 'A critical humidity threshold for monsoon transitions', Climate of the Past, 8(2), pp. 535–544. Available at: https://doi.org/10.5194/cp-8-535-2012.

Schickhoff, M., de Vrese, P., Bartsch, A., Widhalm, B. and Brovkin, V. (2024) 'Effects of land surface model resolution on fluxes and soil state in the Arctic', Environmental Research Letters, 19(10), p. 104032. Available at: https://doi.org/10.1088/1748-9326/ad6019.

Schneider, T., Kaul, C.M. and Pressel, K.G. (2019) 'Possible climate transitions from breakup of stratocumulus decks under greenhouse warming', Nature Geoscience, 12(3), pp. 163–167. Available at: https://doi.org/10.1038/s41561-019-0310-1.

Schoof, C. (2007) 'Ice sheet grounding line dynamics: Steady states, stability, and hysteresis', Journal of Geophysical Research: Earth Surface, 112(F3). Available at: https://doi.org/10.1029/2006JF000664.

Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M.L., Wolff, C., Lincke, D., McOwen, C.J., Pickering, M.D., Reef, R., Vafeidis, A.T., Hinkel, J., Nicholls, R.J. and Brown, S. (2018) 'Future response of global coastal wetlands to sea-level rise', Nature, 561(7722), pp. 231–234. Available at: https://doi.org/10.1038/s41586-018-0476-5.

Schwinger, J., Asaadi, A., Goris, N. and Lee, H. (2022) 'Possibility for strong northern hemisphere high-latitude cooling under negative emissions', Nature Communications, 13(1), p. 1095. Available at: https://doi.org/10.1038/s41467-022-28573-5.

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

Science Panel for the Amazon (2021) Amazon Assessment Report 2021. 1st edn. Edited by C. Nobre, A. Encalada, E. Anderson, F.H. Roca Alcazar, M. Bustamante, C. Mena, M. Peña-Claros, G. Poveda, J.P. Rodriguez, S. Saleska, S.E. Trumbore, A. Val, L. Villa Nova, R. Abramovay, A. Alencar, A.C. Rodriguez Alzza, D. Armenteras, P. Artaxo, S. Athayde, H.T. Barretto Filho, J. Barlow, E. Berenguer, F. Bortolotto, F.D.A. Costa, M.H. Costa, N. Cuvi, P. Fearnside, J. Ferreira, B.M. Flores, S. Frieri, L.V. Gatti, J.M. Guayasamin, S. Hecht, M. Hirota, C. Hoorn, C. Josse, D.M. Lapola, C. Larrea, D.M. Larrea-Alcazar, Z. Lehm Ardaya, Y. Malhi, J.A. Marengo, J. Melack, M. Moraes R., P. Moutinho, M.R. Murmis, E.G. Neves, B. Paez, L. Painter, A. Ramos, M.C. Rosero-Peña, M. Schmink, P. Sist, H. Ter Steege, P. Val, H. Van Der Voort, M. Varese, and G. Zapata-Ríos. UN Sustainable Development Solutions Network (SDSN). Available at: https://doi.org/10.55161/RWSX6527.

Seager, R., Henderson, N. and Cane, M. (2022) 'Persistent Discrepancies between Observed and Modeled Trends in the Tropical Pacific Ocean'. Available at: https://doi.org/10.1175/JCLI-D-21-0648.1.

Seeley, J.T. and Wordsworth, R.D. (2021) 'Episodic deluges in simulated hothouse climates', Nature, 599(7883), pp. 74–79. Available at: https://doi.org/10.1038/s41586-021-03919-z.

Seemann, F. and Sannel, A.B.K. (2024) 'Morphology and dynamics of thermokarst ponds in a subarctic permafrost peatland, northern Sweden', Earth Surface Processes and Landforms, 49(15), pp. 5377–5389. Available at: https://doi.org/10.1002/esp.6021.

Selivanova, J., Iovino, D. and Cocetta, F. (2024) 'Past and future of the Arctic sea ice in High-Resolution Model Intercomparison Project (HighResMIP) climate models', The Cryosphere, 18(6), pp. 2739–2763. Available at: https://doi.org/10.5194/tc-18-2739-2024.

Senf, C., Buras, A., Zang, C.S., Rammig, A. and Seidl, R. (2020) 'Excess forest mortality is consistently linked to drought across Europe', Nature Communications, 11(1), p. 6200. Available at: https://doi.org/10.1038/s41467-020-19924-1.

Seroussi, H., Nakayama, Y., Larour, E., Menemenlis, D., Morlighem, M., Rignot, E. and Khazendar, A. (2017) 'Continued retreat of Thwaites Glacier, West Antarctica, controlled by bed topography and ocean circulation', Geophysical Research Letters, 44(12), pp. 6191–6199. Available at: https://doi.org/10.1002/2017GL072910.

Seroussi, H., Pelle, T., Lipscomb, W.H., Abe-Ouchi, A., Albrecht, T., Alvarez-Solas, J., Asay-Davis, X., Barre, J.-B., Berends, C.J., Bernales, J., Blasco, J., Caillet, J., Chandler, D.M., Coulon, V., Cullather, R., Dumas, C., Galton-Fenzi, B.K., Garbe, J., Gillet-Chaulet, F., Gladstone, R., Goelzer, H., Golledge, N., Greve, R., Gudmundsson, G.H., Han, H.K., Hillebrand, T.R., Hoffman, M.J., Huybrechts, P., Jourdain, N.C., Klose, A.K., Langebroek, P.M., Leguy, G.R., Lowry, D.P., Mathiot, P., Montoya, M., Morlighem, M., Nowicki, S., Pattyn, F., Payne, A.J., Quiquet, A., Reese, R., Robinson, A., Saraste, L., Simon, E.G., Sun, S., Twarog, J.P., Trusel, L.D., Urruty, B., Van Breedam, J., van de Wal, R.S.W., Wang, Y., Zhao, C. and Zwinger, T. (2024) 'Evolution of the Antarctic Ice Sheet Over the Next Three Centuries From an ISMIP6 Model Ensemble', Earth's Future, 12(9), p. e2024EF004561. Available at: https://doi.org/10.1029/2024EF004561.

Seshadri, A.K. (2017) 'Energetics and monsoon bifurcations', Climate Dynamics, 48(1), pp. 561–576. Available at: https://doi.org/10.1007/s00382-016-3094-7.

Setter, R.O., Franklin, E.C. and Mora, C. (2022) 'Co-occurring anthropogenic stressors reduce the timeframe of environmental viability for the world's coral reefs', PLOS Biology, 20(10), p. e3001821. Available at: https://doi.org/10.1371/journal.pbio.3001821.

Sgubin, G., Swingedouw, D., Drijfhout, S., Mary, Y. and Bennabi, A. (2017) 'Abrupt cooling over the North Atlantic in modern climate models', Nature Communications, 8(1), p. 14375. Available at: https://doi.org/10.1038/ncomms14375.

Sguotti, C., Blöcker, A.M., Färber, L., Blanz, B., Cormier, R., Diekmann, R., Letschert, J., Rambo, H., Stollberg, N., Stelzenmüller, V., Stier, A.C. and Möllmann, C. (2022) 'Irreversibility of regime shifts in the North Sea', Frontiers in Marine Science, 9. Available at: https://doi.org/10.3389/fmars.2022.945204.

Sguotti, C., Otto, S.A., Frelat, R., Langbehn, T.J., Ryberg, M.P., Lindegren, M., Durant, J.M., Chr. Stenseth, N. and Möllmann, C. (2019) 'Catastrophic dynamics limit Atlantic cod recovery', Proceedings of the Royal Society B: Biological Sciences, 286(1898), p. 20182877. Available at: https://doi.org/10.1098/rspb.2018.2877.

Shanahan, T.M., Overpeck, J.T., Beck, J.W., Wheeler, C.W., Peck, J.A., King, J.W. and Scholz, C.A. (2008) 'The formation of biogeochemical laminations in Lake Bosumtwi, Ghana, and their usefulness as indicators of past environmental changes', Journal of Paleolimnology, 40(1), pp. 339–355. Available at: https://doi.org/10.1007/s10933-007-9164-4.

Shaw, T.E., Buri, P., McCarthy, M., Miles, E.S., Ayala, Á. and Pellicciotti, F. (2023) 'The Decaying Near-Surface Boundary Layer of a Retreating Alpine Glacier', Geophysical Research Letters, 50(11), p. e2023GL103043. Available at: https://doi.org/10.1029/2023GL103043.

Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., Whitehouse, P., Briggs, K., Joughin, I., Krinner, G., Nowicki, S., Payne, T., Scambos, T., Schlegel, N., A, G., Agosta, C., Ahlstrøm, A., Babonis, G., Barletta, V., Blazquez, A., Bonin, J., Csatho, B., Cullather, R., Felikson, D., Fettweis, X., Forsberg, R., Gallee, H., Gardner, A., Gilbert, L., Groh, A., Gunter, B., Hanna, E., Harig, C., Helm, V., Horvath, A., Horwath, M., Khan, S., Kjeldsen, K.K., Konrad, H., Langen, P., Lecavalier, B., Loomis, B., Luthcke, S., McMillan, M., Melini, D., Mernild, S., Mohajerani, Y., Moore, P., Mouginot, J., Moyano, G., Muir, A., Nagler, T., Nield, G., Nilsson, J., Noel, B., Otosaka, I., Pattle, M.E., Peltier, W.R., Pie, N., Rietbroek, R., Rott, H., Sandberg-Sørensen, L., Sasgen, I., Save, H., Scheuchl, B., Schrama, E., Schröder, L., Seo, K.-W., Simonsen, S., Slater, T., Spada, G., Sutterley, T., Talpe, M., Tarasov, L., van de Berg, W.J., van der Wal, W., van Wessem, M., Vishwakarma, B.D., Wiese, D., Wouters, B., and The IMBIE team (2018) 'Mass balance of the Antarctic Ice Sheet from 1992 to 2017', Nature, 558(7709), pp. 219–222. Available at: https://doi.org/10.1038/s41586-018-0179-y.

Sheppard, C., Sheppard, A. and Fenner, D. (2020) 'Coral mass mortalities in the Chagos Archipelago over 40 years: Regional species and assemblage extinctions and indications of positive feedbacks', Marine Pollution Bulletin, 154, p. 111075. Available at: https://doi.org/10.1016/j.marpolbul.2020.111075.

Sherwood, S.C., Webb, M.J., Annan, J.D., Armour, K.C., Forster, P.M., Hargreaves, J.C., Hegerl, G., Klein, S.A., Marvel, K.D., Rohling, E.J., Watanabe, M., Andrews, T., Braconnot, P., Bretherton, C.S., Foster, G.L., Hausfather, Z., von der Heydt, A.S., Knutti, R., Mauritsen, T., Norris, J.R., Proistosescu, C., Rugenstein, M., Schmidt, G.A., Tokarska, K.B. and Zelinka, M.D. (2020) 'An Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence', Reviews of Geophysics, 58(4), p. e2019RG000678. Available at: https://doi.org/10.1029/2019RG000678.

Shin, Y., Geng, X., Oh, J.-H., Noh, K.-M., Jin, E.K. and Kug, J.-S. (2024) 'Fast and Slow Responses of Atlantic Meridional Overturning Circulation to Antarctic Meltwater Forcing', Geophysical Research Letters, 51(9), p. e2024GL108272. Available at: https://doi.org/10.1029/2024GL108272.

Siahaan, A., Smith, R.S., Holland, P.R., Jenkins, A., Gregory, J.M., Lee, V., Mathiot, P., Payne, A.J., Ridley, J.K. and Jones, C.G. (2022) 'The Antarctic contribution to 21st-century sea-level rise predicted by the UK Earth System Model with an interactive ice sheet', The Cryosphere, 16(10), pp. 4053–4086. Available at: https://doi.org/10.5194/tc-16-4053-2022.

Siew, P.Y.F., Wu, Y., Ting, M., Zheng, C., Ding, Q. and Seager, R. (2024) 'Significant contribution of internal variability to recent Barents–Kara sea ice loss in winter', Communications Earth & Environment, 5(1), p. 411. Available at: https://doi.org/10.1038/s43247-024-01582-6.

Silvano, A., Narayanan, A., Catany, R., Olmedo, E., González Gambau, V., Turiel, A., Sabia, R., Mazloff, M.R., Spira, T., Haumann, F.A. and Naveira Garabato, A.C. (2025) 'Rising surface salinity and declining sea ice: A new Southern Ocean state revealed by satellites', Proceedings of the National Academy of Sciences, 122(27), p. e2500440122. Available at: https://doi.org/10.1073/pnas.2500440122.

Sinet, S., Heydt, A.S. von der and Dijkstra, H.A. (2025) 'West Antarctic Meltwater can Prevent an AMOC Collapse'. arXiv. Available at: https://doi.org/10.48550/arXiv.2502.17104.

Singh, C., van der Ent, R., Fetzer, I. and Wang-Erlandsson, L. (2024) 'Multi-fold increase in rainforest tipping risk beyond 1.5–2 °C warming', Earth System Dynamics, 15(6), pp. 1543–1565. Available at: https://doi.org/10.5194/esd-15-1543-2024.

Skinner, L.C., Fallon, S., Waelbroeck, C., Michel, E. and Barker, S. (2010) 'Ventilation of the Deep Southern Ocean and Deglacial CO_2 Rise', Science, 328(5982), pp. 1147–1151. Available at: https://doi.org/10.1126/science.1183627.

Slik, J.W.F., Arroyo-Rodríguez, V., Aiba, S.-I., Alvarez-Loayza, P., Alves, L.F., Ashton, P., Balvanera, P., Bastian, M.L., Bellingham, P.J., van den Berg, E., Bernacci, L., da Conceição Bispo, P., Blanc, L., Böhning-Gaese, K., Boeckx, P., Bongers, F., Boyle, B., Bradford, M., Brearley, F.Q., Breuer-Ndoundou Hockemba, M., Bunyavejchewin, S., Calderado Leal Matos, D., Castillo-Santiago, M., Catharino, E.L.M., Chai, S.-L., Chen, Y., Colwell, R.K., Chazdon, R.L., Clark, C., Clark, D.B., Clark, D.A., Culmsee, H., Damas, K., Dattaraja, H.S., Dauby, G., Davidar, P., DeWalt, S.J., Doucet, J.-L., Duque, A., Durigan, G., Eichhorn, K.A.O., Eisenlohr, P.V., Eler, E., Ewango, C., Farwig, N., Feeley, K.J., Ferreira, L., Field, R., de Oliveira Filho, A.T., Fletcher, C., Forshed, O., Franco, G., Fredriksson, G., Gillespie, T., Gillet, J.-F., Amarnath, G., Griffith, D.M., Grogan, J., Gunatilleke, N., Harris, D., Harrison, R., Hector, A., Homeier, J., Imai, N., Itoh, A., Jansen, P.A., Joly, C.A., de Jong, B.H.J., Kartawinata, K., Kearsley, E., Kelly, D.L., Kenfack, D., Kessler, M., Kitayama, K., Kooyman, R., Larney, E., Laumonier, Y., Laurance, S., Laurance, W.F., Lawes, M.J., Amaral, I.L. do, Letcher, S.G., Lindsell, J., Lu, X., Mansor, A., Marjokorpi, A., Martin, E.H., Meilby, H., Melo, F.P.L., Metcalfe, D.J., Medjibe, V.P., Metzger, J.P., Millet, J., Mohandass, D., Montero, J.C., de Morisson Valeriano, M., Mugerwa, B., Nagamasu, H., Nilus, R., Ochoa-Gaona, S., Onrizal, Page, N., Parolin, P., Parren, M., Parthasarathy, N., Paudel, E., Permana, A., Piedade, M.T.F., Pitman, N.C.A., Poorter, L., Poulsen, A.D., Poulsen, J., Powers, J., Prasad, R.C., Puyravaud, J.-P., Razafimahaimodison, J.-C., Reitsma, J., dos Santos, J.R., Roberto Spironello, W., Romero-Saltos, H., Rovero, F., Rozak, A.H., Ruokolainen, K., Rutishauser, E., Saiter, F., Saner, P., Santos, B.A., Santos, F., Sarker, S.K., Satdichanh, M., Schmitt, C.B., Schöngart, J., Schulze, M., Suganuma, M.S., Sheil, D., da Silva Pinheiro, E., Sist, P., Stevart, T., Sukumar, R., Sun, I.-F., Sunderland, T., Suresh, H.S., Suzuki, E., Tabarelli, M., Tang, J., Targhetta, N., Theilade, I., Thomas, D.W., Tchouto, P., Hurtado, J., Valencia, R., van Valkenburg, J.L.C.H., Van Do, T., Vasquez, R., Verbeeck, H., Adekunle, V., Vieira, S.A., Webb, C.O., Whitfeld, T., Wich, S.A., Williams, J., Wittmann, F., Wöll, H., Yang, X., Adou Yao, C.Y., Yap, S.L., Yoneda, T., Zahawi, R.A., Zakaria, R., Zang, R., de Assis, R.L., Garcia Luize, B. and Venticinque, E.M. (2015) 'An estimate of the number of tropical tree species', Proceedings of the National Academy of Sciences, 112(24), pp. 7472–7477. Available at: https://doi.org/10.1073/pnas.1423147112.

Smith, J.G., Malone, D. and Carr, M.H. (2024) 'Consequences of kelp forest ecosystem shifts and predictors of persistence through multiple stressors', Proceedings of the Royal Society B: Biological Sciences, 291(2016), p. 20232749. Available at: https://doi.org/10.1098/rspb.2023.2749.

Son, J.-H., Seo, K.-H. and Wang, B. (2019) 'Dynamical Control of the Tibetan Plateau on the East Asian Summer Monsoon', Geophysical Research Letters, 46(13), pp. 7672–7679. Available at: https://doi.org/10.1029/2019GL083104.

Song, H., Choi, Y., Doddridge, E.W. and Marshall, J. (2025) 'The Responses of Antarctic Sea Ice and Overturning Cells to Meridional Wind Forcing'. Available at: https://doi.org/10.1175/JCLI-D-24-0070.1.

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J. and Willett, W. (2018) 'Options for keeping the food system within environmental limits', Nature, 562(7728), pp. 519–525. Available at: https://doi.org/10.1038/s41586-018-0594-0.

Staal, A., Fetzer, I., Wang-Erlandsson, L., Bosmans, J.H.C., Dekker, S.C., van Nes, E.H., Rockström, J. and Tuinenburg, O.A. (2020) 'Hysteresis of tropical forests in the 21st century', Nature Communications, 11(1), p. 4978. Available at: https://doi.org/10.1038/s41467-020-18728-7.

Staal, A., Tuinenburg, O.A., Bosmans, J.H.C., Holmgren, M., van Nes, E.H., Scheffer, M., Zemp, D.C. and Dekker, S.C. (2018) 'Forest-rainfall cascades buffer against drought across the Amazon', Nature Climate Change, 8(6), pp. 539–543. Available at: https://doi.org/10.1038/s41558-018-0177-y.

Stager, J.C., Ryves, D.B., Chase, B.M. and Pausata, F.S.R. (2011) 'Catastrophic Drought in the Afro-Asian Monsoon Region During Heinrich Event 1', Science, 331(6022), pp. 1299–1302. Available at: https://doi.org/10.1126/science.1198322.

Staver, A.C. (2018) 'Prediction and scale in savanna ecosystems', New Phytologist, 219(1), pp. 52–57. Available at: https://doi.org/10.1111/nph.14829.

Staver, A.C., Archibald, S. and Levin, S.A. (2011) 'The Global Extent and Determinants of Savanna and Forest as Alternative Biome States', Science, 334(6053), pp. 230–232. Available at: https://doi.org/10.1126/science.1210465.

Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D., Summerhayes, C.P., Barnosky, A.D., Cornell, S.E., Crucifix, M., Donges, J.F., Fetzer, I., Lade, S.J., Scheffer, M., Winkelmann, R. and Schellnhuber, H.J. (2018) 'Trajectories of the Earth System in the Anthropocene', Proceedings of the National Academy of Sciences, 115(33), pp. 8252–8259. Available at: https://doi.org/10.1073/pnas.1810141115.

Steinert, N.J. (2023) 'Distribution maps of Biosphere and Cryosphere tipping elements'. Zenodo. Available at: https://zenodo.org/records/10119479 (Accessed: 8 September 2025).

Steinert, N.J., Debolskiy, M.V., Burke, E.J., García-Pereira, F. and Lee, H. (2023) 'Evaluating permafrost definitions for global permafrost area estimates in CMIP6 climate models', Environmental Research Letters, 19(1), p. 014033. Available at: https://doi.org/10.1088/1748-9326/ad10d7.

Steinert, N.J., Schwinger, J., Burke, E., Zhu, B., Gasser, T., Munday, G., Mathison, C., Park, S.-W. and Lee, H. (2025) 'AMOC tipping slows permafrost carbon release during overshoot'. Research Square. Available at: https://doi.org/10.21203/rs.3.rs-7031516/v1. [Under review]

Steinman, A.D. and Spears, B.M. (eds) (2020) Internal phosphorus loading in lakes: causes, case studies, and management. Plantation, Florida: J. Ross Publishing. Available at: https://nora.nerc.ac.uk/id/eprint/529457/ (Accessed: 1 September 2025).

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

Stevens, N., Lehmann, C.E.R., Murphy, B.P. and Durigan, G. (2017) 'Savanna woody encroachment is widespread across three continents', Global Change Biology, 23(1), pp. 235–244. Available at: https://doi.org/10.1111/gcb.13409.

Stokes, C.R., Abram, N.J., Bentley, M.J., Edwards, T.L., England, M.H., Foppert, A., Jamieson, S.S.R., Jones, R.S., King, M.A., Lenaerts, J.T.M., Medley, B., Miles, B.W.J., Paxman, G.J.G., Ritz, C., van de Flierdt, T. and Whitehouse, P.L. (2022) 'Response of the East Antarctic Ice Sheet to past and future climate change', Nature, 608(7922), pp. 275–286. Available at: https://doi.org/10.1038/s41586-022-04946-0.

Stokes, C.R., Bamber, J.L., Dutton, A. and DeConto, R.M. (2025) 'Warming of +1.5 °C is too high for polar ice sheets', Communications Earth & Environment, 6(1), pp. 1–12. Available at: https://doi.org/10.1038/s43247-025-02299-w.

Strömberg, C.A.E. and Staver, A.C. (2022) 'The history and challenge of grassy biomes', Science, 377(6606), pp. 592–593. Available at: https://doi.org/10.1126/science.add1347.

Sutanto, S.J., Vitolo, C., Di Napoli, C., D'Andrea, M. and Van Lanen, H.A.J. (2020) 'Heatwaves, droughts, and fires: Exploring compound and cascading dry hazards at the pan-European scale', Environment International, 134, p. 105276. Available at: https://doi.org/10.1016/j.envint.2019.105276.

Sutter, J., Gierz, P., Grosfeld, K., Thoma, M. and Lohmann, G. (2016) 'Ocean temperature thresholds for Last Interglacial West Antarctic Ice Sheet collapse', Geophysical Research Letters, 43(6), pp. 2675–2682. Available at: https://doi.org/10.1002/2016GL067818.

Swingedouw, D., Bily, A., Esquerdo, C., Borchert, L.F., Sgubin, G., Mignot, J. and Menary, M. (2021) 'On the risk of abrupt changes in the North Atlantic subpolar gyre in CMIP6 models', Annals of the New York Academy of Sciences, 1504(1), pp. 187–201. Available at: https://doi.org/10.1111/nyas.14659.

Tátrai, I., Boros, G., György, Á.I., Mátyás, K., Korponai, J., Pomogyi, P., Havasi, M. and Kucserka, T. (2009) 'Abrupt shift from clear to turbid state in a shallow eutrophic, biomanipulated lake', Hydrobiologia, 620(1), pp. 149–161. Available at: https://doi.org/10.1007/s10750-008-9625-4.

Temmink, R.J.M., Angelini, C., Verkuijl, M. and van der Heide, T. (2023) 'Restoration ecology meets design-engineering: Mimicking emergent traits to restore feedback-driven ecosystems', Science of The Total Environment, 902, p. 166460. Available at: https://doi.org/10.1016/j.scitotenv.2023.166460.

Temmink, R.J.M., Lamers, L.P.M., Angelini, C., Bouma, T.J., Fritz, C., van de Koppel, J., Lexmond, R., Rietkerk, M., Silliman, B.R., Joosten, H. and van der Heide, T. (2022) 'Recovering wetland biogeomorphic feedbacks to restore the world's biotic carbon hotspots', Science, 376(6593), p. eabn1479. Available at: https://doi.org/10.1126/science.abn1479.

Terhaar, J., Burger, F.A., Vogt, L., Frölicher, T.L. and Stocker, T.F. (2025) 'Record sea surface temperature jump in 2023–2024 unlikely but not unexpected', Nature, 639(8056), pp. 942–946. Available at: https://doi.org/10.1038/s41586-025-08674-z.

Terhaar, J., Vogt, L. and Foukal, N.P. (2025) 'Atlantic overturning inferred from air-sea heat fluxes indicates no decline since the 1960s', Nature Communications, 16(1), p. 222. Available at: https://doi.org/10.1038/s41467-024-55297-5.

Terpstra, S., Falkena, S.K.J., Bastiaansen, R., Bathiany, S., Dijkstra, H.A. and von der Heydt, A.S. (2025) 'Assessment of Abrupt Shifts in CMIP6 Models Using Edge Detection', AGU Advances, 6(3), p. e2025AV001698. Available at: https://doi.org/10.1029/2025AV001698.

Thirumalai, K., DiNezio, P.N., Partin, J.W., Liu, D., Costa, K. and Jacobel, A. (2024) 'Future increase in extreme El Niño supported by past glacial changes', Nature, 634(8033), pp. 374–380. Available at: https://doi.org/10.1038/s41586-024-07984-y.

Thom, D. (2023) 'Natural disturbances as drivers of tipping points in forest ecosystems under climate change – implications for adaptive management', Forestry: An International Journal of Forest Research, 96(3), pp. 305–315. Available at: https://doi.org/10.1093/forestry/cpad011.

Thomas, Z.A., Jones, R.T., Turney, C.S.M., Golledge, N., Fogwill, C., Bradshaw, C.J.A., Menviel, L., McKay, N.P., Bird, M., Palmer, J., Kershaw, P., Wilmshurst, J. and Muscheler, R. (2020) 'Tipping elements and amplified polar warming during the Last Interglacial', Quaternary Science Reviews, 233, p. 106222. Available at: https://doi.org/10.1016/j.quascirev.2020.106222.

Thonicke, K., Billing, M., von Bloh, W., Sakschewski, B., Niinemets, Ü., Peñuelas, J., Cornelissen, J.H.C., Onoda, Y., van Bodegom, P., Schaepman, M.E., Schneider, F.D. and Walz, A. (2020) 'Simulating functional diversity of European natural forests along climatic gradients', Journal of Biogeography, 47(5), pp. 1069–1085. Available at: https://doi.org/10.1111/jbi.13809.

Tierney, J.E., Haywood, A.M., Feng, R., Bhattacharya, T. and Otto-Bliesner, B.L. (2019) 'Pliocene Warmth Consistent With Greenhouse Gas Forcing', Geophysical Research Letters, 46(15), pp. 9136–9144. Available at: https://doi.org/10.1029/2019GL083802.

Tietsche, S., Notz, D., Jungclaus, J.H. and Marotzke, J. (2011) 'Recovery mechanisms of Arctic summer sea ice', Geophysical Research Letters, 38(2). Available at: https://doi.org/10.1029/2010GL045698.

Timmermann, A., An, S.-I., Kug, J.-S., Jin, F.-F., Cai, W., Capotondi, A., Cobb, K.M., Lengaigne, M., McPhaden, M.J., Stuecker, M.F., Stein, K., Wittenberg, A.T., Yun, K.-S., Bayr, T., Chen, H.-C., Chikamoto, Y., Dewitte, B., Dommenget, D., Grothe, P., Guilyardi, E., Ham, Y.-G., Hayashi, M., Ineson, S., Kang, D., Kim, S., Kim, W., Lee, J.-Y., Li, T., Luo, J.-J., McGregor, S., Planton, Y., Power, S., Rashid, H., Ren, H.-L., Santoso, A., Takahashi, K., Todd, A., Wang, Guomin, Wang, Guojian, Xie, R., Yang, W.-H., Yeh, S.-W., Yoon, J., Zeller, E. and Zhang, X. (2018) 'El Niño–Southern Oscillation complexity', Nature, 559(7715), pp. 535–545. Available at: https://doi.org/10.1038/s41586-018-0252-6.

TiPACCs (2023) TiPACCs #3: Tipping points of the Antarctic Ice Sheet - YouTube. Available at: https://www.youtube.com/watch?v=wsSD_vuBz-s (Accessed: 26 August 2025).

Törnqvist, T.E., Jankowski, K.L., Li, Y.-X. and González, J.L. (2020) 'Tipping points of Mississippi Delta marshes due to accelerated sea-level rise', Science Advances, 6(21), p. eaaz5512. Available at: https://doi.org/10.1126/sciadv.aaz5512.

Turetsky, M.R., Abbott, B.W., Jones, M.C., Anthony, K.W., Olefeldt, D., Schuur, E.A.G., Grosse, G., Kuhry, P., Hugelius, G., Koven, C., Lawrence, D.M., Gibson, C., Sannel, A.B.K. and McGuire, A.D. (2020) 'Carbon release through abrupt permafrost thaw', Nature Geoscience, 13(2), pp. 138–143. Available at: https://doi.org/10.1038/s41561-019-0526-0.

Turney, C.S.M., Fogwill, C.J., Golledge, N.R., McKay, N.P., van Sebille, E., Jones, R.T., Etheridge, D., Rubino, M., Thornton, D.P., Davies, S.M., Ramsey, C.B., Thomas, Z.A., Bird, M.I., Munksgaard, N.C., Kohno, M., Woodward, J., Winter, K., Weyrich, L.S., Rootes, C.M., Millman, H., Albert, P.G., Rivera, A., van Ommen, T., Curran, M., Moy, A., Rahmstorf, S., Kawamura, K., Hillenbrand, C.-D., Weber, M.E., Manning, C.J., Young, J. and Cooper, A. (2020) 'Early Last Interglacial ocean warming drove substantial ice mass loss from Antarctica', Proceedings of the National Academy of Sciences, 117(8), pp. 3996–4006. Available at: https://doi.org/10.1073/pnas.1902469117.

Tziperman, E. and Farrell, B. (2009) 'Pliocene equatorial temperature: Lessons from atmospheric superrotation', Paleoceanography, 24(1). Available at: https://doi.org/10.1029/2008PA001652.

Vaks, A., Mason, A.J., Breitenbach, S.F.M., Kononov, A.M., Osinzev, A.V., Rosensaft, M., Borshevsky, A., Gutareva, O.S. and Henderson, G.M. (2020) 'Palaeoclimate evidence of vulnerable permafrost during times of low sea ice', Nature, 577(7789), pp. 221–225. Available at: https://doi.org/10.1038/s41586-019-1880-1.

Van Passel, J., Bernardino, P.N., Lhermitte, S., Rius, B.F., Hirota, M., Conradi, T., de Keersmaecker, W., Van Meerbeek, K. and Somers, B. (2024) 'Critical slowing down of the Amazon forest after increased drought occurrence', Proceedings of the National Academy of Sciences, 121(22), p. e2316924121. Available at: https://doi.org/10.1073/pnas.2316924121.

Vanderborght, E., Westen, R.M. van and Dijkstra, H.A. (2025) 'Feedback Processes Causing an AMOC Collapse in the Community Earth System Model', Journal of Climate, 38(19), pp. 5083–5102. Available at: https://doi.org/10.1175/JCLI-D-24-0570.1.

Vasconcelos, J., Sanabria-Fernandez, J.A., Tuset, V.M., Sousa, R., Faria, G. and Riera, R. (2024) 'Rising temperatures, falling fisheries: causes and consequences of crossing the tipping point in a small-pelagic community', Reviews in Fish Biology and Fisheries, 34(4), pp. 1511–1530. Available at: https://doi.org/10.1007/s11160-024-09885-9.

Veldman, J.W., Mattingly, W.B. and Brudvig, L.A. (2013) 'Understory plant communities and the functional distinction between savanna trees, forest trees, and pines', Ecology, 94(2), pp. 424–434. Available at: https://doi.org/10.1890/12-1019.1.

Veldman, J.W. and Putz, F.E. (2011) 'Grass-dominated vegetation, not species-diverse natural savanna, replaces degraded tropical forests on the southern edge of the Amazon Basin', Biological Conservation, 144(5), pp. 1419–1429. Available at: https://doi.org/10.1016/j.biocon.2011.01.011.

Vercelloni, J., Caley, M.J. and Mengersen, K.L. (2020) 'Thresholds of Coral Cover That Support Coral Reef Biodiversity', in K.L. Mengersen, P. Pudlo, and C.P. Robert (eds) Case Studies in Applied Bayesian Data Science: CIRM Jean-Morlet Chair, Fall 2018. Cham: Springer International Publishing, pp. 385–398. Available at: https://doi.org/10.1007/978-3-030-42553-1_16.

Verfaillie, D., Pelletier, C., Goosse, H., Jourdain, N.C., Bull, C.Y.S., Dalaiden, Q., Favier, V., Fichefet, T. and Wille, J.D. (2022) 'The circum-Antarctic ice-shelves respond to a more positive Southern Annular Mode with regionally varied melting', Communications Earth & Environment, 3(1), p. 139. Available at: https://doi.org/10.1038/s43247-022-00458-x.

Vert-pre, K.A., Amoroso, R.O., Jensen, O.P. and Hilborn, R. (2013) 'Frequency and intensity of productivity regime shifts in marine fish stocks', Proceedings of the National Academy of Sciences, 110(5), pp. 1779–1784. Available at: https://doi.org/10.1073/pnas.1214879110.

van de Vijsel, R.C., Scheffer, M. and Hoitink, A.J.F. (2024) 'Tipping points in river deltas', Nature Reviews Earth & Environment, 5(12), pp. 843–858. Available at: https://doi.org/10.1038/s43017-024-00610-5.

Vogt-Vincent, N.S., Pringle, J.M., Cornwall, C.E. and McManus, L.C. (2025) 'Anthropogenic climate change will likely outpace coral range expansion', Science Advances, 11(23), p. eadr2545. Available at: https://doi.org/10.1126/sciadv.adr2545.

van der Voort, J., Baudena, M., Meron, E., Rietkerk, M. and Doelman, A. (2025) 'Vegetation patterning can both impede and trigger critical transitions from savanna to grassland', Environmental Research Letters, 20(9), p. 094052. Available at: https://doi.org/10.1088/1748-9326/adc3ab.

de Vrese, P. and Brovkin, V. (2021) 'Timescales of the permafrost carbon cycle and legacy effects of temperature overshoot scenarios', Nature Communications, 12(1), p. 2688. Available at: https://doi.org/10.1038/s41467-021-23010-5.

de Vrese, P., Stacke, T., Gayler, V. and Brovkin, V. (2024) 'Permafrost Cloud Feedback May Amplify Climate Change', Geophysical Research Letters, 51(12), p. e2024GL109034. Available at: https://doi.org/10.1029/2024GL109034.

Waddington, J.M., Moore, P., Sutton, O., Furukawa, A., Moore, M., Verkaik, G., Huizen, B.V. and Wilkinson, S. (2025) Quantifying Peatland Ecohydrological Resilience to Drought and Wildfire by Thinking Outside the Bog EGU25-13948. Copernicus Meetings. Available at: https://doi.org/10.5194/egusphere-egu25-13948.

Wagner, T.J.W. and Eisenman, I. (2015) 'How Climate Model Complexity Influences Sea Ice Stability'. Available at: https://doi.org/10.1175/JCLI-D-14-00654.1.

Walker, C.C., Millstein, J.D., Miles, B.W.J., Cook, S., Fraser, A.D., Colliander, A., Misra, S., Trusel, L.D., Adusumilli, S., Roberts, C. and Fricker, H.A. (2024) 'Multi-decadal collapse of East Antarctica's Conger–Glenzer Ice Shelf', Nature Geoscience, 17(12), pp. 1240–1248. Available at: https://doi.org/10.1038/s41561-024-01582-3.

Wang, B., Sun, W., Jin, C., Luo, X., Yang, Y.-M., Li, T., Xiang, B., McPhaden, M.J., Cane, M.A., Jin, F., Liu, F. and Liu, J. (2023) 'Understanding the recent increase in multiyear La Niñas', Nature Climate Change, 13(10), pp. 1075–1081. Available at: https://doi.org/10.1038/s41558-023-01801-6.

Wang, H., Ciais, P., Sitch, S., Green, J.K., Tao, S., Fu, Z., Albergel, C., Bastos, A., Wang, M., Fawcett, D., Frappart, F., Li, X., Liu, X., Li, S. and Wigneron, J.-P. (2024) 'Anthropogenic disturbance exacerbates resilience loss in the Amazon rainforests', Global Change Biology, 30(1), p. e17006. Available at: https://doi.org/10.1111/gcb.17006.

Wang, H.-J., Wang, H.-Z., Liang, X.-M. and Wu, S.-K. (2014) 'Total phosphorus thresholds for regime shifts are nearly equal in subtropical and temperate shallow lakes with moderate depths and areas', Freshwater Biology, 59(8), pp. 1659–1671. Available at: https://doi.org/10.1111/fwb.12372.

Wang, P., Huang, Q., Pozdniakov, S.P., Liu, S., Ma, N., Wang, T., Zhang, Y., Yu, J., Xie, J., Fu, G., Frolova, N.L. and Liu, C. (2021) 'Potential role of permafrost thaw on increasing Siberian river discharge', Environmental Research Letters, 16(3), p. 034046. Available at: https://doi.org/10.1088/1748-9326/abe326.

Wang, Q., Shu, Q., Wang, S., Li, X., Danilov, S., Qiao, F., Song, Z., Wang, F. and Jung, T. (2025) 'Dominant inflation of the Arctic Ocean's Beaufort Gyre in a warming climate', Communications Earth & Environment, 6(1), p. 40. Available at: https://doi.org/10.1038/s43247-025-02028-3.

Wang, S., Foster, A., Lenz, E.A., Kessler, J.D., Stroeve, J.C., Anderson, L.O., Turetsky, M., Betts, R., Zou, S., Liu, W., Boos, W.R. and Hausfather, Z. (2023) 'Mechanisms and Impacts of Earth System Tipping Elements', Reviews of Geophysics, 61(1), p. e2021RG000757. Available at: https://doi.org/10.1029/2021RG000757.

Wara, M.W., Ravelo, A.C. and Delaney, M.L. (2005) 'Permanent El Niño-like conditions during the Pliocene warm period', Science (New York, N.Y.), 309(5735), pp. 758–761. Available at: https://doi.org/10.1126/science.1112596.

Webb, H., Fuchs, M., Abbott, B.W., Douglas, T.A., Elder, C.D., Ernakovich, J.G., Euskirchen, E.S., Göckede, M., Grosse, G., Hugelius, G., Jones, M.C., Koven, C., Kropp, H., Lathrop, E., Li, W., Loranty, M.M., Natali, S.M., Olefeldt, D., Schädel, C., Schuur, E.A.G., Sonnentag, O., Strauss, J., Virkkala, A.-M. and Turetsky, M.R. (2025) 'A Review of Abrupt Permafrost Thaw: Definitions, Usage, and a Proposed Conceptual Framework', Current Climate Change Reports, 11(1), p. 7. Available at: https://doi.org/10.1007/s40641-025-00204-3.

Weber, M.E., Golledge, N.R., Fogwill, C.J., Turney, C.S.M. and Thomas, Z.A. (2021) 'Decadal-scale onset and termination of Antarctic ice-mass loss during the last deglaciation', Nature Communications, 12(1), p. 6683. Available at: https://doi.org/10.1038/s41467-021-27053-6.

Weertman, J. (1974) 'Stability of the Junction of an Ice Sheet and an Ice Shelf', Journal of Glaciology, 13(67), pp. 3–11. Available at: https://doi.org/10.3189/S0022143000023327.

Weijer, W., Cheng, W., Drijfhout, S.S., Fedorov, A.V., Hu, A., Jackson, L.C., Liu, W., McDonagh, E.L., Mecking, J.V. and Zhang, J. (2019) 'Stability of the Atlantic Meridional Overturning Circulation: A Review and Synthesis', Journal of Geophysical Research: Oceans, 124(8), pp. 5336–5375. Available at: https://doi.org/10.1029/2019JC015083.

Weijer, W., Cheng, W., Garuba, O.A., Hu, A. and Nadiga, B.T. (2020) 'CMIP6 Models Predict Significant 21st Century Decline of the Atlantic Meridional Overturning Circulation', Geophysical Research Letters, 47(12), p. e2019GL086075. Available at: https://doi.org/10.1029/2019GL086075.

van Westen, R.M. and Baatsen, M.L.J. (2025) 'European Temperature Extremes Under Different AMOC Scenarios in the Community Earth System Model', Geophysical Research Letters, 52(12), p. e2025GL114611. Available at: https://doi.org/10.1029/2025GL114611.

van Westen, R.M., Kliphuis, M. and Dijkstra, H.A. (2024) 'Physics-based early warning signal shows that AMOC is on tipping course', Science Advances, 10(6), p. eadk1189. Available at: https://doi.org/10.1126/sciadv.adk1189.

van Westen, R.M., Kliphuis, M. and Dijkstra, H.A. (2025) 'Collapse of the Atlantic Meridional Overturning Circulation in a Strongly Eddying Ocean-Only Model', Geophysical Research Letters, 52(6), p. e2024GL114532. Available at: https://doi.org/10.1029/2024GL114532.

van Westen, R.M., van der Wiel, K., Falkena, S.K.J. and Selten, F. (2025) 'Changing European Hydroclimate under a Collapsed AMOC in the Community Earth System Model', EGUsphere, pp. 1–29. Available at: https://doi.org/10.5194/egusphere-2025-1440.

Wilkinson, C.R. (2004) Status of coral reefs of the world : 2004. Vol. 1. Australian Institute of Marine Science (AIMS), AU. Available at: https://portals.iucn.org/library/node/8583 (Accessed: 2 September 2025).

Wille, J.D., Favier, V., Gorodetskaya, I.V., Agosta, C., Baiman, R., Barrett, J.E., Barthelemy, L., Boza, B., Bozkurt, D., Casado, M., Chyhareva, A., Clem, K.R., Codron, F., Datta, R.T., Durán-Alarcón, C., Francis, D., Hoffman, A.O., Kolbe, M., Krakovska, S., Linscott, G., Maclennan, M.L., Mattingly, K.S., Mu, Y., Pohl, B., Santos, C.L.-D., Shields, C.A., Toker, E., Winters, A.C., Yin, Z., Zou, X., Zhang, C. and Zhang, Z. (2025) 'Atmospheric rivers in Antarctica', Nature Reviews Earth & Environment, 6(3), pp. 178–192. Available at: https://doi.org/10.1038/s43017-024-00638-7.

Willeit, M. and Ganopolski, A. (2024) 'Generalized stability landscape of the Atlantic meridional overturning circulation', Earth System Dynamics, 15(6), pp. 1417–1434. Available at: https://doi.org/10.5194/esd-15-1417-2024.

Wills, R.C.J., Dong, Y., Proistosecu, C., Armour, K.C. and Battisti, D.S. (2022) 'Systematic Climate Model Biases in the Large-Scale Patterns of Recent Sea-Surface Temperature and Sea-Level Pressure Change', Geophysical Research Letters, 49(17), p. e2022GL100011. Available at: https://doi.org/10.1029/2022GL100011.

Winkelmann, R., Steinert, N.J., Armstrong McKay, D.I., Brovkin, V., Kääb, A., Notz, D., Aksenov, Y., Arndt, S., Bathiany, S., Burke, E., Garbe, J., Gasson, E., Goelzer, H., Hugelius, G., Klose, A.K., Langebroek, P.M., Marzeion, B., Maussion, F., Nitzbon, J., Robinson, A., Rynders, S. and Sudakow, I. (2023) 'Chapter 1.2 Tipping points in the cryosphere', in Global Tipping Points Report 2023. Exeter, UK: University of Exeter. Available at: https://report-2023.global-tipping-points.org/section1/1-earth-system-tipping-points/1-2-tipping-points-in-the-cryosphere/.

Winton, M. (2006) 'Does the Arctic sea ice have a tipping point?', Geophysical Research Letters, 33(23). Available at: https://doi.org/10.1029/2006GL028017.

Winton, M. (2008) 'Sea Ice–Albedo Feedback and Nonlinear Arctic Climate Change', in Arctic Sea Ice Decline: Observations, Projections, Mechanisms, and Implications. American Geophysical Union (AGU), pp. 111–131. Available at: https://doi.org/10.1029/180GM09.

WMO (2025) State of the Global Climate 2024. WMO-No. 1368. Geneva: World Meteorological Organization, p. 42. Available at: https://library.wmo.int/idurl/4/69455 (Accessed: 4 September 2025).

Wolff, E.W., Mulvaney, R., Grieman, M.M., Hoffmann, H.M., Humby, J., Nehrbass-Ahles, C., Rhodes, R.H., Rowell, I.F., Sime, L.C., Fischer, H., Stocker, T.F., Landais, A., Parrenin, F., Steig, E.J., Dütsch, M. and Golledge, N.R. (2025) 'The Ronne Ice Shelf survived the last interglacial', Nature, 638(8049), pp. 133–137. Available at: https://doi.org/10.1038/s41586-024-08394-w.

Woollings, T., Drouard, M., O'Reilly, C.H., Sexton, D.M.H. and McSweeney, C. (2023) 'Trends in the atmospheric jet streams are emerging in observations and could be linked to tropical warming', Communications Earth & Environment, 4(1), p. 125. Available at: https://doi.org/10.1038/s43247-023-00792-8.

Wunderling, N., von der Heydt, A.S., Aksenov, Y., Barker, S., Bastiaansen, R., Brovkin, V., Brunetti, M., Couplet, V., Kleinen, T., Lear, C.H., Lohmann, J., Roman-Cuesta, R.M., Sinet, S., Swingedouw, D., Winkelmann, R., Anand, P., Barichivich, J., Bathiany, S., Baudena, M., Bruun, J.T., Chiessi, C.M., Coxall, H.K., Docquier, D., Donges, J.F., Falkena, S.K.J., Klose, A.K., Obura, D., Rocha, J., Rynders, S., Steinert, N.J. and Willeit, M. (2024) 'Climate tipping point interactions and cascades: a review', Earth System Dynamics, 15(1), pp. 41–74. Available at: https://doi.org/10.5194/esd-15-41-2024.

Wunderling, N., Sakschewski, B., Rockström, J., Flores, B., Hirota, M. and Staal, A. (2025) 'Pinpointing Amazon forest tipping in global warming and deforestation pathways'. Research Square. Available at: https://doi.org/10.21203/rs.3.rs-5840795/v1.

Xi, Y., Zhang, W., Wei, F., Fang, Z. and Fensholt, R. (2024) 'Boreal tree species diversity increases with global warming but is reversed by extremes', Nature Plants, 10(10), pp. 1473–1483. Available at: https://doi.org/10.1038/s41477-024-01794-w.

Xie, C., Zhang, Z., Chen, Y. and Wang, C. (2025) 'Substantial Contraction of Dense Shelf Water in the Ross Sea Under Future Climate Scenarios', Geophysical Research Letters, 52(6), p. e2024GL112581. Available at: https://doi.org/10.1029/2024GL112581.

Xu, Z., Mason, J.A., Xu, C., Yi, S., Bathiany, S., Yizhaq, H., Zhou, Y., Cheng, J., Holmgren, M. and Lu, H. (2020) 'Critical transitions in Chinese dunes during the past 12,000 years', Science Advances, 6(9), p. eaay8020. Available at: https://doi.org/10.1126/sciadv.aay8020.

Yashayaev, I. (2024) 'Intensification and shutdown of deep convection in the Labrador Sea were caused by changes in atmospheric and freshwater dynamics', Communications Earth & Environment, 5(1), p. 156. Available at: https://doi.org/10.1038/s43247-024-01296-9.

Yoon, A. and Hohenegger, C. (2025) 'Muted Amazon Rainfall Response to Deforestation in a Global Storm-Resolving Model', Geophysical Research Letters, 52(4), p. e2024GL110503. Available at: https://doi.org/10.1029/2024GL110503.

Yu, H., Screen, J.A., Xu, M., Hay, S., Qiu, W. and Catto, J.L. (2025) 'Incomplete Arctic Sea-Ice Recovery Under CO^2 Removal and Its Effects on the Winter Atmospheric Circulation', Geophysical Research Letters, 52(5), p. e2024GL113541. Available at: https://doi.org/10.1029/2024GL113541.

Zekollari, H., Schuster, L., Maussion, F., Hock, R., Marzeion, B., Rounce, D.R., Compagno, L., Fujita, K., Huss, M., James, M., Kraaijenbrink, P.D.A., Lipscomb, W.H., Minallah, S., Oberrauch, M., Van Tricht, L., Champollion, N., Edwards, T., Farinotti, D., Immerzeel, W., Leguy, G. and Sakai, A. (2025) 'Glacier preservation doubled by limiting warming to 1.5°C versus 2.7°C', Science, 388(6750), pp. 979–983. Available at: https://doi.org/10.1126/science.adu4675.

Zemp, D.C., Schleussner, C.-F., Barbosa, H.M.J., Hirota, M., Montade, V., Sampaio, G., Staal, A., Wang-Erlandsson, L. and Rammig, A. (2017) 'Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks', Nature Communications, 8(1), p. 14681. Available at: https://doi.org/10.1038/ncomms14681.

Zemp, M., Jakob, L., Dussaillant, I., Nussbaumer, S.U., Gourmelen, N., Dubber, S., A, G., Abdullahi, S., Andreassen, L.M., Berthier, E., Bhattacharya, A., Blazquez, A., Boehm Vock, L.F., Bolch, T., Box, J., Braun, M.H., Brun, F., Cicero, E., Colgan, W., Eckert, N., Farinotti, D., Florentine, C., Floricioiu, D., Gardner, A., Harig, C., Hassan, J., Hugonnet, R., Huss, M., Jóhannesson, T., Liang, C.-C.A., Ke, C.-Q., Khan, S.A., King, O., Kneib, M., Krieger, L., Maussion, F., Mattea, E., McNabb, R., Menounos, B., Miles, E., Moholdt, G., Nilsson, J., Pálsson, F., Pfeffer, J., Piermattei, L., Plummer, S., Richter, A., Sasgen, I., Schuster, L., Seehaus, T., Shen, X., Sommer, C., Sutterley, T., Treichler, D., Velicogna, I., Wouters, B., Zekollari, H., Zheng, W., and The GlaMBIE Team (2025) 'Community estimate of global glacier mass changes from 2000 to 2023', Nature, 639(8054), pp. 382–388. Available at: https://doi.org/10.1038/s41586-024-08545-z.

Zhang, Q., Barnes, M., Benson, M., Burakowski, E., Oishi, A.C., Ouimette, A., Sanders-DeMott, R., Stoy, P.C., Wenzel, M., Xiong, L., Yi, K. and Novick, K.A. (2020) 'Reforestation and surface cooling in temperate zones: Mechanisms and implications', Global Change Biology, 26(6), pp. 3384–3401. Available at: https://doi.org/10.1111/gcb.15069.

Zhang, X., Evans, J.P. and Burrell, A.L. (2024) 'Less than 4% of dryland areas are projected to desertify despite increased aridity under climate change', Communications Earth & Environment, 5(1), p. 300. Available at: https://doi.org/10.1038/s43247-024-01463-y.

Zhang, Yu, Liu, X., Wang, L., Zeng, X., Zhao, L., Wu, X., Luo, Z., Yan, J., Hong, Y., Li, X. and Xiao, J. (2024) 'Reductions in Forest Resilience: Unraveling the Decoupling Between Gross Primary Productivity and Photosynthetic Efficiency', Geophysical Research Letters, 51(16), p. e2024GL110148. Available at: https://doi.org/10.1029/2024GL110148.

Zhang, Yue, Wang, J.A., Berner, L.T., Goetz, S.J., Zhao, K. and Liu, Y. (2024) 'Warming and disturbances affect Arctic-boreal vegetation resilience across northwestern North America', Nature Ecology & Evolution, 8(12), pp. 2265–2276. Available at: https://doi.org/10.1038/s41559-024-02551-0.

Zhang, Z., Luo, X., Friess, D.A. and Li, Y. (2025) 'Global mangrove growth variability driven by climatic oscillation-induced sea-level fluctuations', Nature Geoscience, 18(6), pp. 488–494. Available at: https://doi.org/10.1038/s41561-025-01701-8.

Zhang, Z., Luo, X., Friess, D.A., Wang, S., Li, Yi and Li, Yangfan (2024) 'Stronger increases but greater variability in global mangrove productivity compared to that of adjacent terrestrial forests', Nature Ecology & Evolution, 8(2), pp. 239–250. Available at: https://doi.org/10.1038/s41559-023-02264-w.

Zhao, C., Gladstone, R., Zwinger, T., Gillet-Chaulet, F., Wang, Y., Caillet, J., Mathiot, P., Saraste, L., Jager, E., Galton-Fenzi, B.K., Christoffersen, P. and King, M.A. (2025) 'Subglacial water amplifies Antarctic contributions to sea-level rise', Nature Communications, 16(1), p. 3187. Available at: https://doi.org/10.1038/s41467-025-58375-4.

Zhao, Y., Wang, X., Novillo, C.J., Arrogante-Funes, P., Vázquez-Jiménez, R., Berdugo, M. and Maestre, F.T. (2019) 'Remotely sensed albedo allows the identification of two ecosystem states along aridity gradients in Africa', Land Degradation & Development, 30(12), pp. 1502–1515. Available at: https://doi.org/10.1002/ldr.3338.

Zhou, S., Meijers, A.J.S., Meredith, M.P., Abrahamsen, E.P., Holland, P.R., Silvano, A., Sallée, J.-B. and Østerhus, S. (2023) 'Slowdown of Antarctic Bottom Water export driven by climatic wind and sea-ice changes', Nature Climate Change, 13(7), pp. 701–709. Available at: https://doi.org/10.1038/s41558-023-01695-4.

Zimmerman, C.C., Wagner, T.J.W., Maroon, E.A. and McNamara, D.E. (2025) 'Slowed Response of Atlantic Meridional Overturning Circulation Not a Robust Signal of Collapse', Geophysical Research Letters, 52(2), p. e2024GL112415. Available at: https://doi.org/10.1029/2024GL112415.

Zou, J., Ziegler, A.D., Chen, D., McNicol, G., Ciais, P., Jiang, X., Zheng, C., Wu, Jie, Wu, Jin, Lin, Z., He, X., Brown, L.E., Holden, J., Zhang, Z., Ramchunder, S.J., Chen, A. and Zeng, Z. (2022) 'Rewetting global wetlands effectively reduces major greenhouse gas emissions', Nature Geoscience, 15(8), pp. 627–632. Available at: https://doi.org/10.1038/s41561-022-00989-0.

Zwaan, A., Staal, A., Beest, M. te and Rietkerk, M. (2024) 'Widespread forest-savanna coexistence but limited bistability at a landscape scale in Central Africa', Environmental Research Letters, 19(12), p. 124035. Available at: https://doi.org/10.1088/1748-9326/ad8cef.

References 2.3

Abrams, J.F., Huntingford, C., Williamson, M.S., Armstrong McKay, D.I., Boulton, C.A., Buxton, J.E., Sakschewski, B., Loriani, S., Zimm, C., Winkelmann, R. and Lenton, T.M., 2023. Committed global warming risks triggering multiple climate tipping points. Earth's Future, 11(11), p.e2022EF003250.

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., ... & Lenton, T. M. (2022). Exceeding 1.5 C global warming could trigger multiple climate tipping points. Science, 377(6611), eabn7950.

Bdolach, T., Kurths, J. and Yanchuk, S. (2025). Tipping in an adaptive climate network model. arXiv preprint arXiv:2505.04533, in review.

Ben-Yami, M., Morr, A., Bathiany, S., & Boers, N. (2024). Uncertainties too large to predict tipping times of major Earth system components from historical data. Science Advances, 10(31), eadl4841.

Bevacqua, E., Schleussner, C. F., & Zscheischler, J. (2025). A year above 1.5° C signals that Earth is most probably within the 20-year period that will reach the Paris Agreement limit. Nature Climate Change, 1-4.

Bjordal, J., Storelvmo, T., Alterskjær, K. et al. (2020). Equilibrium climate sensitivity above 5 °C plausible due to state-dependent cloud feedback. Nat. Geosci. 13, 718–721 .

Bochow, N., Poltronieri, A., Robinson, A., Montoya, M., Rypdal, M., & Boers, N. (2023). Overshooting the critical threshold for the Greenland ice sheet. Nature, 622(7983), 528-536.

Bustamante, M., Roy, J., Ospina, D., Achakulwisut, P., Aggarwal, A., Bastos, A., ... & Zscheischler, J. (2023). Ten new insights in climate science 2023. Global Sustainability, 7, e19.

Ceppi, P. & Nowack, P. (2021). Observational evidence that cloud feedback amplifies global warming. PNAS, 118 (30) e2026290118.

Climate Action Tracker (2024). Warming projections global update. Climate Analytics and New Climate Institute: Berlin, Germany. URL: https://climateactiontracker.org/publications/the-climate-crisis-worsens-the-warming-outlook-stagnates/.

Corner, S., Siegert, M., Ceppi, P., Fox-Kemper, B., Frölicher, T. L., Gallego-Sala, A., ... & Rogelj, J. (2023). The zero emissions commitment and climate stabilization. Frontiers in Science, 1, 1170744.

Dekker, M. M., Von Der Heydt, A. S., & Dijkstra, H. A. (2018). Cascading transitions in the climate system. Earth System Dynamics, 9(4), 1243-1260.

Deutloff, J., Held, H., and Lenton, T. M. (2025). High probability of triggering climate tipping points under current policies modestly amplified by Amazon dieback and permafrost thaw, Earth Syst. Dynam., 16, 565–583.

Falkena, S. K., & von der Heydt, A. S. (2024). Subpolar Gyre Variability in CMIP6 Models: Is there a Mechanism for Bistability?. arXiv preprint arXiv:2408.16541, in review.

Flores, B.M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R.A., Levis, C., Lapola, D.M., Esquível-Muelbert, A., Jakovac, C. and Nobre, C.A. (2024). Critical transitions in the Amazon forest system. Nature, 626(7999), 555-564.

Friedlingstein, P., O'sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Landschützer, P., ... & Zeng, J. (2025). Global carbon budget 2024. Earth System Science Data, 17(3), 965-1039.

Gatti, L. V., Basso, L. S., Miller, J. B., Gloor, M., Gatti Domingues, L., Cassol, H. L., ... & Neves, R. A. (2021). Amazonia as a carbon source linked to deforestation and climate change. Nature, 595(7867), 388-393.

Hughes, T. P., Kerry, J. T., Baird, A. H., Connolly, S. R., Dietzel, A., Eakin, C. M., ... & Torda, G. (2018). Global warming transforms coral reef assemblages. Nature, 556(7702), 492-496.

IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3–32, doi:10.1017/9781009157896.001.

Ke, P., Ciais, P., Sitch, S., Li, W., Bastos, A., Liu, Z., ... & Chevallier, F. (2024). Low latency carbon budget analysis reveals a large decline of the land carbon sink in 2023. National Science Review, 11(12), nwae367.

Kikstra, J. S., Nicholls, Z. R., Smith, C. J., Lewis, J., Lamboll, R. D., Byers, E., ... & Riahi, K. (2022). The IPCC Sixth Assessment Report WGIII climate assessment of mitigation pathways: from emissions to global temperatures. Geoscientific Model Development, 15(24), 9075-9109.

Koven, C. D., Sanderson, B. M., & Swann, A. L. (2023). Much of zero emissions commitment occurs before reaching net zero emissions. Environmental Research Letters, 18(1), 014017.

Laybourn L, Abrams J F, Benton D, Brown K, Evans J, Elliott J, Swingedouw D, Lenton T M and Dyke J G (2024) The security blind spot: Cascading climate impacts and tipping points threaten national security, IPPR. http://www.ippr.org/articles/security-blind-spot

Lee, J.-Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J. P., Engelbrecht, F., Fischer, E., Fyfe, J. C., Jones, C., Maycock, A., Mutemi, J., Niaye, O., Panickal, S., Zhou, T., & Christensen, H. M. (2021). Future global climate: scenario-based projections and near-term information (pp. 553–672). Cambridge University Press.

Lenton, T. M., Mckay, D. I. A., Loriani, S., Abrams, J. F., Lade, S. J., Donges, J. F., ... & Rockström, J. (2023). The global tipping points report 2023. University of Exeter, Exeter, UK

Lenton, T. M., Abrams, J. F., Bartsch, A., Bathiany, S., Boulton, C. A., Buxton, J. E., ... & Boers, N. (2024). Remotely sensing potential climate change tipping points across scales. Nature Communications, 15(1), 343.

Lovejoy, T. E., & Nobre, C. (2018). Amazon tipping point. Science advances, 4(2), eaat2340.

MacDougall, A. H., Frölicher, T. L., Jones, C. D., Rogelj, J., Matthews, H. D., Zickfeld, K., Arora, V. K., Barrett, N. J., Brovkin, V., Burger, F. A., Eby, M., Eliseev, A. V., Hajima, T., Holden, P. B., Jeltsch-Thömmes, A., Koven, C., Mengis, N., Menviel, L., Michou, M., Mokhov, I. I., Oka, A., Schwinger, J., Séférian, R., Shaffer, G., Sokolov, A., Tachiiri, K., Tjiputra , J., Wiltshire, A., and Ziehn, T. (2020). Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO2, Biogeosciences, 17, 2987–3016.

Möller, T., Högner, A. E., Schleussner, C. F., Bien, S., Kitzmann, N. H., Lamboll, R. D., ... & Wunderling, N. (2024). Achieving net zero greenhouse gas emissions critical to limit climate tipping risks. Nature Communications, 15(1), 6192.

Nicholls, Z., Meinshausen, M., Lewis, J., Smith, C. J., Forster, P. M., Fuglestvedt, J. S., ... & Byers, E. (2022). Changes in IPCC scenario assessment emulators between SR1. 5 and AR6 unraveled. Geophysical Research Letters, 49(20), e2022GL099788.

Pearce-Kelly, P., Altieri, A. H., Bruno, J. F., Cornwall, C. E., McField, M., Muñiz-Castillo, A. I., ... & Yesson, C. (2025). Considerations for determining warm-water coral reef tipping points. Earth System Dynamics, 16(1), 275-292.

Reisinger, A., Fuglestvedt, J.S., Pirani, A., Geden, O., Jones, C.D., Maharaj, S., Poloczanska, E.S., Morelli, A., Johansen, T.G., Adler, C. and Betts, R.A., 2025. Overshoot: A Conceptual Review of Exceeding and Returning to Global Warming of 1.5° C. Annual Review of Environment and Resources, 50.

Ripple, W. J., Wolf, C., Lenton, T. M., Gregg, J. W., Natali, S. M., Duffy, P. B., ... & Schellnhuber, H. J. (2023). Many risky feedback loops amplify the need for climate action. One Earth, 6(2), 86-91.

Ritchie, P., Karabacak, Ö., & Sieber, J. (2019). Inverse-square law between time and amplitude for crossing tipping thresholds. Proceedings of the Royal Society A, 475(2222), 20180504.

Ritchie, P. D., Clarke, J. J., Cox, P. M., & Huntingford, C. (2021). Overshooting tipping point thresholds in a changing climate. Nature, 592(7855), 517-523.

Ritchie, P. D., Huntingford, C., & Cox, P. M. (2025). ESD Ideas. Climate tipping is not instantaneous–the duration of an overshoot matters. Egusphere (in review).

Sanderson, B. M., Brovkin, V., Fisher, R., Hohn, D., Ilyina, T., Jones, C., ... & Ziehn, T. (2024). flat10MIP: An emissions-driven experiment to diagnose the climate response to positive, zero, and negative CO2 emissions. EGUsphere, 2024, 1-39, in review.

Saye, L., Bettis, O., Bedenham, G., Hampshire, O., Lenton, T.M. and Abrams, J.F. (2025). Planetary Solvency - finding our balance with nature.

Schleussner, C. F., Ganti, G., Lejeune, Q., Zhu, B., Pfleiderer, P., Prütz, R., ... & Rogelj, J. (2024). Overconfidence in climate overshoot. Nature, 634(8033), 366-373.

Schwinger, J., Asaadi, A., Steinert, N. J., & Lee, H. (2022). Emit now, mitigate later? Earth system reversibility under overshoots of different magnitudes and durations. Earth System Dynamics, 13(4), 1641-1665.

Setter, R. O., Franklin, E. C., & Mora, C. (2022). Co-occurring anthropogenic stressors reduce the timeframe of environmental viability for the world's coral reefs. PLoS Biology, 20(10), e3001821.

Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I., Vaughan, N. E. (eds.) The State of Carbon Dioxide Removal 2024 - 2nd Edition. DOI 10.17605/OSF.IO/F85QJ (2024)

Steinert, N.J. and Sanderson, B.M. (2025). Normalizing the permafrost carbon feedback contribution to TCRE and ZEC. EGUsphere, 2025, pp.1-14, in review.

Stokes, C. R., Bamber, J. L., Dutton, A., & DeConto, R. M. (2025). Warming of+ 1.5° C is too high for polar ice sheets. Communications Earth & Environment, 6(1), 1-12.

Swingedouw, D., Bily, A., Esquerdo, C., Borchert, L. F., Sgubin, G., Mignot, J., & Menary, M. (2021). On the risk of abrupt changes in the North Atlantic subpolar gyre in CMIP6 models. Annals of the New York Academy of Sciences, 1504(1), 187-201.

Tokarska, K. B., Zickfeld, K., & Rogelj, J. (2019). Path independence of carbon budgets when meeting a stringent global mean temperature target after an overshoot. Earth's Future, 7(12), 1283-1295.

Trust, S. Bettis, O., Saye, L., Bedenham, G., Lenton, T.M., Abrams, J.F., Kemp, L. (2024). Climate scorpion - the sting is in the tail: introducing planetary solvency.

Willcock, S., Cooper, G. S., Addy, J., & Dearing, J. A. (2023). Earlier collapse of Anthropocene ecosystems driven by multiple faster and noisier drivers. Nature Sustainability, 6(11), 1331-1342.

World Meteorological Organization (2025). State of the Global Climate 2024, WMO-No. 1368, Publications Board WMO, Geneva, Switzerland.

Wunderling, N., Donges, J. F., Kurths, J., & Winkelmann, R. (2021). Interacting tipping elements increase risk of climate domino effects under global warming. Earth System Dynamics, 12(2), 601-619.

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

Wunderling, N., von der Heydt, A. S., Aksenov, Y., Barker, S., Bastiaansen, R., Brovkin, V., ... & Willeit, M. (2024). Climate tipping point interactions and cascades: A review. Earth System Dynamics, 15(1), 41-74.

References 2.4

de Abreu, V. H. S., Santos, A. S. and Monteiro, T. G. M. (2022) "Climate change impacts on the road transport infrastructure: A systematic review on adaptation measures," *Sustainability*, vol. 14, no. 14, p. 8864 [Online]. DOI: 10.3390/su14148864.

Aguilera, R., Corringham, T., Gershunov, A. and Benmarhnia, T. (2021) "Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California.," *Nature Communications*, vol. 12, no. 1, p. 1493 [Online]. DOI: 10.1038/s41467-021-21708-0.

Akabane, T. K., Chiessi, C. M., Hirota, M., Bouimetarhan, I., Prange, M., Mulitza, S., Bertassoli Jr, D. J., Häggi, C., Staal, A., Lohmann, G., Boers, N., Daniau, A. L., Oliveira, R. S., Campos, M. C., Shi, X. and De Oliveira, P. E. (2024) "Weaker Atlantic overturning circulation increases the vulnerability of northern Amazon forests," *Nature geoscience*, vol. 17, no. 12, pp. 1284–1290 [Online]. DOI: 10.1038/s41561-024-01578-z.

Allen, S. K., Linsbauer, A., Randhawa, S. S., Huggel, C., Rana, P. and Kumari, A. (2016) "Glacial lake outburst flood risk in Himachal Pradesh, India: an integrative and anticipatory approach considering current and future threats," Natural Hazards, vol. 84, no. 3, pp. 1741–1763 [Online]. DOI: 10.1007/s11069-016-2511-x.

Alley, R. B., Clark, P. U., Huybrechts, P. and Joughin, I. (2005) "Ice-sheet and sea-level changes.," *Science*, vol. 310, no. 5747, pp. 456–460 [Online]. DOI: 10.1126/science.1114613.

Almulhim, A. I., Alverio, G. N., Sharifi, A., Shaw, R., Huq, S., Mahmud, M. J., Ahmad, S. and Abubakar, I. R. (2024) "Climate-induced migration in the Global South: an in depth analysis," *npj Climate Action*, vol. 3, no. 1, p. 47 [Online]. DOI: 10.1038/s44168-024-00133-1.

Alogoskoufis, S., Carbone, S., Coussens, W., Fahr, S., Giuzio, M., Kuik, F., Parisi, L., Salakhova, D. and Spaggiari, M. (2021) *Climate-related risks to financial stability. Financial Stability Review*, European Central Bank.

Altdorff, D., Borchard, N., Young, E. H., Galagedara, L., Sorvali, J., Quideau, S. and Unc, A. (2021) "Agriculture in boreal and Arctic regions requires an integrated global approach for research and policy," *Agronomy for Sustainable Development*, vol. 41, no. 2, p. 23 [Online]. DOI: 10.1007/s13593-021-00676-1.

Amrith, S. S. (2016) "Risk and the South Asian monsoon," *Climatic Change*, vol. 151, no. 1, pp. 1–12 [Online]. DOI: 10.1007/s10584-016-1629-x.

Anderson, W., Shukla, S., Verdin, J., Hoell, A., Justice, C., Barker, B., Slinski, K., Lenssen, N., Lou, J., Cook, B. I. and McNally, A. (2024) "Preseason maize and wheat yield forecasts for early warning of crop failure.," *Nature Communications*, vol. 15, no. 1, p. 7262 [Online]. DOI: 10.1038/s41467-024-51555-8.

Anderson, W. B., Seager, R., Baethgen, W., Cane, M. and You, L. (2019) "Synchronous crop failures and climate-forced production variability.," *Science Advances*, vol. 5, no. 7, p. eaaw1976 [Online]. DOI: 10.1126/sciadv.aaw1976.

Anthoff, D., Estrada, F. and Tol, R. S. J. (2016) "Shutting down the thermohaline circulation," *American Economic Review*, vol. 106, no. 5, pp. 602–606 [Online]. DOI: 10.1257/aer.p20161102.

Ao, Z., Hu, Xiaomei, Tao, S., Hu, Xie, Wang, G., Li, M., Wang, F., Hu, L., Liang, X., Xiao, J., Yusup, A., Qi, W., Ran, Q., Fang, Jiayi, Chang, J., Zeng, Z., Fu, Y., Xue, B., Wang, P., Zhao, K. and Fang, Jingyun (2024) "A national-scale assessment of land subsidence in China's major cities.," *Science*, vol. 384, no. 6693, pp. 301–306 [Online]. DOI: 10.1126/science.adl4366.

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J. and Lenton, T. M. (2022) "Exceeding 1.5°C global warming could trigger multiple climate tipping points.," *Science*, vol. 377, no. 6611, p. eabn7950 [Online]. DOI: 10.1126/science.abn7950.

Arraut, J. M., Nobre, C., Barbosa, H. M. J., Obregon, G. and Marengo, J. (2012) "Aerial Rivers and Lakes: Looking at Large-Scale Moisture Transport and Its Relation to Amazonia and to Subtropical Rainfall in South America," *Journal of climate*, vol. 25, no. 2, pp. 543–556 [Online]. DOI: 10.1175/2011JCLI4189.1.

Askland, H. H., Shannon, B., Chiong, R., Lockart, N., Maguire, A., Rich, J. and Groizard, J. (2022) "Beyond migration: a critical review of climate change induced displacement," *Environmental Sociology*, pp. 1–12 [Online]. DOI: 10.1080/23251042.2022.2042888.

Asutosh, A., Tilmes, S., Bednarz, E. M. and Fadnavis, S. (2025) "South Asian Summer Monsoon under stratospheric aerosol intervention," *npj Climate and Atmospheric Science*, vol. 8, no. 1, p. 3 [Online]. DOI: 10.1038/s41612-024-00875-z.

Baez-Gonzalez, A. D., Kiniry, J. R., Meki, M. N., Williams, J. R., Alvarez Cilva, M., Ramos Gonzalez, J. L. and Magallanes Estala, A. (2018) "Potential impact of future climate change on sugarcane under dryland conditions in Mexico," *Journal of Agronomy and Crop Science*, vol. 204, no. 5, pp. 515–528 [Online]. DOI: 10.1111/jac.12278.

Bajracharya, S. R. and Mool, P. (2009) "Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal," Annals of Glaciology, vol. 50, no. 53, pp. 81–86 [Online]. DOI: 10.3189/172756410790595895.

Baker, J. C. A. and Spracklen, D. V. (2022) "Divergent representation of precipitation recycling in the amazon and the congo in CMIP6 models.," *Geophysical research letters*, vol. 49, no. 10, p. e2021GL095136 [Online]. DOI: 10.1029/2021GL095136.

Bamber, J. L., Riva, R. E. M., Vermeersen, B. L. A. and LeBrocq, A. M. (2009) "Reassessment of the potential sea-level rise from a collapse of the West Antarctic Ice Sheet.," *Science*, vol. 324, no. 5929, pp. 901–903 [Online]. DOI: 10.1126/science.1169335.

Banerjee, O., Cicowiez, M., Macedo, M. N., Malek, Ž., Verburg, P. H., Goodwin, S., Vargas, R., Rattis, L., Bagstad, K. J., Brando, P. M., Coe, M. T., Neill, C., Marti, O. D. and Murillo, J. Á. (2022) "Can we avert an Amazon tipping point? The economic and environmental costs," *Environmental Research Letters*, vol. 17, no. 12, p. 125005 [Online]. DOI: 10.1088/1748-9326/aca3b8.

Bathiany, S., Dijkstra, H., Crucifix, M., Dakos, V., Brovkin, V., Williamson, M. S., Lenton, T. M. and Scheffer, M. (2016) "Beyond bifurcation: using complex models to understand and predict abrupt climate change," *Dynamics and Statistics of the Climate System*, p. dzw004 [Online]. DOI: 10.1093/climsys/dzw004.

Bathiany, S., Scheffer, M., van Nes, E. H., Williamson, M. S. and Lenton, T. M. (2018) "Abrupt climate change in an oscillating world.," *Scientific Reports*, vol. 8, no. 1, p. 5040 [Online]. DOI: 10.1038/s41598-018-23377-4.

Becker, M., Papa, F., Karpytchev, M., Delebecque, C., Krien, Y., Khan, J. U., Ballu, V., Durand, F., Le Cozannet, G., Islam, A. K. M. S., Calmant, S. and Shum, C. K. (2020) "Water level changes, subsidence and sea level rise in the Ganges-Brahmaputra-Meghna delta.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 117, no. 4, pp. 1867–1876 [Online]. DOI: 10.1073/pnas.1912921117.

van Beek, L., Hajer, M., Pelzer, P., van Vuuren, D. and Cassen, C. (2020) "Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science-policy interface since 1970," *Global Environmental Change*, vol. 65, p. 102191 [Online]. DOI: 10.1016/j.gloenvcha.2020.102191.

Begazo-Curie, K. and Vranken, L. (2025) "Forests' contribution to rural livelihoods and food security: Insights from a study case in the Peruvian Amazon," *Food Security*, vol. 17, no. 2, pp. 387–403 [Online]. DOI: 10.1007/s12571-025-01521-z.

Behlul, T. (2011) "Was it really a Minsky moment?," *Journal of post Keynesian economics*, vol. 34, no. 1, pp. 137–158 [Online]. DOI: 10.2753/PKE0160-3477340106.

Bellomo, K., Meccia, V. L., D'Agostino, R., Fabiano, F., Larson, S. M., von Hardenberg, J. and Corti, S. (2023) "Impacts of a weakened AMOC on precipitation over the Euro-Atlantic region in the EC-Earth3 climate model," *Climate dynamics*, vol. 61, no. 7–8, pp. 3397–3416 [Online]. DOI: 10.1007/s00382-023-06754-2.

Bellomo, K. and Mehling, O. (2024) "Impacts and state-dependence of AMOC weakening in a warming climate," *Geophysical research letters*, vol. 51, no. 10 [Online]. DOI: 10.1029/2023GL107624.

Beltran-Peña, A., Rhoades, A., Burakowski, E., Girotto, M., Michalak, A. M., Diffenbaugh, N. S., Inda-Diaz, H. and D'Odorico, P. (2025) "Future implications of enhanced hydroclimate variability and reduced snowpack on California's water resources," Environmental Research: Water, vol. 1, no. 2, p. 025004 [Online]. DOI: 10.1088/3033-4942/ade7aa.

Ben-Yami, M., Good, P., Jackson, L. C., Crucifix, M., Hu, A., Saenko, O. A., Swingedouw, D. and Boers, N. (2023) "Robust and irreversible impacts of an AMOC collapse on tropical monsoon systems: a multi-model comparison," *Authorea, Inc.* [Online]. DOI: 10.22541/essoar.169447451.12077946/v1.

Ben-Yami, M., Good, P., Jackson, L. C., Crucifix, M., Hu, A., Saenko, O., Swingedouw, D. and Boers, N. (2024) "Impacts of AMOC collapse on monsoon rainfall: A multi-model comparison," *Earth's Future*, vol. 12, no. 9 [Online]. DOI: 10.1029/2023EF003959.

Berteaux, D., Gauthier, G., Domine, F., Ims, R. A., Lamoureux, S. F., Lévesque, E. and Yoccoz, N. (2017) "Effects of changing permafrost and snow conditions on tundra wildlife: critical places and times," *Arctic Science*, vol. 3, no. 2, pp. 65–90 [Online]. DOI: 10.1139/as-2016-0023.

Beveridge, C. F., Espinoza, J.-C., Athayde, S., Correa, S. B., Couto, T. B. A., Heilpern, S. A., Jenkins, C. N., Piland, N. C., Utsunomiya, R., Wongchuig, S. and Anderson, E. P. (2024) "The Andes-Amazon-Atlantic pathway: A foundational hydroclimate system for social-ecological system sustainability.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 121, no. 22, p. e2306229121 [Online]. DOI: 10.1073/pnas.2306229121.

Bhagtani, D., Hogg, A. McC., Holmes, R. M., Constantinou, N. C. and Khatri, H. (2024) "Impact of the North Atlantic Oscillation on the subtropical and subpolar gyres," *ESS Open Archive* [Online]. DOI: 10.22541/essoar.172938986.66856327/v1.

Bhagtani, D., McC. Hogg, A., Holmes, R. M., Constantinou, N. C. and Khatri, H. (2025) "Asymmetric response of the north atlantic gyres to the north atlantic oscillation," *Journal of Geophysical Research: Oceans*, vol. 130, no. 6 [Online]. DOI: 10.1029/2024JC021997.

Bhatia, K., Vecchi, G., Murakami, H., Underwood, S. and Kossin, J. (2018) "Projected response of tropical cyclone intensity and intensification in a global climate model," Journal of climate, vol. 31, no. 20, pp. 8281–8303 [Online]. DOI: 10.1175/JCLI-D-17-0898.1.

Bhattacharya, A., Papakonstantinou, K. G., Warn, G. P., McPhillips, L., Bilec, M. M., Forest, C. E., Hasan, R. and Chavda, D. (2025) "Optimal life-cycle adaptation of coastal infrastructure under climate change.," *Nature Communications*, vol. 16, no. 1, p. 1076 [Online]. DOI: 10.1038/s41467-024-55679-9.

Bloom, D. E., Canning, D., Kotschy, R., Prettner, K. and Schünemann, J. (2024) "Health and economic growth: reconciling the micro and macro evidence.," *World development*, vol. 178 [Online]. DOI: 10.1016/j.worlddev.2024.106575.

Boomhower, J., Fowlie, M., Gellman, J. and Plantinga, A. (2024) *How are insurance markets adapting to climate change? risk classification and pricing in the market for homeowners insurance*, Cambridge, MA, National Bureau of Economic Research [Online]. DOI: 10.3386/w32625.

Boot, A. A., von der Heydt, A. S. and Dijkstra, H. A. (2024) "Response of atmospheric pCO 2 to a strong AMOC weakening under low and high emission scenarios.," *Climate dynamics*, vol. 62, no. 8, pp. 7559–7574 [Online]. DOI: 10.1007/s00382-024-07295-y.

Boot, A. A., Steenbeek, J., Coll, M., von der Heydt, A. S. and Dijkstra, H. A. (2025) "Global marine ecosystem response to a strong AMOC weakening under low and high future emission scenarios," *Earth's Future*, vol. 13, no. 1 [Online]. DOI: 10.1029/2024EF004741.

Bose, S. (2013) "Sea-level Rise and Population Displacement in Bangladesh: Impact on India," *Maritime Affairs:Journal of the National Maritime Foundation of India*, vol. 9, no. 2, pp. 62–81 [Online]. DOI: 10.1080/09733159.2013.848616.

Bosserelle, A. L., Morgan, L. K. and Hughes, M. W. (2022) "Groundwater rise and associated flooding in coastal settlements due to sea-level rise: A review of processes and methods," *Earth's Future*, vol. 10, no. 7 [Online]. DOI: 10.1029/2021EF002580.

Bottino, M. J., Nobre, P., Giarolla, E., da Silva Junior, M. B., Capistrano, V. B., Malagutti, M., Tamaoki, J. N., de Oliveira, B. F. A. and Nobre, C. A. (2024) "Amazon savannization and climate change are projected to increase dry season length and temperature extremes over Brazil.," *Scientific Reports*, vol. 14, no. 1, p. 5131 [Online]. DOI: 10.1038/s41598-024-55176-5.

Bouttes, N., Gregory, J. M., Kuhlbrodt, T. and Smith, R. S. (2014) "The drivers of projected North Atlantic sea level change," *Climate dynamics*, vol. 43, no. 5–6, pp. 1531–1544 [Online]. DOI: 10.1007/s00382-013-1973-8.

Bradshaw, C. J. A. and Warkentin, I. G. (2015) "Global estimates of boreal forest carbon stocks and flux," *Global and planetary change*, vol. 128, pp. 24–30 [Online]. DOI: 10.1016/j.gloplacha.2015.02.004.

Brown, J. M., Morrissey, K., Knight, P., Prime, T. D., Almeida, L. P., Masselink, G., Bird, C. O., Dodds, D. and Plater, A. J. (2018) "A coastal vulnerability assessment for planning climate resilient infrastructure," *Ocean & coastal management*, vol. 163, pp. 101–112 [Online]. DOI: 10.1016/j.ocecoaman.2018.06.007.

Buckley, B. M., Fletcher, R., Wang, S.-Y. S., Zottoli, B. and Pottier, C. (2014) "Monsoon extremes and society over the past millennium on mainland Southeast Asia," *Quaternary science reviews*, vol. 95, no. 1, pp. 1–19 [Online]. DOI: 10.1016/j.quascirev.2014.04.022.

Buhl, M. and Markolf, S. (2023) "A review of emerging strategies for incorporating climate change considerations into infrastructure planning, design and decision making," *Sustainable and Resilient Infrastructure*, vol. 8, no. sup1, pp. 157–169 [Online]. DOI: 10.1080/23789689.2022.2134646.

Buma, B., Hayes, K., Weiss, S. and Lucash, M. (2022) "Short-interval fires increasing in the Alaskan boreal forest as fire self-regulation decays across forest types.," *Scientific Reports*, vol. 12, no. 1, p. 4901 [Online]. DOI: 10.1038/s41598-022-08912-8.

Burke, M., Hsiang, S. M. and Miguel, E. (2015) "Climate and Conflict," *Annual review of economics*, vol. 7, no. 1, pp. 577–617 [Online]. DOI: 10.1146/annurev-economics-080614-115430.

Burlig, F. and Preonas, L. (2024) "Out of the Darkness and into the Light? Development Effects of Rural Electrification," *Journal of Political Economy*, vol. 132, no. 9, pp. 2937–2971 [Online]. DOI: 10.1086/730204.

Bury, J. T., Mark, B. G., McKenzie, J. M., French, A., Baraer, M., Huh, K. I., Zapata Luyo, M. A. and Gómez López, R. J. (2011) "Glacier recession and human vulnerability in the Yanamarey watershed of the Cordillera Blanca, Peru," Climatic Change, vol. 105, no. 1–2, pp. 179–206 [Online]. DOI: 10.1007/s10584-010-9870-1.

Bury, T. M., Sujith, R. I., Pavithran, I., Scheffer, M., Lenton, T. M., Anand, M. and Bauch, C. T. (2021) "Deep learning for early warning signals of tipping points.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 118, no. 39 [Online]. DOI: 10.1073/pnas.2106140118.

Butt, E. W., Baker, J. C. A., Bezerra, F. G. S., von Randow, C., Aguiar, A. P. D. and Spracklen, D. V. (2023) "Amazon deforestation causes strong regional warming.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 120, no. 45, p. e2309123120 [Online]. DOI: 10.1073/pnas.2309123120.

Byrne, M., Waller, A., Clements, M., Kelly, A. S., Kingsford, M. J., Liu, B., Reymond, C. E., Vila-Concejo, A., Webb, M., Whitton, K. and Foo, S. A. (2025) "Catastrophic bleaching in protected reefs of the Southern Great Barrier Reef," *Limnology and Oceanography Letters*, vol. 10, no. 3, pp. 340–348 [Online]. DOI: 10.1002/lol2.10456.

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G. and Saba, V. (2018) "Observed fingerprint of a weakening Atlantic Ocean overturning circulation.," *Nature*, vol. 556, no. 7700, pp. 191–196 [Online]. DOI: 10.1038/s41586-018-0006-5.

Cai, W., Borlace, S., Lengaigne, M., van Rensch, P., Collins, M., Vecchi, G., Timmermann, A., Santoso, A., McPhaden, M. J., Wu, L., England, M. H., Wang, G., Guilyardi, E. and Jin, F.-F. (2014) "Increasing frequency of extreme El Niño events due to greenhouse warming," Nature climate change, vol. 4, no. 2, pp. 111–116 [Online]. DOI: 10.1038/nclimate2100.

Cannaby, H. and Hüsrevoğlu, Y. S. (2009) "The influence of low-frequency variability and long-term trends in North Atlantic sea surface temperature on Irish waters," *ICES Journal of Marine Science*, vol. 66, no. 7, pp. 1480–1489 [Online]. DOI: 10.1093/icesjms/fsp062.

Carey, M. (2005) "Living and dying with glaciers: people's historical vulnerability to avalanches and outburst floods in Peru," Global and planetary change, vol. 47, no. 2–4, pp. 122–134 [Online]. DOI: 10.1016/j.gloplacha.2004.10.007.

Cerato, G., Bellomo, K., D'Agostino, R. and von Hardenberg, J. (2025) "Multimodel evidence of future tropical atlantic precipitation change modulated by AMOC decline," *Journal of climate*, vol. 38, no. 13, pp. 3093–3107 [Online]. DOI: 10.1175/JCLI-D-24-0333.1.

Chafik, L., Nilsen, J. E. Ø., Dangendorf, S., Reverdin, G. and Frederikse, T. (2019) "North atlantic ocean circulation and decadal sea level change during the altimetry era.," *Scientific Reports*, vol. 9, no. 1, p. 1041 [Online]. DOI: 10.1038/s41598-018-37603-6.

Chandio, A. A., Jiang, Y., Amin, A., Ahmad, M., Akram, W. and Ahmad, F. (2023) "Climate change and food security of South Asia: fresh evidence from a policy perspective using novel empirical analysis," *Journal of Environmental Planning and Management*, vol. 66, no. 1, pp. 169–190 [Online]. DOI: 10.1080/09640568.2021.1980378.

Chemison, A., Defrance, D., Ramstein, G. and Caminade, C. (2022) "Impact of an acceleration of ice sheet melting on monsoon systems," *Earth System Dynamics*, vol. 13, no. 3, pp. 1259–1287 [Online]. DOI: 10.5194/esd-13-1259-2022.

Chen, C., Liu, W. and Wang, G. (2019) "Understanding the uncertainty in the 21st century dynamic sea level projections: the role of the AMOC," *Geophysical Research Letters*, vol. 46, no. 1, pp. 210–217 [Online]. DOI: 10.1029/2018GL080676.

Chin, K. S., Lento, J., Culp, J. M., Lacelle, D. and Kokelj, S. V. (2016) "Permafrost thaw and intense thermokarst activity decreases abundance of stream benthic macroinvertebrates.," *Global Change Biology*, vol. 22, no. 8, pp. 2715–2728 [Online]. DOI: 10.1111/gcb.13225.

Christensen, M. F., Heaton, M. J., Rupper, S., Reese, C. S. and Christensen, W. F. (2019) "Bayesian Multi-Scale Spatio-Temporal Modeling of Precipitation in the Indus Watershed," *Frontiers in Earth Science*, vol. 7 [Online]. DOI: 10.3389/feart.2019.00210.

Chug, D., Dominguez, F. and Yang, Z. (2022) "The amazon and la plata river basins as moisture sources of south america: climatology and intraseasonal variability," *Journal of Geophysical Research: Atmospheres*, vol. 127, no. 12 [Online]. DOI: 10.1029/2021JD035455.

Ciemer, C., Winkelmann, R., Kurths, J. and Boers, N. (2021) "Impact of an AMOC weakening on the stability of the southern Amazon rainforest," *The European Physical Journal Special Topics*, vol. 230, no. 14–15, pp. 3065–3073 [Online]. DOI: 10.1140/epjs/s11734-021-00186-x.

Cinner, J. E., McClanahan, T. R., Graham, N. A. J., Daw, T. M., Maina, J., Stead, S. M., Wamukota, A., Brown, K. and Bodin, Ö. (2012) "Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries," *Global Environmental Change*, vol. 22, no. 1, pp. 12–20 [Online]. DOI: 10.1016/j.gloenvcha.2011.09.018.

Coe, J. A., Bessette-Kirton, E. K. and Geertsema, M. (2017) "Increasing rock-avalanche size and mobility in Glacier Bay National Park and Preserve, Alaska detected from 1984 to 2016 Landsat imagery," Landslides, vol. 15, no. 3, pp. 1–15 [Online]. DOI: 10.1007/s10346-017-0879-7.

Cooper, S., Cloos, P., Abraham, C., McPherson, N., Ravaliere, T. and Harris-Glenville, F. (2025) "What can be said about risks, vulnerabilities and adaptation to climate change in Caribbean small island developing states (SIDS)? The case of Dominica. A qualitative study," *PLOS Climate*, vol. 4, no. 4, p. e0000275 [Online]. DOI: 10.1371/journal.pclm.0000275.

Creel, R., Guimond, J., Jones, B. M., Nielsen, D. M., Bristol, E., Tweedie, C. E. and Overduin, P. P. (2024) "Permafrost thaw subsidence, sea-level rise and erosion are transforming Alaska's Arctic coastal zone.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 121, no. 50, p. e2409411121 [Online]. DOI: 10.1073/pnas.2409411121.

Croitoru, L., Miranda, J. J. and Sarraf, M. (2019) *The Cost of Coastal Zone Degradation in West Africa*, World Bank Group.

Crona, B. I., Van Holt, T., Petersson, M., Daw, T. M. and Buchary, E. (2015) "Using social–ecological syndromes to understand impacts of international seafood trade on small-scale fisheries," *Global Environmental Change*, vol. 35, pp. 162–175 [Online]. DOI: 10.1016/j.gloenvcha.2015.07.006.

Cruz-Trinidad, A., Aliño, P. M., Geronimo, R. C. and Cabral, R. B. (2014) "Linking Food Security with Coral Reefs and Fisheries in the Coral Triangle," *Coastal Management*, vol. 42, no. 2, pp. 160–182 [Online]. DOI: 10.1080/08920753.2014.877761.

Currie-Alder, B., Rosenzweig, C., Chen, M., Nalau, J., Patwardhan, A. and Wang, Y. (2021) "Research for climate adaptation," *Communications Earth & Environment*, vol. 2, no. 1, p. 220 [Online]. DOI: 10.1038/s43247-021-00294-5.

van Daalen, K. R., Tonne, C., Semenza, J. C., Rocklöv, J., Markandya, A., Dasandi, N., Jankin, S., Achebak, H., Ballester, J., Bechara, H., Beck, T. M., Callaghan, M. W., Carvalho, B. M., Chambers, J., Pradas, M. C., Courtenay, O., Dasgupta, S., Eckelman, M. J., Farooq, Z., Fransson, P. and Lowe, R. (2024) "The 2024 Europe report of the Lancet Countdown on health and climate change: unprecedented warming demands unprecedented action.," *The Lancet. Public health*, vol. 9, no. 7, pp. e495–e522 [Online]. DOI: 10.1016/S2468-2667(24)00055-0.

Dagdeviren, H., Elangovan, A. and Parimalavalli, R. (2021) "Climate change, monsoon failures and inequality of impacts in South India.," *Journal of Environmental Management*, vol. 299, p. 113555 [Online]. DOI: 10.1016/j.jenvman.2021.113555.

Dakos, V., Matthews, B., Hendry, A. P., Levine, J., Loeuille, N., Norberg, J., Nosil, P., Scheffer, M. and De Meester, L. (2019) "Ecosystem tipping points in an evolving world.," *Nature Ecology & Evolution*, vol. 3, no. 3, pp. 355–362 [Online]. DOI: 10.1038/s41559-019-0797-2.

Dasgupta, P. (2021) *The Economics Of Biodiversity: The Dasgupta Review*,.

Davis, K. F., Downs, S. and Gephart, J. A. (2020) "Towards food supply chain resilience to environmental shocks," *Nature Food* [Online]. DOI: 10.1038/s43016-020-00196-3.

Defrance, D., Ramstein, G., Charbit, S., Vrac, M., Famien, A. M., Sultan, B., Swingedouw, D., Dumas, C., Gemenne, F., Alvarez-Solas, J. and Vanderlinden, J.-P. (2017) "Consequences of rapid ice sheet melting on the Sahelian population vulnerability.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 114, no. 25, pp. 6533–6538 [Online]. DOI: 10.1073/pnas.1619358114.

Defrance, D., Sultan, B., Castets, M., Famien, A. M. and Baron, C. (2020) "Impact of climate change in west africa on cereal production per capita in 2050," *Sustainability*, vol. 12, no. 18, p. 7585 [Online]. DOI: 10.3390/su12187585.

Deutsch, C. A., Tewksbury, J. J., Tigchelaar, M., Battisti, D. S., Merrill, S. C., Huey, R. B. and Naylor, R. L. (2018) "Increase in crop losses to insect pests in a warming climate.," *Science*, vol. 361, no. 6405, pp. 916–919 [Online]. DOI: 10.1126/science.aat3466.

Diallo, I., Giorgi, F., Deme, A., Tall, M., Mariotti, L. and Gaye, A. T. (2016) "Projected changes of summer monsoon extremes and hydroclimatic regimes over West Africa for the twenty-first century," *Climate dynamics*, vol. 47, no. 12, pp. 3931–3954 [Online]. DOI: 10.1007/s00382-016-3052-4.

Dietz, S. and Koninx, F. (2022) "Economic impacts of melting of the Antarctic Ice Sheet.," *Nature Communications*, vol. 13, no. 1, p. 5819 [Online]. DOI: 10.1038/s41467-022-33406-6.

Dietz, S., Rising, J., Stoerk, T. and Wagner, G. (2021) "Economic impacts of tipping points in the climate system.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 118, no. 34 [Online]. DOI: 10.1073/pnas.2103081118.

DiNezio, P. N., Shanahan, T. M., Sun, T., Sun, C., Wu, X., Lawman, A., Lea, D., Kageyama, M., Merkel, U., Prange, M., Otto-Bliesner, B. and Zhang, X. (2025) "Tropical response to ocean circulation slowdown raises future drought risk.," *Nature*, vol. 644, no. 8077, pp. 676–683 [Online]. DOI: 10.1038/s41586-025-09319-x.

Dixon, A. M., Forster, P. M., Heron, S. F., Stoner, A. M. K. and Beger, M. (2022) "Future loss of local-scale thermal refugia in coral reef ecosystems," *PLOS Climate*, vol. 1, no. 2, p. e0000004 [Online]. DOI: 10.1371/journal.pclm.0000004.

Domínguez-Tuda, M. and Gutiérrez-Jurado, H. A. (2024) "Global analysis of forest tipping points leading to changing water cycle dynamics," *Journal of Hydrology X*, vol. 25, p. 100187 [Online]. DOI: 10.1016/j.hydroa.2024.100187.

Dowdeswell, J. A. (2006) "Atmospheric science. The Greenland Ice Sheet and global sea-level rise.," *Science*, vol. 311, no. 5763, pp. 963–964 [Online]. DOI: 10.1126/science.1124190.

Drewnik, A., Węsławski, J. M., Włodarska-Kowalczuk, M., Łącka, M., Promińska, A., Zaborska, A. and Gluchowska, M. (2016) "From the worm's point of view. I: Environmental settings of benthic ecosystems in Arctic fjord (Hornsund, Spitsbergen)," *Polar Biology*, vol. 39, no. 8, pp. 1411–1424 [Online]. DOI: 10.1007/s00300-015-1867-9.

Drijfhout, S. (2015) "Competition between global warming and an abrupt collapse of the AMOC in Earth's energy imbalance.," *Scientific Reports*, vol. 5, p. 14877 [Online]. DOI: 10.1038/srep14877.

Drijfhout, S. S. (2015) "Global radiative adjustment after a collapse of the Atlantic meridional overturning circulation," *Climate dynamics*, vol. 45, no. 7–8, pp. 1789–1799 [Online]. DOI: 10.1007/s00382-014-2433-9.

Duijndam, S. J., Botzen, W. J. W., Hagedoorn, L. C., Ton, M., de Bruijn, J., Carretero, S., Dachary-Bernard, J., Rulleau, B. and Aerts, J. C. J. H. (2025) "Global determinants of coastal migration under climate change.," *Nature Communications*, vol. 16, no. 1, p. 6866 [Online]. DOI: 10.1038/s41467-025-59199-y.

Dutton, A., Carlson, A. E., Long, A. J., Milne, G. A., Clark, P. U., DeConto, R., Horton, B. P., Rahmstorf, S. and Raymo, M. E. (2015) "SEA-LEVEL RISE. Sea-level rise due to polar ice-sheet mass loss during past warm periods.," *Science*, vol. 349, no. 6244, p. aaa4019 [Online]. DOI: 10.1126/science.aaa4019.

Du, Y., Brown, J. R., Menviel, L., Saini, H. and Drysdale, R. N. (2025) "The impacts of an AMOC slowdown on southern hemisphere and australian climates at 8.2 ka in ACCESS-ESM1.5 model," *Journal of Geophysical Research: Atmospheres*, vol. 130, no. 8 [Online]. DOI: 10.1029/2024JD042432.

Dylewsky, D., Lenton, T. M., Scheffer, M., Bury, T. M., Fletcher, C. G., Anand, M. and Bauch, C. T. (2023) "Universal early warning signals of phase transitions in climate systems.," *Journal of the Royal Society, Interface*, vol. 20, no. 201, p. 20220562 [Online]. DOI: 10.1098/rsif.2022.0562.

Ebi, K. L., Capon, A., Berry, P., Broderick, C., de Dear, R., Havenith, G., Honda, Y., Kovats, R. S., Ma, W., Malik, A., Morris, N. B., Nybo, L., Seneviratne, S. I., Vanos, J. and Jay, O. (2021) "Hot weather and heat extremes: health risks.," *The Lancet*, vol. 398, no. 10301, pp. 698–708 [Online]. DOI: 10.1016/S0140-6736(21)01208-3.

Ebi, K. L., Vanos, J., Baldwin, J. W., Bell, J. E., Hondula, D. M., Errett, N. A., Hayes, K., Reid, C. E., Saha, S., Spector, J. and Berry, P. (2021) "Extreme weather and climate change: population health and health system implications.," *Annual review of public health*, vol. 42, pp. 293–315 [Online]. DOI: 10.1146/annurev-publhealth-012420-105026.

Eckdahl, J. A., Kristensen, J. A. and Metcalfe, D. B. (2023) "Climate and forest properties explain wildfire impact on microbial community and nutrient mobilization in boreal soil," *Frontiers in Forests and Global Change*, vol. 6 [Online]. DOI: 10.3389/ffgc.2023.1136354.

Eladawy, A., Nakamura, T., Shaltout, M., Mohammed, A., Nadaoka, K., Fox, M. D. and Osman, E. O. (2022) "Appraisal of coral bleaching thresholds and thermal projections for the northern Red Sea refugia," *Frontiers in Marine Science*, vol. 9 [Online]. DOI: 10.3389/fmars.2022.938454.

El Garroussi, S., Di Giuseppe, F., Barnard, C. and Wetterhall, F. (2024) "Europe faces up to tenfold increase in extreme fires in a warming climate," *npj Climate and Atmospheric Science*, vol. 7, no. 1, p. 30 [Online]. DOI: 10.1038/s41612-024-00575-8.

Ezer, T., Atkinson, L. P., Corlett, W. B. and Blanco, J. L. (2013) "Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast," *Journal of Geophysical Research: Oceans*, vol. 118, no. 2, pp. 685–697 [Online]. DOI: 10.1002/jgrc.20091.

Fanzo, J., de Steenhuijsen Piters, B., Soto-Caro, A., Saint Ville, A., Mainuddin, M. and Battersby, J. (2024) "Global and local perspectives on food security and food systems," *Communications Earth & Environment*, vol. 5, no. 1, p. 227 [Online]. DOI: 10.1038/s43247-024-01398-4.

Fekete, A. and Nehren, U. (2024) "Climate change increased risk of forest fire, winter storm and technical failure risks related to power transmission lines – a spatial GIS risk assessment at Cologne district, Germany," *Progress in Disaster Science*, vol. 24, p. 100387 [Online]. DOI: 10.1016/j.pdisas.2024.100387.

Fiaz, A., Rahman, G. and Kwon, H.-H. (2025) "Impacts of climate change on the South Asian monsoon: A comprehensive review of its variability and future projections," *Journal of Hydro-environment Research*, vol. 59, p. 100654 [Online]. DOI: 10.1016/j.jher.2025.100654.

Ficchì, A., Cloke, H., Neves, C., Woolnough, S., Coughlan de Perez, E., Zsoter, E., Pinto, I., Meque, A. and Stephens, E. (2021) "Beyond El Niño: Unsung climate modes drive African floods," *Weather and Climate Extremes*, vol. 33, p. 100345 [Online]. DOI: 10.1016/j.wace.2021.100345.

Field, C. B., Barros, V., Stocker, T. F. and Dahe, Q. (eds.) (2012) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*, Cambridge, Cambridge University Press [Online]. DOI: 10.1017/CBO9781139177245.

Fine, M., Gildor, H. and Genin, A. (2013) "A coral reef refuge in the Red Sea.," *Global Change Biology*, vol. 19, no. 12, pp. 3640–3647 [Online]. DOI: 10.1111/gcb.12356.

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T. and Rockström, J. (2010) "Resilience thinking: integrating resilience, adaptability and transformability," *Ecology & Society*, vol. 15, no. 4 [Online]. DOI: 10.5751/ES-03610-150420.

Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., Scheffer, M., Österblom, H., Carpenter, S. R., Chapin, F. S., Seto, K. C., Weber, E. U., Crona, B. I., Daily, G. C., Dasgupta, P., Gaffney, O., Gordon, L. J., Hoff, H., Levin, S. A., Lubchenco, J. and Walker, B. H. (2021) "Our future in the Anthropocene biosphere.," *Ambio*, vol. 50, no. 4, pp. 834–869 [Online]. DOI: 10.1007/s13280-021-01544-8.

Fu, W., Tian, L., Tao, Y., Li, M. and Guo, H. (2023) "Spatiotemporal changes in the boreal forest in Siberia over the period 1985–2015 against the background of climate change," *Earth System Dynamics*, vol. 14, no. 1, pp. 223–239 [Online]. DOI: 10.5194/esd-14-223-2023.

Gao, H., Wang, J., Yang, Y., Pan, X., Ding, Y. and Duan, Z. (2021) "Permafrost Hydrology of the Qinghai-Tibet Plateau: A Review of Processes and Modeling," *Frontiers in Earth Science*, vol. 8 [Online]. DOI: 10.3389/feart.2020.576838.

Gauthier, S., Bernier, P., Kuuluvainen, T., Shvidenko, A. Z. and Schepaschenko, D. G. (2015) "Boreal forest health and global change.," *Science*, vol. 349, no. 6250, pp. 819–822 [Online]. DOI: 10.1126/science.aaa9092.

Gesualdo, G. C., Benso, M. R., Mendiondo, E. M. and Brunner, M. I. (2024) "Spatially compounding drought events in brazil," *Water resources research*, vol. 60, no. 11 [Online]. DOI: 10.1029/2023WR036629.

Gibson, C. M., Brinkman, T., Cold, H., Brown, D. and Turetsky, M. (2021) "Identifying increasing risks of hazards for northern land-users caused by permafrost thaw: integrating scientific and community-based research approaches," *Environmental Research Letters*, vol. 16, no. 6, p. 064047 [Online]. DOI: 10.1088/1748-9326/abfc79.

Gilman, E. L., Ellison, J., Duke, N. C. and Field, C. (2008) "Threats to mangroves from climate change and adaptation options: A review," *Aquatic Botany*, vol. 89, no. 2, pp. 237–250 [Online]. DOI: 10.1016/j.aquabot.2007.12.009.

Gingerich, S. B., Voss, C. I. and Johnson, A. G. (2017) "Seawater-flooding events and impact on freshwater lenses of low-lying islands: Controlling factors, basic management and mitigation," *Journal of hydrology*, vol. 551, pp. 676–688 [Online]. DOI: 10.1016/j.jhydrol.2017.03.001.

Goddard, P. B., Yin, J., Griffies, S. M. and Zhang, S. (2015) "An extreme event of sea-level rise along the Northeast Coast of North America in 2009-2010.," *Nature Communications*, vol. 6, p. 6346 [Online]. DOI: 10.1038/ncomms7346.

Golledge, N. R. (2020) "Long-term projections of sea-level rise from ice sheets," *Wiley Interdisciplinary Reviews: Climate Change*, vol. 11, no. 2 [Online]. DOI: 10.1002/wcc.634.

Good, P., Boers, N., Boulton, C. A., Lowe, J. A. and Richter, I. (2022) "How might a collapse in the Atlantic Meridional Overturning Circulation affect rainfall over tropical South America?," *Climate Resilience and Sustainability*, vol. 1, no. 1 [Online]. DOI: 10.1002/cli2.26.

Goreau, T. J. F. and Hayes, R. L. (2024) "2023 Record marine heat waves: coral reef bleaching HotSpot maps reveal global sea surface temperature extremes, coral mortality and ocean circulation changes," *Oxford Open Climate Change*, vol. 4, no. 1 [Online]. DOI: 10.1093/oxfclm/kgae005.

Griggs, G. and Reguero, B. G. (2021) "Coastal Adaptation to Climate Change and Sea-Level Rise," *Water*, vol. 13, no. 16, p. 2151 [Online]. DOI: 10.3390/w13162151.

Guannel, G., Arkema, K., Ruggiero, P. and Verutes, G. (2016) "The power of three: coral reefs, seagrasses and mangroves protect coastal regions and increase their resilience.," *Plos One*, vol. 11, no. 7, p. e0158094 [Online]. DOI: 10.1371/journal.pone.0158094.

Gupta, S., Su, Z., Boers, N., Kurths, J., Marwan, N. and Pappenberger, F. (2023) "Interconnection between the Indian and the East Asian summer monsoon: Spatial synchronization patterns of extreme rainfall events," *International Journal of Climatology*, vol. 43, no. 2, pp. 1034–1049 [Online]. DOI: 10.1002/joc.7861.

Haarsma, R. J., Selten, F. M. and Drijfhout, S. S. (2015) "Decelerating Atlantic meridional overturning circulation main cause of future west European summer atmospheric circulation changes," *Environmental Research Letters*, vol. 10, no. 9, p. 094007 [Online]. DOI: 10.1088/1748-9326/10/9/094007.

Hallegatte, S. and Walsh, B. (2021) "Natural disasters, poverty and inequality," in *The routledge handbook of the political economy of the environment*, London, Routledge, pp. 111–131 [Online]. DOI: 10.4324/9780367814533-10.

Harvey, N. and Nicholls, R. (2008) "Global sea-level rise and coastal vulnerability," *Sustainability Science*, vol. 3, no. 1, pp. 5–7 [Online]. DOI: 10.1007/s11625-008-0049-x.

Hasegawa, T., Wakatsuki, H. and Nelson, G. C. (2022) "Evidence for and projection of multi-breadbasket failure caused by climate change," *Current Opinion in Environmental Sustainability*, vol. 58, p. 101217 [Online]. DOI: 10.1016/j.cosust.2022.101217.

Hauer, M. E., Evans, J. M. and Mishra, D. R. (2016) "Millions projected to be at risk from sea-level rise in the continental United States," *Nature climate change*, vol. 6, no. 7, pp. 691–695 [Online]. DOI: 10.1038/nclimate2961.

Hawchar, L., Naughton, O., Nolan, P., Stewart, M. G. and Ryan, P. C. (2020) "A GIS-based framework for high-level climate change risk assessment of critical infrastructure," *Climate Risk Management*, vol. 29, p. 100235 [Online]. DOI: 10.1016/j.crm.2020.100235.

Heidemann, H., Cowan, T., Henley, B. J., Ribbe, J., Freund, M. and Power, S. (2023) "Variability and long-term change in Australian monsoon rainfall: A review," *WIREs Climate Change*, vol. 14, no. 3 [Online]. DOI: 10.1002/wcc.823.

Heidemann, H., Ribbe, J., Cowan, T., Henley, B. J., Pudmenzky, C., Stone, R. and Cobon, D. H. (2022) "The Influence of Interannual and Decadal Indo-Pacific Sea Surface Temperature Variability on Australian Monsoon Rainfall," *Journal of climate*, vol. 35, no. 1, pp. 425–444 [Online]. DOI: 10.1175/JCLI-D-21-0264.1.

Held, I. M., Delworth, T. L., Lu, J., Findell, K. L. and Knutson, T. R. (2005) "Simulation of Sahel drought in the 20th and 21st centuries.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 102, no. 50, pp. 17891–17896 [Online]. DOI: 10.1073/pnas.0509057102.

Henley, B. J., McGregor, H. V., King, A. D., Hoegh-Guldberg, O., Arzey, A. K., Karoly, D. J., Lough, J. M., DeCarlo, T. M. and Linsley, B. K. (2024) "Highest ocean heat in four centuries places Great Barrier Reef in danger.," *Nature*, vol. 632, no. 8024, pp. 320–326 [Online]. DOI: 10.1038/s41586-024-07672-x.

Hicks, C. C., Cohen, P. J., Graham, N. A. J., Nash, K. L., Allison, E. H., D'Lima, C., Mills, D. J., Roscher, M., Thilsted, S. H., Thorne-Lyman, A. L. and MacNeil, M. A. (2019) "Harnessing global fisheries to tackle micronutrient deficiencies.," *Nature*, vol. 574, pp. 95–98 [Online]. DOI: 10.1038/s41586-019-1592-6.

Higgins, P. A., Palmer, J. G., Rao, M. P., Andersen, M. S., Turney, C. S. M. and Johnson, F. (2022) "Unprecedented high northern australian streamflow linked to an intensification of the indo-australian monsoon," *Water resources research*, vol. 58, no. 3 [Online]. DOI: 10.1029/2021WR030881.

Higman, B., Shugar, D. H., Stark, C. P., Ekström, G., Koppes, M. N., Lynett, P., Dufresne, A., Haeussler, P. J., Geertsema, M., Gulick, S., Mattox, A., Venditti, J. G., Walton, M. A. L., McCall, N., Mckittrick, E., MacInnes, B., Bilderback, E. L., Tang, H., Willis, M. J., Richmond, B. and Loso, M. (2018) "The 2015 landslide and tsunami in Taan Fiord, Alaska.," Scientific Reports, vol. 8, no. 1, p. 12993 [Online]. DOI: 10.1038/s41598-018-30475-w.

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J., Tol, R. S. J., Marzeion, B., Fettweis, X., Ionescu, C. and Levermann, A. (2014) "Coastal flood damage and adaptation costs under 21st century sea-level rise.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 111, no. 9, pp. 3292–3297 [Online]. DOI: 10.1073/pnas.1222469111.

Hjort, J., Streletskiy, D., Doré, G., Wu, Q., Bjella, K. and Luoto, M. (2022) "Impacts of permafrost degradation on infrastructure," *Nature Reviews Earth & Environment*, vol. 3, no. 1, pp. 24–38 [Online]. DOI: 10.1038/s43017-021-00247-8.

Hoffmann, R., Abel, G., Malpede, M., Muttarak, R. and Percoco, M. (2024) "Drought and aridity influence internal migration worldwide," *Nature Climate Change*, vol. 14, no. 12, pp. 1245–1253 [Online]. DOI: 10.1038/s41558-024-02165-1.

van Hooidonk, R., Maynard, J. A. and Planes, S. (2013) "Temporary refugia for coral reefs in a warming world," *Nature climate change*, vol. 3, no. 5, pp. 508–511 [Online]. DOI: 10.1038/nclimate1829.

Hossain, B., Sohel, Md. S. and Ryakitimbo, C. M. (2020) "Climate change induced extreme flood disaster in Bangladesh: Implications on people's livelihoods in the Char Village and their coping mechanisms," *Progress in Disaster Science*, vol. 6, p. 100079 [Online]. DOI: 10.1016/j.pdisas.2020.100079.

Howard, T., Palmer, M. D., Jackson, L. C. and Yamazaki, K. (2024) "Storm surge changes around the UK under a weakened Atlantic meridional overturning circulation," *Environmental Research Communications*, vol. 6, no. 3, p. 035026 [Online]. DOI: 10.1088/2515-7620/ad3368.

Hsiang, S. M., Meng, K. C. and Cane, M. A. (2011) "Civil conflicts are associated with the global climate.," *Nature*, vol. 476, no. 7361, pp. 438–441 [Online]. DOI: 10.1038/nature10311.

Hsiang, S. M. (2010) "Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 107, no. 35, pp. 15367–15372 [Online]. DOI: 10.1073/pnas.1009510107.

Hsiao, S.-C., Chiang, W.-S., Jang, J.-H., Wu, H.-L., Lu, W.-S., Chen, W.-B. and Wu, Y.-T. (2021) "Flood risk influenced by the compound effect of storm surge and rainfall under climate change for low-lying coastal areas.," *The Science of the Total Environment*, vol. 764, p. 144439 [Online]. DOI: 10.1016/j.scitotenv.2020.144439.

Hughes, T. P., Anderson, K. D., Connolly, S. R., Heron, S. F., Kerry, J. T., Lough, J. M., Baird, A. H., Baum, J. K., Berumen, M. L., Bridge, T. C., Claar, D. C., Eakin, C. M., Gilmour, J. P., Graham, N. A. J., Harrison, H., Hobbs, J.-P. A., Hoey, A. S., Hoogenboom, M., Lowe, R. J., McCulloch, M. T. and Wilson, S. K. (2018) "Spatial and temporal patterns of mass bleaching of corals in the Anthropocene.," *Science*, vol. 359, no. 6371, pp. 80–83 [Online]. DOI: 10.1126/science.aan8048.

Hughes, T. P., Barnes, M. L., Bellwood, D. R., Cinner, J. E., Cumming, G. S., Jackson, J. B. C., Kleypas, J., van de Leemput, I. A., Lough, J. M., Morrison, T. H., Palumbi, S. R., van Nes, E. H. and Scheffer, M. (2017) "Coral reefs in the Anthropocene.," *Nature*, vol. 546, no. 7656, pp. 82–90 [Online]. DOI: 10.1038/nature22901.

Hughes, T. P., Kerry, J. T., Baird, A. H., Connolly, S. R., Dietzel, A., Eakin, C. M., Heron, S. F., Hoey, A. S., Hoogenboom, M. O., Liu, G., McWilliam, M. J., Pears, R. J., Pratchett, M. S., Skirving, W. J., Stella, J. S. and Torda, G. (2018) "Global warming transforms coral reef assemblages.," *Nature*, vol. 556, no. 7702, pp. 492–496 [Online]. DOI: 10.1038/s41586-018-0041-2.

Hülsen, S., Dee, L. E., Kropf, C. M., Meiler, S. and Bresch, D. N. (2025) "Mangroves and their services are at risk from tropical cyclones and sea level rise under climate change," *Communications Earth & Environment*, vol. 6, no. 1, p. 262 [Online]. DOI: 10.1038/s43247-025-02242-z.

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., Nepal, S. and Baillie, J. E. M. (2020) "Importance and vulnerability of the world's water towers.," Nature, vol. 577, no. 7790, pp. 364–369 [Online]. DOI: 10.1038/s41586-019-1822-y.

Intergovernmental Panel on Climate Change (ed.) (2014) "Climate Phenomena and their Relevance for Future Regional Climate Change," in *Climate Change 2013 - The Physical Science Basis*, Cambridge, Cambridge University Press, pp. 1217–1308 [Online]. DOI: 10.1017/CBO9781107415324.028.

International Rescue Committee. (2023) *The Central Sahel: How conflict and climate change drive crisis* [Online]. Available at https://www.rescue.org/article/central-sahel-how-conflict-and-climate-change-drive-crisis (Accessed 4 September 2025).

IPCC (2018) *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development and efforts to eradicate poverty* , Cambridge University Press,.

IPCC (2022) *Climate change 2022 – impacts, adaptation and vulnerability*, Pörtner, H. O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A. and Rama, B. (eds), Contribution of Working Group II to the Sixth Assessment Report of theIntergovernmental Panel on Climate Change, Cambridge University Press [Online]. DOI: 10.1017/9781009325844.

Islam, Md. T., Hossain, Md. M., Ha-Mim, N. M., Hossain, Md. Z. and Sikder, S. K. (2025) "Climate change impacts on shoreline migration and community livelihood resilience: evidence from coastal Bangladesh," *Frontiers in Sustainability*, vol. 5 [Online]. DOI: 10.3389/frsus.2024.1525483.

Jackson, L. C., Alastrué de Asenjo, E., Bellomo, K., Danabasoglu, G., Haak, H., Hu, A., Jungclaus, J., Lee, W., Meccia, V. L., Saenko, O., Shao, A. and Swingedouw, D. (2023) "Understanding AMOC stability: the North Atlantic Hosing Model Intercomparison Project," *Geoscientific Model Development*, vol. 16, no. 7, pp. 1975–1995 [Online]. DOI: 10.5194/gmd-16-1975-2023.

Jackson, L. C., Kahana, R., Graham, T., Ringer, M. A., Woollings, T., Mecking, J. V. and Wood, R. A. (2015) "Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM," *Climate dynamics*, vol. 45, no. 11–12, pp. 3299–3316 [Online]. DOI: 10.1007/s00382-015-2540-2.

Jin, X.-Y., Jin, H.-J., Iwahana, G., Marchenko, S. S., Luo, D.-L., Li, X.-Y. and Liang, S.-H. (2021) "Impacts of climate-induced permafrost degradation on vegetation: A review," *Advances in Climate Change Research*, vol. 12, no. 1, pp. 29–47 [Online]. DOI: 10.1016/j.accre.2020.07.002.

Jones, B. M., Grosse, G., Arp, C. D., Miller, E., Liu, L., Hayes, D. J. and Larsen, C. F. (2015) "Recent Arctic tundra fire initiates widespread thermokarst development.," *Scientific Reports*, vol. 5, p. 15865 [Online]. DOI: 10.1038/srep15865.

Jones, P. G. and Thornton, P. K. (2009) "Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change," *Environmental Science & Policy*, vol. 12, no. 4, pp. 427–437 [Online]. DOI: 10.1016/j.envsci.2008.08.006.

JRC (2025a) *Earth system tipping points are a threat to Europe – how to get prepared?* , Joint Research Centre Policy Brief., Publications Office of the European Union.

JRC (2025b) *Infrastructure risk and adaptation in permafrost regions*. , European Commission, Joint Research Centre.

Kaldorf, M. and Rottner, M. (2024) *Climate Minsky Moments and endogenous financial crises* , Frankfurt a. M., Deutsche Bundesbank.

van der Kamp, A. A. W., Triginer, V. G. and Sen, A. (2025) "Billefjorden's benthic biodiversity: the impact of glacier retreat on faunal communities in a high Arctic fjord," *Polar Biology*, vol. 48, no. 3, p. 71 [Online]. DOI: 10.1007/s00300-025-03390-w.

Keen, S. (2020) "The appallingly bad neoclassical economics of climate change," *Globalizations*, pp. 1–29 [Online]. DOI: 10.1080/14747731.2020.1807856.

Kelly, J., Kljun, N., Cai, Z., Doerr, S. H., D'Onofrio, C., Holst, T., Lehner, I., Lindroth, A., Thapa, S., Vestin, P. and Santín, C. (2024) "Wildfire impacts on the carbon budget of a managed Nordic boreal forest," *Agricultural and Forest Meteorology*, vol. 351, p. 110016 [Online]. DOI: 10.1016/j.agrformet.2024.110016.

Kelly, S., Popova, E., Yool, A., Jebri, F., Oliver, S. and Srokosz, M. (2025) "Abrupt changes in the timing and magnitude of the north atlantic bloom over the 21st century," *Journal of Geophysical Research: Oceans*, vol. 130, no. 3 [Online]. DOI: 10.1029/2024JC022284.

Kenyon, T. M., Doropoulos, C., Wolfe, K., Webb, G. E., Dove, S., Harris, D. and Mumby, P. J. (2023) "Coral rubble dynamics in the Anthropocene and implications for reef recovery," *Limnology and oceanography*, vol. 68, no. 1, pp. 110–147 [Online]. DOI: 10.1002/lno.12254.

Kenyon, T. M., Harris, D., Baldock, T., Callaghan, D., Doropoulos, C., Webb, G., Newman, S. P. and Mumby, P. J. (2023) "Mobilisation thresholds for coral rubble and consequences for windows of reef recovery," *Biogeosciences*, vol. 20, no. 20, pp. 4339–4357 [Online]. DOI: 10.5194/bg-20-4339-2023.

Keuper, F., Bodegom, P. M., Dorrepaal, E., Weedon, J. T., Hal, J., Logtestijn, R. S. P. and Aerts, R. (2012) "A frozen feast: thawing permafrost increases plant-available nitrogen in subarctic peatlands," *Glob Change Biol*, vol. 18, no. 6, pp. 1998–2007 [Online]. DOI: 10.1111/j.1365-2486.2012.02663.x.

Kim, I.-W., Timmermann, A., Kim, J.-E., Rodgers, K. B., Lee, S.-S., Lee, H. and Wieder, W. R. (2024) "Abrupt increase in Arctic-Subarctic wildfires caused by future permafrost thaw.," *Nature Communications*, vol. 15, no. 1, p. 7868 [Online]. DOI: 10.1038/s41467-024-51471-x.

Kipo-Sunyehzi, D. D. and Lambon, P. J. (2025) "Military coups in west africa," *Africa Review*, vol. 17, no. 3, pp. 237–250 [Online]. DOI: 10.1163/09744061-bja10259.

Klose, A. K., Wunderling, N., Winkelmann, R. and Donges, J. F. (2021) "What do we mean, 'tipping cascade'?," *Environmental Research Letters*, vol. 16, no. 12, p. 125011 [Online]. DOI: 10.1088/1748-9326/ac3955.

Kopecky, Kai L., Pavoni, G., Nocerino, E., Brooks, A. J., Corsini, M., Menna, F., Gallagher, J. P., Capra, A., Castagnetti, C., Rossi, P., Gruen, A., Neyer, F., Muntoni, A., Ponchio, F., Cignoni, P., Troyer, M., Holbrook, S. J. and Schmitt, R. J. (2023) "Quantifying the Loss of Coral from a Bleaching Event Using Underwater Photogrammetry and AI-Assisted Image Segmentation," *Remote Sensing*, vol. 15, no. 16, p. 4077 [Online]. DOI: 10.3390/rs15164077.

Kopecky, Kai L, Stier, A. C., Schmitt, R. J., Holbrook, S. J. and Moeller, H. V. (2023) "Material legacies can degrade resilience: Structure-retaining disturbances promote regime shifts on coral reefs.," *Ecology*, vol. 104, no. 4, p. e4006 [Online]. DOI: 10.1002/ecy.4006.

Kopp, R. E., DeConto, R. M., Bader, D. A., Hay, C. C., Horton, R. M., Kulp, S., Oppenheimer, M., Pollard, D. and Strauss, B. H. (2017) "Evolving Understanding of Antarctic Ice-Sheet Physics and Ambiguity in Probabilistic Sea-Level Projections," *Earth's Future*, vol. 5, no. 12, pp. 1217–1233 [Online]. DOI: 10.1002/2017EF000663.

Kopp, R. E., Horton, R. M., Little, C. M., Mitrovica, J. X., Oppenheimer, M., Rasmussen, D. J., Strauss, B. H. and Tebaldi, C. (2014) "Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites," *Earth's Future*, vol. 2, no. 8, pp. 383–406 [Online]. DOI: 10.1002/2014EF000239.

Kornhuber, K., Lesk, C., Schleussner, C. F., Jägermeyr, J., Pfleiderer, P. and Horton, R. M. (2023) "Risks of synchronized low yields are underestimated in climate and crop model projections.," *Nature Communications*, vol. 14, no. 1, p. 3528 [Online]. DOI: 10.1038/s41467-023-38906-7.

Körper, J., Spangehl, T., Cubasch, U. and Huebener, H. (2009) "Decomposition of projected regional sea level rise in the North Atlantic and its relation to the AMOC," *Geophysical Research Letters*, vol. 36, no. 19 [Online]. DOI: 10.1029/2009GL039757.

Koul, V., Tesdal, J.-E., Bersch, M., Hátún, H., Brune, S., Borchert, L., Haak, H., Schrum, C. and Baehr, J. (2020) "Unraveling the choice of the north Atlantic subpolar gyre index.," *Scientific Reports*, vol. 10, no. 1, p. 1005 [Online]. DOI: 10.1038/s41598-020-57790-5.

Kousky, C., Treuer, G. and Mach, K. J. (2024) "Insurance and climate risks: Policy lessons from three bounding scenarios.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 121, no. 48, p. e2317875121 [Online]. DOI: 10.1073/pnas.2317875121.

Kovats, R. S. and Hajat, S. (2008) "Heat Stress and Public Health: a Critical Review," *Annual review of public health*, vol. 29, pp. 41–55 [Online]. DOI: 10.1146/annurev.publhealth.29.020907.090843.

Kug, J.-S., Oh, J.-H., An, S.-I., Yeh, S.-W., Min, S.-K., Son, S.-W., Kam, J., Ham, Y.-G. and Shin, J. (2022) "Hysteresis of the intertropical convergence zone to CO2 forcing," *Nature Climate Change*, vol. 12, no. 1, pp. 47–53 [Online]. DOI: 10.1038/s41558-021-01211-6.

Lal, R., Sivakumar, M. V. K., Faiz, S. M. A., Mustafizur Rahman, A. H. M. and Islam, K. R. (eds.) (2011) *Climate change and food security in south asia*, Dordrecht, Springer Netherlands [Online]. DOI: 10.1007/978-90-481-9516-9.

Langer, M., von Deimling, T. S., Westermann, S., Rolph, R., Rutte, R., Antonova, S., Rachold, V., Schultz, M., Oehme, A. and Grosse, G. (2023) "Thawing permafrost poses environmental threat to thousands of sites with legacy industrial contamination.," *Nature Communications*, vol. 14, no. 1, p. 1721 [Online]. DOI: 10.1038/s41467-023-37276-4.

Lapola, D. M., Pinho, P., Quesada, C. A., Strassburg, B. B. N., Rammig, A., Kruijt, B., Brown, F., Ometto, J. P. H. B., Premebida, A., Marengo, J. A., Vergara, W. and Nobre, C. A. (2018) "Limiting the high impacts of Amazon forest dieback with no-regrets science and policy action.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 115, no. 46, pp. 11671–11679 [Online]. DOI: 10.1073/pnas.1721770115.

Larémont, R. R. (2021) "Climate change and conflict in the western sahel," *African studies review*, vol. 64, no. 4, pp. 748–759 [Online]. DOI: 10.1017/asr.2021.114.

Lawrence, J., Blackett, P. and Cradock-Henry, N. A. (2020) "Cascading climate change impacts and implications," *Climate Risk Management*, vol. 29, p. 100234 [Online]. DOI: 10.1016/j.crm.2020.100234.

Laybourn, L., Abrams, J. F., Benton, D., Brown, K., Evans, J., Elliott, J., Swingedouw, D., Lenton, T. M. and Dyke, J. G. (2024) *The security blind spot: Cascading climate impacts and tipping points threaten national security* , IPPR, the Institute for Public Policy Research.

Leal Filho, W., Dinis, M. A. P., Canova, M. A., Cataldi, M., da Costa, G. A. S., Enrich-Prast, A., Symeonakis, E. and Brearley, F. Q. (2025) "Managing ecosystem services in the Brazilian Amazon: the influence of deforestation and forest degradation in the world's largest rain forest," *Geoscience Letters*, vol. 12, no. 1, p. 24 [Online]. DOI: 10.1186/s40562-025-00391-9.

Leal Filho, W., Krishnapillai, M., Sidsaph, H., Nagy, G. J., Luetz, J. M., Dyer, J., Otoara Ha'apio, M., Havea, P. H., Raj, K., Singh, P., Rogers, T., Li, C., Boodhan, M. K., Wolf, F., Yayeh Ayal, D. and Azadi, H. (2021) "Climate change adaptation on small island states: an assessment of limits and constraints," *JOURNAL of MATHEMATICS SCIENCE and EDUCATION*, vol. 9, no. 6, p. 602 [Online]. DOI: 10.3390/jmse9060602.

Lehmann, J., Coumou, D., Frieler, K., Eliseev, A. V. and Levermann, A. (2014) "Future changes in extratropical storm tracks and baroclinicity under climate change," *Environmental Research Letters*, vol. 9, no. 8, p. 084002 [Online]. DOI: 10.1088/1748-9326/9/8/084002.

Lenton, T. M., Abrams, J. F., Bartsch, A., Bathiany, S., Boulton, C. A., Buxton, J. E., Conversi, A., Cunliffe, A. M., Hebden, S., Lavergne, T., Poulter, B., Shepherd, A., Smith, T., Swingedouw, D., Winkelmann, R. and Boers, N. (2024) "Remotely sensing potential climate change tipping points across scales.," *Nature Communications*, vol. 15, no. 1, p. 343 [Online]. DOI: 10.1038/s41467-023-44609-w.

Lenton, T. M., Armstrong McKay, D. I., Loriani, S., Abrams, J. F., Lade, S. J., Donges, J. F., Milkoreit, M., Powell, T., Smith, S. R., Zimm, C., Buxton, J. E., Bailey, E., Laybourn, L., Ghadiali, A. and Dyke, J. G. (2023) *The Global Tipping Points Report 2023*, Exeter, UK, University of Exeter.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S. and Schellnhuber, H. J. (2008) "Tipping elements in the Earth's climate system.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 105, no. 6, pp. 1786–1793 [Online]. DOI: 10.1073/pnas.0705414105.

Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W. and Schellnhuber, H. J. (2019) "Climate tipping points - too risky to bet against.," *Nature*, vol. 575, no. 7784, pp. 592–595 [Online]. DOI: 10.1038/d41586-019-03595-0.

Levermann, A., Griesel, A., Hofmann, M., Montoya, M. and Rahmstorf, S. (2005) "Dynamic sea level changes following changes in the thermohaline circulation," *Climate dynamics*, vol. 24, no. 4, pp. 347–354 [Online]. DOI: 10.1007/s00382-004-0505-y.

Liu, T., Chen, Dean, Yang, L., Meng, J., Wang, Z., Ludescher, J., Fan, J., Yang, S., Chen, Deliang, Kurths, J., Chen, X., Havlin, S. and Schellnhuber, H. J. (2023) "Teleconnections among tipping elements in the Earth system," *Nature Climate Change* [Online]. DOI: 10.1038/s41558-022-01558-4.

Li, J., Wang, G., Li, K., Li, Y., Guo, L. and Song, C. (2023) "Impacts of climate change and freeze–thaw cycles on water and sediment fluxes in the headwater region of the Yangtze River, Qinghai–Tibet Plateau," *CATENA*, vol. 227, p. 107112 [Online]. DOI: 10.1016/j.catena.2023.107112.

Loo, Y. Y., Billa, L. and Singh, A. (2015) "Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia," *Geoscience Frontiers*, vol. 6, no. 6, pp. 817–823 [Online]. DOI: 10.1016/j.gsf.2014.02.009.

Lynch-Stieglitz, J. (2017) "The atlantic meridional overturning circulation and abrupt climate change.," *Annual review of marine science*, vol. 9, pp. 83–104 [Online]. DOI: 10.1146/annurev-marine-010816-060415.

Mach, K. J., Kraan, C. M., Adger, W. N., Buhaug, H., Burke, M., Fearon, J. D., Field, C. B., Hendrix, C. S., Maystadt, J.-F., O'Loughlin, J., Roessler, P., Scheffran, J., Schultz, K. A. and von Uexkull, N. (2019) "Climate as a risk factor for armed conflict.," *Nature*, vol. 571, no. 7764, pp. 193–197 [Online]. DOI: 10.1038/s41586-019-1300-6.

Mackelprang, R., Barbato, R. A., Ramey, A. M., Schütte, U. M. E. and Waldrop, M. P. (2025) "Cooling perspectives on the risk of pathogenic viruses from thawing permafrost.," *mSystems*, vol. 10, no. 2, p. e0004224 [Online]. DOI: 10.1128/msystems.00042-24.

Magnan, A. K., Anisimov, A. and Duvat, V. K. E. (2022) "Strengthen climate adaptation research globally.," *Science*, vol. 376, no. 6600, pp. 1398–1400 [Online]. DOI: 10.1126/science.abq0737.

Mai, T., Reardon-Smith, K., Cobon, D. H., Nguyen-Huy, T. and Mushtaq, S. (2025) "Defining potential pathways for improving the resilience and sustainable development of rangeland grazing systems: Insights from northern Australia.," *The Science of the Total Environment*, vol. 978, p. 179488 [Online]. DOI: 10.1016/j.scitotenv.2025.179488.

Manos, E., Witharana, C. and Liljedahl, A. K. (2025) "Permafrost thaw-related infrastructure damage costs in Alaska are projected to double under medium and high emission scenarios," *Communications Earth & Environment*, vol. 6, no. 1, p. 221 [Online]. DOI: 10.1038/s43247-025-02191-7.

Marengo, Jose A., Cunha, A. P., Espinoza, J.-C., Fu, R., Schöngart, J., Jimenez, J. C., Costa, M. C., Ribeiro, J. M., Wongchuig, S. and Zhao, S. (2024) "The Drought of Amazonia in 2023-2024," *American Journal of Climate Change*, vol. 13, no. 03, pp. 567–597 [Online]. DOI: 10.4236/ajcc.2024.133026.

Marengo, J. A., Galdos, M. V., Challinor, A., Cunha, A. P., Marin, F. R., Vianna, M. dos S., Alvala, R. C. S., Alves, L. M., Moraes, O. L. and Bender, F. (2022) "Drought in Northeast Brazil: A review of agricultural and policy adaptation options for food security," *Climate Resilience and Sustainability*, vol. 1, no. 1 [Online]. DOI: 10.1002/cli2.17.

Marengo, J. A., Souza, C. M., Thonicke, K., Burton, C., Halladay, K., Betts, R. A., Alves, L. M. and Soares, W. R. (2018) "Changes in climate and land use over the amazon region: current and future variability and trends," *Frontiers in Earth Science*, vol. 6 [Online]. DOI: 10.3389/feart.2018.00228.

Marsden, L., Ryan-Collins, J., Abrams, J. F. and Lenton, T. M. (2024) *Ecosystem tipping points:Understanding risks to theeconomy and financial system*, Policy Report, UCL Institute for Innovation and Public Purpose.

Marshall, S. J. (2021) "Regime shifts in glacier and ice sheet response to climate change: examples from the northern hemisphere," *Frontiers in Climate*, vol. 3 [Online]. DOI: 10.3389/fclim.2021.702585.

Marx, S. K., Reynolds, W., May, J.-H., Forbes, M. S., Stromsoe, N., Fletcher, M.-S., Cohen, T., Moss, P., Mazumder, D. and Gadd, P. (2021) "Monsoon driven ecosystem and landscape change in the 'Top End' of Australia during the past 35 kyr," *Palaeogeography, Palaeoclimatology, Palaeoecology*, vol. 583, p. 110659 [Online]. DOI: 10.1016/j.palaeo.2021.110659.

Maslakov, A., Sotnikova, K., Gribovskii, G. and Evlanov, D. (2022) "Thermal simulation of ice cellars as a basis for food security and energy sustainability of isolated indigenous communities in the arctic," *Energies*, vol. 15, no. 3, p. 972 [Online]. DOI: 10.3390/en15030972.

Ma, Q., Shi, X., Scholz, P., Sidorenko, D., Lohmann, G. and Ionita, M. (2024) "Revisiting climate impacts of an AMOC slowdown: dependence on freshwater locations in the North Atlantic.," *Science Advances*, vol. 10, no. 47, p. eadr3243 [Online]. DOI: 10.1126/sciadv.adr3243.

Marengo, Jose Antonio, Espinoza, J.-C., Fu, R., Jimenez Muñoz, J. C., Alves, L. M., Da Rocha, H. R. and Schöngart, J. (2024) "Long-term variability, extremes and changes in temperature and hydrometeorology in the Amazon region: A review," *Acta amazonica*, vol. 54, no. spe1 [Online]. DOI: 10.1590/1809-4392202200980.

McMichael, C., Barnett, J. and McMichael, A. J. (2012) "An ill wind? Climate change, migration and health.," *Environmental Health Perspectives*, vol. 120, no. 5, pp. 646–654 [Online]. DOI: 10.1289/ehp.1104375.

Meccia, V. L., Simolo, C., Bellomo, K. and Corti, S. (2024) "Extreme cold events in Europe under a reduced AMOC," *Environmental Research Letters*, vol. 19, no. 1, p. 014054 [Online]. DOI: 10.1088/1748-9326/ad14b0.

Meccia, V. L., Simolo, C., Bellomo, K. and Corti, S. (2025) "The impact of a weakened AMOC on European heatwaves," *Environmental Research Letters*, vol. 20, no. 2, p. 024005 [Online]. DOI: 10.1088/1748-9326/ada3e7.

Mehrabi, Z. and Ramankutty, N. (2019) "Synchronized failure of global crop production.," *Nature Ecology & Evolution*, vol. 3, no. 5, pp. 780–786 [Online]. DOI: 10.1038/s41559-019-0862-x.

Milkoreit, M., Boyd, E., Constantino, S. M., Hausner, V. H., Hessen, D. O., Kääb, A., McLaren, D., Nadeau, C., O'Brien, K., Parmentier, F.-J., Rotbarth, R., Rødven, R., Treichler, D., Wilson-Rowe, E. and Yamineva, Y. (2024) "Governance for Earth system tipping points – A research agenda," *Earth System Governance*, vol. 21, p. 100216 [Online]. DOI: 10.1016/j.esg.2024.100216.

Miller, H. and Dikau, S. (2022) *Preventing a 'climate Minsky moment': environmentalfinancial risks and prudential exposure limits.*, London, Grantham Research Institute on Climate Change, London School of Economics and Political Science.

Miner, K. R., D'Andrilli, J., Mackelprang, R., Edwards, A., Malaska, M. J., Waldrop, M. P. and Miller, C. E. (2021) "Emergent biogeochemical risks from Arctic permafrost degradation," *Nature Climate Change*, vol. 11, no. 10, pp. 809–819 [Online]. DOI: 10.1038/s41558-021-01162-y.

Mirzabaev, A., Olsson, L., Kerr, R. B., Pradhan, P., Ferre, M. G. R. and Lotze-Campen, H. (2023) "Climate change and food systems," in von Braun, J., Afsana, K., Fresco, L. O. and Hassan, M. H. A. (eds), *Science and innovations for food systems transformation*, Cham, Springer International Publishing, pp. 511–529 [Online]. DOI: 10.1007/978-3-031-15703-5_27.

Mohd, F. A., Abdul Maulud, K. N., Karim, O. A., Begum, R. A., Awang, N. A., Hamid, M. R. A., Rahim, N. A. A. and Razak, A. H. A. (2018) "Assessment of coastal inundation of low lying areas due to sea level rise," *IOP Conference Series: Earth and Environmental Science*, vol. 169, no. 1, p. 012046 [Online]. DOI: 10.1088/1755-1315/169/1/012046.

Mohtadi, M., Prange, M., Oppo, D. W., De Pol-Holz, R., Merkel, U., Zhang, X., Steinke, S. and Lückge, A. (2014) "North Atlantic forcing of tropical Indian Ocean climate.," *Nature*, vol. 509, no. 7498, pp. 76–80 [Online]. DOI: 10.1038/nature13196.

Mohtadi, M., Prange, M. and Steinke, S. (2016) "Palaeoclimatic insights into forcing and response of monsoon rainfall.," *Nature*, vol. 533, no. 7602, pp. 191–199 [Online]. DOI: 10.1038/nature17450.

Monteverde, C., Quandt, A., Gilberto de Souza Ribeiro, J. and De Sales, F. (2024) "Changing climates, changing lives: Voices of a Brazilian Amazon farming community in a time of climate crisis," *PLOS Climate*, vol. 3, no. 11, p. e0000522 [Online]. DOI: 10.1371/journal.pclm.0000522.

Moon, T., Joughin, I. and Smith, B. (2015) "Seasonal to multiyear variability of glacier surface velocity, terminus position and sea ice/ice mélange in northwest Greenland," *Journal of Geophysical Research: Earth Surface*, vol. 120, no. 5, pp. 818–833 [Online]. DOI: 10.1002/2015JF003494.

Muema, J., Mutono, N., Kisaka, S., Ogoti, B., Oyugi, J., Bukania, Z., Daniel, T., Njuguna, J., Kimani, I., Makori, A., Omulo, S., Boyd, E., Osman, A. M., Gwenaelle, L., Jost, C. and Thumbi, S. M. (2023) "The impact of livestock interventions on nutritional outcomes of children younger than 5 years old and women in Africa: a systematic review and meta-analysis.," *Frontiers in nutrition*, vol. 10, p. 1166495 [Online]. DOI: 10.3389/fnut.2023.1166495.

Mulitza, S., Prange, M., Stuut, J., Zabel, M., von Dobeneck, T., Itambi, A. C., Nizou, J., Schulz, M. and Wefer, G. (2008) "Sahel megadroughts triggered by glacial slowdowns of Atlantic meridional overturning," *Paleoceanography*, vol. 23, no. 4 [Online]. DOI: 10.1029/2008PA001637.

Nagy, G. J., Gutiérrez, O., Brugnoli, E., Verocai, J. E., Gómez-Erache, M., Villamizar, A., Olivares, I., Azeiteiro, U. M., Leal Filho, W. and Amaro, N. (2019) "Climate vulnerability, impacts and adaptation in Central and South America coastal areas," *Regional Studies in Marine Science*, vol. 29, no. 3, p. 100683 [Online]. DOI: 10.1016/j.rsma.2019.100683.

Neupane, N. and Cook, K. H. (2013) "A nonlinear response of sahel rainfall to atlantic warming," *Journal of climate*, vol. 26, no. 18, pp. 7080–7096 [Online]. DOI: 10.1175/JCLI-D-12-00475.1.

Newman, R. and Noy, I. (2023) "The global costs of extreme weather that are attributable to climate change.," *Nature Communications*, vol. 14, no. 1, p. 6103 [Online]. DOI: 10.1038/s41467-023-41888-1.

Nian, D., Bathiany, S., Ben-Yami, M., Blaschke, L. L., Hirota, M., Rodrigues, R. R. and Boers, N. (2023) "A potential collapse of the Atlantic Meridional Overturning Circulation may stabilise eastern Amazonian rainforests," *Communications Earth & Environment*, vol. 4, no. 1, p. 470 [Online]. DOI: 10.1038/s43247-023-01123-7.

Nicholls, R. J. and Cazenave, A. (2010) "Sea-level rise and its impact on coastal zones.," *Science*, vol. 328, no. 5985, pp. 1517–1520 [Online]. DOI: 10.1126/science.1185782.

Nicholls, R. J. and Kebede, A. S. (2012) "Indirect impacts of coastal climate change and sea-level rise: the UK example," *Climate Policy*, vol. 12, no. sup01, pp. S28–S52 [Online]. DOI: 10.1080/14693062.2012.728792.

Nicholls, R. J. and Tol, R. S. J. (2006) "Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century.," *Philosophical Transactions. Series A, Mathematical, Physical and Engineering Sciences*, vol. 364, no. 1841, pp. 1073–1095 [Online]. DOI: 10.1098/rsta.2006.1754.

Nielsen, D. M., Pieper, P., Barkhordarian, A., Overduin, P., Ilyina, T., Brovkin, V., Baehr, J. and Dobrynin, M. (2022) "Increase in Arctic coastal erosion and its sensitivity to warming in the twenty-first century," *Nature Climate Change*, vol. 12, no. 3, pp. 263–270 [Online]. DOI: 10.1038/s41558-022-01281-0.

NOAA Coral Reef Watch (2024) *NOAA confirms 4th global coral bleaching event* [Online]. Available at https://www.noaa.gov/news-release/noaa-confirms-4th-global-coral-bleaching-event (Accessed 28 August 2025).

NOAA Coral Reef Watch (2025) *Current Global Bleaching: Status Update & Data Submission* [Online]. Available at https://www.coralreefwatch.noaa.gov/satellite/research/coral_bleaching_report.php (Accessed 28 August 2025).

Nooni, I. K., Ogou, F. K., Saidou Chaibou, A. A., Prempeh, N. A., Atta-Darkwa, T., Paing, K. H., Fianko, S. K., Jin, Z. and Yu, X. (2025) "Links between teleconnection patterns and mean precipitation in africa and the arabian peninsula from 1903 to 2023," *International Journal of Climatology* [Online]. DOI: 10.1002/joc.70001.

NRDC (2024) *LIHEAP Needs a Lifeline: A Call to Strengthen the Low Income Home Energy Assistance Program in a Changing Climate*, Natural Resources Defense Council.

Obura, D., Gudka, M., Samoilys, M., Osuka, K., Mbugua, J., Keith, D. A., Porter, S., Roche, R., van Hooidonk, R., Ahamada, S., Araman, A., Karisa, J., Komakoma, J., Madi, M., Ravinia, I., Razafindrainibe, H., Yahya, S. and Zivane, F. (2022) "Vulnerability to collapse of coral reef ecosystems in the Western Indian Ocean," *Nature Sustainability*, vol. 5, no. 2, pp. 104–113 [Online]. DOI: 10.1038/s41893-021-00817-0.

Olefeldt, D., Goswami, S., Grosse, G., Hayes, D., Hugelius, G., Kuhry, P., McGuire, A. D., Romanovsky, V. E., Sannel, A. B. K., Schuur, E. A. G. and Turetsky, M. R. (2016) "Circumpolar distribution and carbon storage of thermokarst landscapes.," *Nature Communications*, vol. 7, p. 13043 [Online]. DOI: 10.1038/ncomms13043.

Omotoso, A. B., Letsoalo, S., Olagunju, K. O., Tshwene, C. S. and Omotayo, A. O. (2023) "Climate change and variability in sub-Saharan Africa: A systematic review of trends and impacts on agriculture," *Journal of Cleaner Production*, vol. 414, p. 137487 [Online]. DOI: 10.1016/j.jclepro.2023.137487.

Omotoso, A. B. and Omotayo, A. O. (2024) "The interplay between agriculture, greenhouse gases and climate change in Sub-Saharan Africa," *Regional Environmental Change*, vol. 24, no. 1, p. 1 [Online]. DOI: 10.1007/s10113-023-02159-3.

Ord, A. (2024) "Decentering the ice : place-based perspectives on the impacts of glacier retreat on downstream landscapes, ecosystems and communities in Lingít Aaní," *University of British Columbia* [Online]. DOI: 10.14288/1.0444134.

Ortiz-Bobea, A., Ault, T. R., Carrillo, C. M., Chambers, R. G. and Lobell, D. B. (2021) "Anthropogenic climate change has slowed global agricultural productivity growth," *Nature Climate Change*, vol. 11, no. 4, pp. 306–312 [Online]. DOI: 10.1038/s41558-021-01000-1.

Osman, E. O., Smith, D. J., Ziegler, M., Kürten, B., Conrad, C., El-Haddad, K. M., Voolstra, C. R. and Suggett, D. J. (2018) "Thermal refugia against coral bleaching throughout the northern Red Sea.," *Global Change Biology*, vol. 24, no. 2, pp. e474–e484 [Online]. DOI: 10.1111/gcb.13895.

Ovalle-Rivera, O., Läderach, P., Bunn, C., Obersteiner, M. and Schroth, G. (2015) "Projected shifts in Coffea arabica suitability among major global producing regions due to climate change.," *Plos One*, vol. 10, no. 4, p. e0124155 [Online]. DOI: 10.1371/journal.pone.0124155.

Palin, E. J., Stipanovic Oslakovic, I., Gavin, K. and Quinn, A. (2021) "Implications of climate change for railway infrastructure," *Wiley Interdisciplinary Reviews: Climate Change*, vol. 12, no. 5 [Online]. DOI: 10.1002/wcc.728.

Palmer, P. I., Wainwright, C. M., Dong, B., Maidment, R. I., Wheeler, K. G., Gedney, N., Hickman, J. E., Madani, N., Folwell, S. S., Abdo, G., Allan, R. P., Black, E. C. L., Feng, L., Gudoshava, M., Haines, K., Huntingford, C., Kilavi, M., Lunt, M. F., Shaaban, A. and Turner, A. G. (2023) "Drivers and impacts of Eastern African rainfall variability," *Nature Reviews Earth & Environment* [Online]. DOI: 10.1038/s43017-023-00397-x.

Parsons, L. A., Yin, J., Overpeck, J. T., Stouffer, R. J. and Malyshev, S. (2014) "Influence of the Atlantic Meridional Overturning Circulation on the monsoon rainfall and carbon balance of the American tropics," *Geophysical Research Letters*, vol. 41, no. 1, pp. 146–151 [Online]. DOI: 10.1002/2013GL058454.

Paxman, G. J. G., Austermann, J. and Hollyday, A. (2022) "Total isostatic response to the complete unloading of the Greenland and Antarctic Ice Sheets.," *Scientific Reports*, vol. 12, no. 1, p. 11399 [Online]. DOI: 10.1038/s41598-022-15440-y.

Payne, A. J., Nowicki, S., Abe-Ouchi, A., Agosta, C., Alexander, P., Albrecht, T., Asay-Davis, X., Aschwanden, A., Barthel, A., Bracegirdle, T. J., Calov, R., Chambers, C., Choi, Y., Cullather, R., Cuzzone, J., Dumas, C., Edwards, T. L., Felikson, D., Fettweis, X., Galton-Fenzi, B. K. and Zwinger, T. (2021) "Future sea level change under coupled model intercomparison project phase 5 and phase 6 scenarios from the greenland and antarctic ice sheets," *Geophysical research letters*, vol. 48, no. 16 [Online]. DOI: 10.1029/2020GL091741.

Pearce-Kelly, P., Altieri, A. H., Bruno, J. F., Cornwall, C. E., McField, M., Muñiz-Castillo, A. I., Rocha, J., Setter, R. O., Sheppard, C., Roman-Cuesta, R. M. and Yesson, C. (2025) "Considerations for determining warm-water coral reef tipping points," *Earth System Dynamics*, vol. 16, no. 1, pp. 275–292 [Online]. DOI: 10.5194/esd-16-275-2025.

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I.-C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., Lenoir, J. and Williams, S. E. (2017) "Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being.," *Science*, vol. 355, no. 6332 [Online]. DOI: 10.1126/science.aai9214.

Pereira, L. M., Gianelli, I., Achieng, T., Amon, D., Archibald, S., Arif, S., Castro, A., Chimbadzwa, T. P., Coetzer, K., Field, T.-L., Selomane, O., Sitas, N., Stevens, N., Villasante, S., Armani, M., Kimuyu, D. M., Adewumi, I. J., Lapola, D. M., Obura, D., Pinho, P. and Sumaila, U. R. (2024) "Equity and justice should underpin the discourse on tipping points," *Earth System Dynamics*, vol. 15, no. 2, pp. 341–366 [Online]. DOI: 10.5194/esd-15-341-2024.

Pereira, L. M., Smith, S. R., Gifford, L., Newell, P., Smith, B., Villasante, S., Achieng, T., Castro, A., Constantino, S. M., Ghadiali, A., Vogel, C. and Zimm, C. (2023) "Risks, Ethics and Justice in the governance of positive tipping points," [Online]. DOI: 10.5194/egusphere-2023-1454.

Pereira, L. M., Smith, S. R., Gifford, L., Newell, P., Villasante, S., Achieng, T., Castro, A., Constantino, S. M., Powell, T., Ghadiali, A., Smith, B., Vogel, C. and Zimm, C. (2025) "Beyond tipping points: risks, equity and the ethics of intervention," *Earth System Dynamics*, vol. 16, no. 4, pp. 1267–1285 [Online]. DOI: 10.5194/esd-16-1267-2025.

Peterson, B. J. (2024) "Drought, revolution and the cold war politics of aid: responding to climate change and mass vulnerability in the african sahel," *Environmental history*, vol. 29, no. 4, pp. 645–672 [Online]. DOI: 10.1086/731592.

Petrov, M. A., Sabitov, T. Y., Tomashevskaya, I. G., Glazirin, G. E., Chernomorets, S. S., Savernyuk, E. A., Tutubalina, O. V., Petrakov, D. A., Sokolov, L. S., Dokukin, M. D., Mountrakis, G., Ruiz-Villanueva, V. and Stoffel, M. (2017) "Glacial lake inventory and lake outburst potential in Uzbekistan.," The Science of the Total Environment, vol. 592, pp. 228–242 [Online]. DOI: 10.1016/j.scitotenv.2017.03.068.

Phillips, C. A., Rogers, B. M., Elder, M., Cooperdock, S., Moubarak, M., Randerson, J. T. and Frumhoff, P. C. (2022) "Escalating carbon emissions from North American boreal forest wildfires and the climate mitigation potential of fire management.," *Science Advances*, vol. 8, no. 17, p. eabl7161 [Online]. DOI: 10.1126/sciadv.abl7161.

Pinho, P. F., Marengo, J. A. and Smith, M. S. (2015) "Complex socio-ecological dynamics driven by extreme events in the Amazon," *Regional Environmental Change*, vol. 15, no. 4, pp. 643–655 [Online]. DOI: 10.1007/s10113-014-0659-z.

Post, E., Forchhammer, M. C., Bret-Harte, M. S., Callaghan, T. V., Christensen, T. R., Elberling, B., Fox, A. D., Gilg, O., Hik, D. S., Høye, T. T., Ims, R. A., Jeppesen, E., Klein, D. R., Madsen, J., McGuire, A. D., Rysgaard, S., Schindler, D. E., Stirling, I., Tamstorf, M. P., Tyler, N. J. C. and Aastrup, P. (2009) "Ecological dynamics across the Arctic associated with recent climate change.," *Science*, vol. 325, no. 5946, pp. 1355–1358 [Online]. DOI: 10.1126/science.1173113.

Qin, Y., Wang, D., Ziegler, A. D., Fu, B. and Zeng, Z. (2025) "Impact of Amazonian deforestation on precipitation reverses between seasons.," *Nature*, vol. 639, no. 8053, pp. 102–108 [Online]. DOI: 10.1038/s41586-024-08570-y.

Quishpe, M., Acosta-Vargas, I., Buenaño, A., Rosero, B., Reyes, M., Duran, G. and Zalakeviciute, R. (2025) "Vulnerability and climate risk assessment in the Ecuadorian Amazon Region, based on ecological and socioeconomic infrastructures," *Climate Risk Management*, vol. 49, p. 100736 [Online]. DOI: 10.1016/j.crm.2025.100736.

Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Ceballos, J. L., Basantes, R., Vuille, M., Sicart, J. E., Huggel, C., Scheel, M., Lejeune, Y., Arnaud, Y., Collet, M., Condom, T., Consoli, G., Favier, V., Jomelli, V., Galarraga, R., Ginot, P. and Wagnon, P. (2013) "Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change," The Cryosphere, vol. 7, no. 1, pp. 81–102 [Online]. DOI: 10.5194/tc-7-81-2013.

Ramage, J., Jungsberg, L., Wang, S., Westermann, S., Lantuit, H. and Heleniak, T. (2021) "Population living on permafrost in the Arctic," *Population and environment*, vol. 43, no. 1, pp. 22–38 [Online]. DOI: 10.1007/s11111-020-00370-6.

Redfern, S. K., Azzu, N. J. and Binamira, J. S. (2012) *Rice in Southeast Asia: facingrisks and vulnerabilities torespond to climate change*, FAOSTAT.

Reguero, B. G., Losada, I. J., Díaz-Simal, P., Méndez, F. J. and Beck, M. W. (2015) "Effects of climate change on exposure to coastal flooding in latin america and the caribbean.," *Plos One*, vol. 10, no. 7, p. e0133409 [Online]. DOI: 10.1371/journal.pone.0133409.

Rehman, A., Batool, Z., Ma, H., Alvarado, R. and Oláh, J. (2024) "Climate change and food security in South Asia: the importance of renewable energy and agricultural credit," *Humanities and Social Sciences Communications*, vol. 11, no. 1, p. 342 [Online]. DOI: 10.1057/s41599-024-02847-3.

Reid, C. E., Brauer, M., Johnston, F. H., Jerrett, M., Balmes, J. R. and Elliott, C. T. (2016) "Critical review of health impacts of wildfire smoke exposure.," *Environmental Health Perspectives*, vol. 124, no. 9, pp. 1334–1343 [Online]. DOI: 10.1289/ehp.1409277.

Reimer, J. D., Peixoto, R. S., Davies, S. W., Traylor-Knowles, N., Short, M. L., Cabral-Tena, R. A., Burt, J. A., Pessoa, I., Banaszak, A. T., Winters, R. S., Moore, T., Schoepf, V., Kaullysing, D., Calderon-Aguilera, L. E., Wörheide, G., Harding, S., Munbodhe, V., Mayfield, A., Ainsworth, T., Vardi, T. and Voolstra, C. R. (2024) "The Fourth Global Coral Bleaching Event: Where do we go from here?," *Coral Reefs*, vol. 43, no. 4, pp. 1121–1125 [Online]. DOI: 10.1007/s00338-024-02504-w.

Revich, B., Tokarevich, N. and Parkinson, A. J. (2012) "Climate change and zoonotic infections in the Russian Arctic.," *International journal of circumpolar health*, vol. 71, p. 18792 [Online]. DOI: 10.3402/ijch.v71i0.18792.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K. and Tavoni, M. (2017) "The Shared Socioeconomic Pathways and their energy, land use and greenhouse gas emissions implications: An overview," *Global Environmental Change*, vol. 42, pp. 153–168 [Online]. DOI: 10.1016/j.gloenvcha.2016.05.009.

Richardson, K., Calow, R., Pichon, F., New, S. and Osborne, R. (2022) *Climate risk report for the East Africa region*, Met Office.

Riedel, J. L., Wilson, S., Baccus, W., Larrabee, M., Fudge, T. J. and Fountain, A. (2015) "Glacier status and contribution to streamflow in the Olympic Mountains, Washington, USA," Journal of Glaciology, vol. 61, no. 225, pp. 8–16 [Online]. DOI: 10.3189/2015JoG14J138.

Ritchie, P. D. L., Smith, G. S., Davis, K. J., Fezzi, C., Halleck-Vega, S., Harper, A. B., Boulton, C. A., Binner, A. R., Day, B. H., Gallego-Sala, A. V., Mecking, J. V., Sitch, S. A., Lenton, T. M. and Bateman, I. J. (2020) "Shifts in national land use and food production in Great Britain after a climate tipping point," *Nature Food*, vol. 1, no. 1, pp. 76–83 [Online]. DOI: 10.1038/s43016-019-0011-3.

Roberts, F. E., De Meyer, K. and Hubble-Rose, L. (2021) "Communicating climate risk: a handbook," [Online]. DOI: 10.33774/coe-2021-kc83n.

Rocha, V. M., Da Silva, P. R. T., Gomes, W. B., Vergasta, L. A. and Jardine, A. (2018) "Precipitation Recycling in the Amazon Basin: A Study Using the ECMWF Era-Interim Reanalysis Dataset," *Geography Department University of Sao Paulo*, vol. 35, pp. 71–82 [Online]. DOI: 10.11606/rdg.v35i0.139494.

Rolstad, J., Blanck, Y. and Storaunet, K. O. (2017) "Fire history in a western Fennoscandian boreal forest as influenced by human land use and climate," *Ecological monographs*, vol. 87, no. 2, pp. 219–245 [Online]. DOI: 10.1002/ecm.1244.

Romanello, M., Walawender, M., Hsu, S.-C., Moskeland, A., Palmeiro-Silva, Y., Scamman, D., Ali, Z., Ameli, N., Angelova, D., Ayeb-Karlsson, S., Basart, S., Beagley, J., Beggs, P. J., Blanco-Villafuerte, L., Cai, W., Callaghan, M., Campbell-Lendrum, D., Chambers, J. D., Chicmana-Zapata, V., Chu, L. and Costello, A. (2024) "The 2024 report of the Lancet Countdown on health and climate change: facing record-breaking threats from delayed action.," *The Lancet*, vol. 404, no. 10465, pp. 1847–1896 [Online]. DOI: 10.1016/S0140-6736(24)01822-1.

Rueda, A., Vitousek, S., Camus, P., Tomás, A., Espejo, A., Losada, I. J., Barnard, P. L., Erikson, L. H., Ruggiero, P., Reguero, B. G. and Mendez, F. J. (2017) "A global classification of coastal flood hazard climates associated with large-scale oceanographic forcing.," *Scientific Reports*, vol. 7, no. 1, p. 5038 [Online]. DOI: 10.1038/s41598-017-05090-w.

Ruiter, M. C., Couasnon, A., Homberg, M. J. C., Daniell, J. E., Gill, J. C. and Ward, P. J. (2020) "Why we can no longer ignore consecutive disasters," *Earth's Future*, vol. 8, no. 3 [Online]. DOI: 10.1029/2019EF001425.

Ruv Lemes, M., Sampaio, G., Garcia-Carreras, L., Fisch, G., Alves, L. M., Bassett, R., Betts, R., Maksic, J., Shimizu, M. H., Torres, R. R., Guatura, M., Basso, L. S. and Bispo, P. da C. (2023) "Impacts on South America moisture transport under Amazon deforestation and 2 °C global warming.," *The Science of the Total Environment*, vol. 905, p. 167407 [Online]. DOI: 10.1016/j.scitotenv.2023.167407.

Saini, H., Pontes, G., Brown, J. R., Drysdale, R. N., Du, Y. and Menviel, L. (2025) "Australasian hydroclimate response to the collapse of the atlantic meridional overturning circulation under pre-industrial and last interglacial climates," *Paleoceanography and Paleoclimatology*, vol. 40, no. 3 [Online]. DOI: 10.1029/2024PA004967.

Sanchez-Martinez, P., Martius, L. R., Bittencourt, P., Silva, M., Binks, O., Coughlin, I., Negrão-Rodrigues, V., Athaydes Silva, J., Da Costa, A. C. L., Selman, R., Rifai, S., Rowland, L., Mencuccini, M. and Meir, P. (2025) "Amazon rainforest adjusts to long-term experimental drought.," *Nature Ecology & Evolution*, vol. 9, no. 6, pp. 970–979 [Online]. DOI: 10.1038/s41559-025-02702-x.

Sandeep, N., Swapna, P., Krishnan, R., Farneti, R., Prajeesh, A. G., Ayantika, D. C. and Manmeet, S. (2020) "South Asian monsoon response to weakening of Atlantic meridional overturning circulation in a warming climate," *Climate dynamics*, vol. 54, no. 7–8, pp. 3507–3524 [Online]. DOI: 10.1007/s00382-020-05180-y.

Sarafanov, A. (2009) "On the effect of the North Atlantic Oscillation on temperature and salinity of the subpolar North Atlantic intermediate and deep waters," *ICES Journal of Marine Science*, vol. 66, no. 7, pp. 1448–1454 [Online]. DOI: 10.1093/icesjms/fsp094.

Schaefer, K., Elshorbany, Y., Jafarov, E., Schuster, P. F., Striegl, R. G., Wickland, K. P. and Sunderland, E. M. (2020) "Potential impacts of mercury released from thawing permafrost.," *Nature Communications*, vol. 11, no. 1, p. 4650 [Online]. DOI: 10.1038/s41467-020-18398-5.

Schaphoff, S., Reyer, C. P. O., Schepaschenko, D., Gerten, D. and Shvidenko, A. (2016) "Tamm Review: Observed and projected climate change impacts on Russia's forests and its carbon balance," *Forest Ecology and Management*, vol. 361, pp. 432–444 [Online]. DOI: 10.1016/j.foreco.2015.11.043.

Schaumann, F. and Alastrué de Asenjo, E. (2025) "Weakening AMOC reduces ocean carbon uptake and increases the social cost of carbon.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 122, no. 9, p. e2419543122 [Online]. DOI: 10.1073/pnas.2419543122.

Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., Held, H., van Nes, E. H., Rietkerk, M. and Sugihara, G. (2009) "Early-warning signals for critical transitions.," *Nature*, vol. 461, no. 7260, pp. 53–59 [Online]. DOI: 10.1038/nature08227.

Scheffran, J., Guo, W., Krampe, F. and Okpara, U. (2025) "Tipping cascades between conflict and cooperation in climate change," *Earth System Dynamics*, vol. 16, no. 4, pp. 1197–1219 [Online]. DOI: 10.5194/esd-16-1197-2025.

Schernewski, G., Konrad, A., Roskothen, J. and von Thenen, M. (2023) "Coastal adaptation to climate change and sea level rise: ecosystem service assessments in spatial and sectoral planning," *Applied Sciences*, vol. 13, no. 4, p. 2623 [Online]. DOI: 10.3390/app13042623.

Schmittner, A. (2005) "Decline of the marine ecosystem caused by a reduction in the Atlantic overturning circulation.," *Nature*, vol. 434, no. 7033, pp. 628–633 [Online]. DOI: 10.1038/nature03476.

Scholten, R. C., Veraverbeke, S., Chen, Y. and Randerson, J. T. (2024) "Spatial variability in Arctic-boreal fire regimes influenced by environmental and human factors.," *Nature geoscience*, vol. 17, no. 9, pp. 866–873 [Online]. DOI: 10.1038/s41561-024-01505-2.

Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, C. D., Kuhry, P., Lawrence, D. M., Natali, S. M., Olefeldt, D., Romanovsky, V. E., Schaefer, K., Turetsky, M. R., Treat, C. C. and Vonk, J. E. (2015) "Climate change and the permafrost carbon feedback.," *Nature*, vol. 520, no. 7546, pp. 171–179 [Online]. DOI: 10.1038/nature14338.

Setter, R. O., Franklin, E. C. and Mora, C. (2022) "Co-occurring anthropogenic stressors reduce the timeframe of environmental viability for the world's coral reefs.," *PLoS Biology*, vol. 20, no. 10, p. e3001821 [Online]. DOI: 10.1371/journal.pbio.3001821.

Sgubin, G., Swingedouw, D., Drijfhout, S., Mary, Y. and Bennabi, A. (2017) "Abrupt cooling over the North Atlantic in modern climate models.," *Nature Communications*, vol. 8 [Online]. DOI: 10.1038/ncomms14375.

Shammi, M., Rahman, M. M., Bondad, S. E. and Bodrud-Doza, M. (2019) "Impacts of Salinity Intrusion in Community Health: A Review of Experiences on Drinking Water Sodium from Coastal Areas of Bangladesh.," *Healthcare (Basel)*, vol. 7, no. 1 [Online]. DOI: 10.3390/healthcare7010050.

Shaw, T. A., Baldwin, M., Barnes, E. A., Caballero, R., Garfinkel, C. I., Hwang, Y. T., Li, C., O'Gorman, P. A., Rivière, G., Simpson, I. R. and Voigt, A. (2016) "Storm track processes and the opposing influences of climate change," *Nature Geoscience*, vol. 9, no. 9, pp. 656–664 [Online]. DOI: 10.1038/ngeo2783.

Shokri, N., Hassani, A. and Sahimi, M. (2024) "Multi-scale soil salinization dynamics from global to pore scale: A review," *Reviews of Geophysics*, vol. 62, no. 4 [Online]. DOI: 10.1029/2023RG000804.

Siahaan, A., Smith, R. S., Holland, P. R., Jenkins, A., Gregory, J. M., Lee, V., Mathiot, P., Payne, A. J. , Ridley, J. K. and Jones, C. G. (2022) "The Antarctic contribution to 21st-century sea-level rise predicted by the UK Earth System Model with an interactive ice sheet," *The Cryosphere*, vol. 16, no. 10, pp. 4053–4086 [Online]. DOI: 10.5194/tc-16-4053-2022.

Silveira, F., Lopes, C. L., Pinheiro, J. P., Pereira, H. and Dias, J. M. (2021) "Coastal floods induced by mean sea level rise—ecological and socioeconomic impacts on a mesotidal lagoon," *JOURNAL of MATHEMATICS SCIENCE and EDUCATION*, vol. 9, no. 12, p. 1430 [Online]. DOI: 10.3390/jmse9121430.

Simpson, N. P., Mach, K. J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R. J., Muccione, V., Mackey, B., New, M. G., O'Neill, B., Otto, F., Pörtner, H.-O., Reisinger, A., Roberts, D., Schmidt, D. N., Seneviratne, S., Strongin, S., van Aalst, M. and Trisos, C. H. (2021) "A framework for complex climate change risk assessment," *One Earth*, vol. 4, no. 4, pp. 489–501 [Online]. DOI: 10.1016/j.oneear.2021.03.005.

Somos-Valenzuela, M. A., Chisolm, R. E., Rivas, D. S., Portocarrero, C. and McKinney, D. C. (2016) "Modeling a glacial lake outburst flood process chain: the case of Lake Palcacocha and Huaraz, Peru," Hydrology and Earth System Sciences, vol. 20, no. 6, pp. 2519–2543 [Online]. DOI: 10.5194/hess-20-2519-2016.

Souza, C. M., Marengo, J., Ferreira, B., Ribeiro, J., Schirmbeck, L. W., Schirmbeck, J., Hirye, M., Cunha, A., Wiederhecker, H. C. and Latuf, M. O. (2024) "Amazon severe drought in 2023 triggered surface water loss," *Environmental Research: Climate*, vol. 3, no. 4, p. 041002 [Online]. DOI: 10.1088/2752-5295/ad7c71.

Spaiser, V., Juhola, S., Constantino, S. M., Guo, W., Watson, T., Sillmann, J., Craparo, A., Basel, A., Bruun, J. T., Krishnamurthy, K., Scheffran, J., Pinho, P., Okpara, U. T., Donges, J. F., Bhowmik, A., Yasseri, T., Safra de Campos, R., Cumming, G. S., Chenet, H., Krampe, F. and Spears, B. M. (2024) "Negative social tipping dynamics resulting from and reinforcing Earth system destabilization," *Earth System Dynamics*, vol. 15, no. 5, pp. 1179–1206 [Online]. DOI: 10.5194/esd-15-1179-2024.

Steinert, N. J., Schwinger, J., Chadwick, R., Kug, J. and Lee, H. (2025) "Irreversible land water availability changes from a potential ITCZ shift during temperature overshoot," *Earth's Future*, vol. 13, no. 5 [Online]. DOI: 10.1029/2024EF005787.

Stokes, C. R., Abram, N. J., Bentley, M. J., Edwards, T. L., England, M. H., Foppert, A., Jamieson, S. S. R., Jones, R. S., King, M. A., Lenaerts, J. T. M., Medley, B., Miles, B. W. J., Paxman, G. J. G., Ritz, C., van de Flierdt, T. and Whitehouse, P. L. (2022) "Response of the East Antarctic Ice Sheet to past and future climate change.," *Nature*, vol. 608, no. 7922, pp. 275–286 [Online]. DOI: 10.1038/s41586-022-04946-0.

Storey, B., Owen, S., Zammit, C. and Noy, I. (2024) "Insurance retreat in residential properties from future sea level rise in Aotearoa New Zealand," *Climatic Change*, vol. 177, no. 3, p. 44 [Online]. DOI: 10.1007/s10584-024-03699-1.

Storlazzi, C. D., Gingerich, S. B., van Dongeren, A., Cheriton, O. M., Swarzenski, P. W., Quataert, E., Voss, C. I., Field, D. W., Annamalai, H., Piniak, G. A. and McCall, R. (2018) "Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding.," *Science Advances*, vol. 4, no. 4, p. eaap9741 [Online]. DOI: 10.1126/sciadv.aap9741.

Sultan, B. and Gaetani, M. (2016) "Agriculture in West Africa in the Twenty-First Century: Climate Change and Impacts Scenarios and Potential for Adaptation.," *Frontiers in Plant Science*, vol. 7, p. 1262 [Online]. DOI: 10.3389/fpls.2016.01262.

Sun, Y., Clauson, K., Zhou, M., Sun, Z., Zheng, C. and Zheng, Y. (2021) "Hillslopes in headwaters of Qinghai-Tibetan Plateau as hotspots for subsurface dissolved organic carbon processing during permafrost thaw," *Journal of Geophysical Research: Biogeosciences*, vol. 126, no. 5, p. e2020JG006222 [Online]. DOI: 10.1029/2020JG006222.

Surazu, M. M. (2024) "The cause of diplomatic failure in the sahel region and the rising coups," *International Journal of Research and Innovation in Social Science*, vol. VII, no. XII, pp. 1005–1012 [Online]. DOI: 10.47772/IJRISS.2023.7012076.

Su, Q., Kambale, R. D., Tzeng, J.-H., Amy, G. L., Ladner, D. A. and Karthikeyan, R. (2025) "The growing trend of saltwater intrusion and its impact on coastal agriculture: Challenges and opportunities.," *The Science of the Total Environment*, vol. 966, p. 178701 [Online]. DOI: 10.1016/j.scitotenv.2025.178701.

Swingedouw, D., Bily, A., Esquerdo, C., Borchert, L. F., Sgubin, G., Mignot, J. and Menary, M. (2021) "On the risk of abrupt changes in the North Atlantic subpolar gyre in CMIP6 models.," *Annals of the New York Academy of Sciences*, vol. 1504, no. 1, pp. 187–201 [Online]. DOI: 10.1111/nyas.14659.

Sylla, M. B., Faye, A., Klutse, N. A. B. and Dimobe, K. (2018) "Projected increased risk of water deficit over major West African river basins under future climates," *Climatic Change*, vol. 151, no. 2, pp. 247–258 [Online]. DOI: 10.1007/s10584-018-2308-x.

Tarolli, P., Luo, J., Straffelini, E., Liou, Y.-A., Nguyen, K.-A., Laurenti, R., Masin, R. and D'Agostino, V. (2023) "Saltwater intrusion and climate change impact on coastal agriculture," *PLOS Water*, vol. 2, no. 4, p. e0000121 [Online]. DOI: 10.1371/journal.pwat.0000121.

Taruvinga, G. R. (2023) "The resurgence of military coups in africa: the case of west africa and the sahel," in *Contemporary issues on governance, conflict and security in africa*, Cham, Springer Nature Switzerland, pp. 147–157 [Online]. DOI: 10.1007/978-3-031-29635-2_9.

Tchonkouang, R. D., Onyeaka, H. and Nkoutchou, H. (2024) "Assessing the vulnerability of food supply chains to climate change-induced disruptions.," *The Science of the Total Environment*, vol. 920, p. 171047 [Online]. DOI: 10.1016/j.scitotenv.2024.171047.

Terry, J. P. and Falkland, A. C. (2010) "Responses of atoll freshwater lenses to storm-surge overwash in the Northern Cook Islands," *Hydrogeology journal*, vol. 18, no. 3, pp. 749–759 [Online]. DOI: 10.1007/s10040-009-0544-x.

van Thienen, P., ter Maat, H. and Stofberg, S. (2025) "Climate tipping points and their potential impact on drinking water supply planning and management in Europe," *Cambridge Prisms: Water*, vol. 3 [Online]. DOI: 10.1017/wat.2024.14.

Thirumalai, K., DiNezio, P. N., Partin, J. W., Liu, D., Costa, K. and Jacobel, A. (2024) "Future increase in extreme El Niño supported by past glacial changes.," Nature, vol. 634, no. 8033, pp. 374–380 [Online]. DOI: 10.1038/s41586-024-07984-y.

Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Zagorodnov, V. S., Howat, I. M., Mikhalenko, V. N. and Lin, P. N. (2013) "Annually resolved ice core records of tropical climate variability over the past ~1800 years.," Science, vol. 340, no. 6135, pp. 945–950 [Online]. DOI: 10.1126/science.1234210.

Thornton, P. K., Ericksen, P. J., Herrero, M. and Challinor, A. J. (2014) "Climate variability and vulnerability to climate change: a review.," *Global Change Biology*, vol. 20, no. 11, pp. 3313–3328 [Online]. DOI: 10.1111/gcb.12581.

Thornton, P. K. and Herrero, M. (2015) "Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa," *Nature climate change*, vol. 5, no. 9, pp. 830–836 [Online]. DOI: 10.1038/nclimate2754.

Thornton, P. K., Jones, P. G., Alagarswamy, G., Andresen, J. and Herrero, M. (2010) "Adapting to climate change: Agricultural system and household impacts in East Africa," *Agricultural systems*, vol. 103, no. 2, pp. 73–82 [Online]. DOI: 10.1016/j.agsy.2009.09.003.

Thornton, Philip K., Jones, P. G., Alagarswamy, G. and Andresen, J. (2009) "Spatial variation of crop yield response to climate change in East Africa," *Global Environmental Change*, vol. 19, no. 1, pp. 54–65 [Online]. DOI: 10.1016/j.gloenvcha.2008.08.005.

Thornton, P K, van de Steeg, J., Notenbaert, A. and Herrero, M. (2009) "The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know," *Agricultural systems*, vol. 101, no. 3, pp. 113–127 [Online]. DOI: 10.1016/j.agsy.2009.05.002.

Tigchelaar, M., Battisti, D. S., Naylor, R. L. and Ray, D. K. (2018) "Future warming increases probability of globally synchronized maize production shocks.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 115, no. 26, pp. 6644–6649 [Online]. DOI: 10.1073/pnas.1718031115.

Torres, J. M. and Casey, J. A. (2017) "The centrality of social ties to climate migration and mental health.," *BMC Public Health*, vol. 17, no. 1, p. 600 [Online]. DOI: 10.1186/s12889-017-4508-0.

Tregidgo, D., Barlow, J., Pompeu, P. S. and Parry, L. (2020) "Tough fishing and severe seasonal food insecurity in Amazonian flooded forests," *People and Nature*, vol. 2, no. 2, pp. 468–482 [Online]. DOI: 10.1002/pan3.10086.

Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A. G., Grosse, G., Kuhry, P., Hugelius, G., Koven, C., Lawrence, D. M., Gibson, C., Sannel, A. B. K. and McGuire, A. D. (2020) "Carbon release through abrupt permafrost thaw," *Nature geoscience*, vol. 13, no. 2, pp. 138–143 [Online]. DOI: 10.1038/s41561-019-0526-0.

Turner, A. G. and Annamalai, H. (2012) "Climate change and the South Asian summer monsoon," *Nature climate change*, vol. 2, no. 8, pp. 587–595 [Online]. DOI: 10.1038/nclimate1495.

UK Government (2024) *UK Covid-19 Inquiry* [Online]. Available at https://covid19.public-inquiry.uk (Accessed 28 August 2025).

UNDR (2015) *Sendai Framework for Disaster Risk Reduction 2015-2030*, United Nations Office for Disaster Risk Reduction.

UNEP (2024) *Adaptation Gap Report 2024: Come hell and high water.*, United Nations Environment Programme.

Urban, M. C. (2015) "Climate change. Accelerating extinction risk from climate change.," *Science*, vol. 348, no. 6234, pp. 571–573 [Online]. DOI: 10.1126/science.aaa4984.

Ureta, C., Ramírez-Barahona, S., Calderón-Bustamante, Ó., Cruz-Santiago, P., Gay-García, C., Swingedouw, D., Defrance, D. and Cuervo-Robayo, A. P. (2022) "Evaluation of animal and plant diversity suggests Greenland's thaw hastens the biodiversity crisis.," *Communications Biology*, vol. 5, no. 1, p. 985 [Online]. DOI: 10.1038/s42003-022-03943-3.

Vallotton, J. D. and Unc, A. (2024) "Soil carbon in the boreal region under climate and land use change," *Soil Use and Management*, vol. 40, no. 3 [Online]. DOI: 10.1111/sum.13108.

Varma, V. and Bebber, D. P. (2019) "Climate change impacts on banana yields around the world.," *Nature climate change*, vol. 9, no. 10, pp. 752–757 [Online]. DOI: 10.1038/s41558-019-0559-9.

Veh, G., Korup, O. and Walz, A. (2020) "Hazard from Himalayan glacier lake outburst floods.," Proceedings of the National Academy of Sciences of the United States of America, vol. 117, no. 2, pp. 907–912 [Online]. DOI: 10.1073/pnas.1914898117.

Velasco, J. A., Estrada, F., Calderón-Bustamante, O., Swingedouw, D., Ureta, C., Gay, C. and Defrance, D. (2021) "Synergistic impacts of global warming and thermohaline circulation collapse on amphibians.," *Communications Biology*, vol. 4, no. 1, p. 141 [Online]. DOI: 10.1038/s42003-021-01665-6.

Vilímek, V., Zapata, M. L., Klimeš, J., Patzelt, Z. and Santillán, N. (2005) "Influence of glacial retreat on natural hazards of the Palcacocha Lake area, Peru," Landslides, vol. 2, no. 2, pp. 107–115 [Online]. DOI: 10.1007/s10346-005-0052-6.

Virkkala, A.-M., Rogers, B. M., Watts, J. D., Arndt, K. A., Potter, S., Wargowsky, I., Schuur, E. A. G., See, C. R., Mauritz, M., Boike, J., Bret-Harte, M. S., Burke, E. J., Burrell, A., Chae, N., Chatterjee, A., Chevallier, F., Christensen, T. R., Commane, R., Dolman, H., Edgar, C. W. and Natali, S. M. (2025) "Wildfires offset the increasing but spatially heterogeneous Arctic–boreal CO2 uptake," *Nature Climate Change*, vol. 15, no. 2, pp. 188–195 [Online]. DOI: 10.1038/s41558-024-02234-5.

Vitousek, S., Barnard, Patrick L, Fletcher, C. H., Frazer, N., Erikson, L. and Storlazzi, C. D. (2017) "Doubling of coastal flooding frequency within decades due to sea-level rise.," *Scientific Reports*, vol. 7, no. 1, p. 1399 [Online]. DOI: 10.1038/s41598-017-01362-7.

Vitousek, S., Barnard, Patrick L. and Limber, P. (2017) "Can beaches survive climate change?," *Journal of Geophysical Research: Earth Surface*, vol. 122, no. 4, pp. 1060–1067 [Online]. DOI: 10.1002/2017JF004308.

van Vliet, M. T. H., Wiberg, D., Leduc, S. and Riahi, K. (2016) "Power-generation system vulnerability and adaptation to changes in climate and water resources," *Nature climate change*, vol. 6, no. 4, pp. 375–380 [Online]. DOI: 10.1038/nclimate2903.

Vousdoukas, M. I., Athanasiou, P., Giardino, A., Mentaschi, L., Stocchino, A., Kopp, R. E., Menéndez, P., Beck, M. W., Ranasinghe, R. and Feyen, L. (2023) "Small Island Developing States under threat by rising seas even in a 1.5 °C warming world," *Nature Sustainability* [Online]. DOI: 10.1038/s41893-023-01230-5.

Vousdoukas, M. I., Mentaschi, L., Hinkel, J., Ward, P. J., Mongelli, I., Ciscar, J.-C. and Feyen, L. (2020) "Economic motivation for raising coastal flood defenses in Europe.," *Nature Communications*, vol. 11, no. 1, p. 2119 [Online]. DOI: 10.1038/s41467-020-15665-3.

Walker, X. J., Baltzer, J. L., Cumming, S. G., Day, N. J., Ebert, C., Goetz, S., Johnstone, J. F., Potter, S., Rogers, B. M., Schuur, E. A. G., Turetsky, M. R. and Mack, M. C. (2019) "Increasing wildfires threaten historic carbon sink of boreal forest soils.," *Nature*, vol. 572, no. 7770, pp. 520–523 [Online]. DOI: 10.1038/s41586-019-1474-y.

Wang, T., Yang, D., Yang, Y., Zheng, G., Jin, H., Li, X., Yao, T. and Cheng, G. (2023) "Pervasive permafrost thaw exacerbates future risk of water shortage across the tibetan plateau," *Earth's Future*, vol. 11, no. 10 [Online]. DOI: 10.1029/2022EF003463.

Wang, Z., Xiao, M., Nicolsky, D., Romanovsky, V., McComb, C. and Farquharson, L. (2023) "Arctic coastal hazard assessment considering permafrost thaw subsidence, coastal erosion and flooding," *Environmental Research Letters*, vol. 18, no. 10, p. 104003 [Online]. DOI: 10.1088/1748-9326/acf4ac.

Ward Jones, M. K., Schwoerer, T., Gannon, G. M., Jones, B. M., Kanevskiy, M. Z., Sutton, I., St. Pierre, B., St. Pierre, C., Russell, J. and Russell, D. (2022) "Climate-driven expansion of northern agriculture must consider permafrost," *Nature Climate Change*, vol. 12, no. 8, pp. 699–703 [Online]. DOI: 10.1038/s41558-022-01436-z.

Wassenburg, J. A., Vonhof, H. B., Cheng, H., Martínez-García, A., Ebner, P.-R., Li, X., Zhang, H., Sha, L., Tian, Y., Edwards, R. L., Fiebig, J. and Haug, G. H. (2021) "Penultimate deglaciation Asian monsoon response to North Atlantic circulation collapse," *Nature geoscience*, vol. 14, no. 12, pp. 937–941 [Online]. DOI: 10.1038/s41561-021-00851-9.

Wassmann, R., Jagadish, S. V. K., Sumfleth, K., Pathak, H., Howell, G., Ismail, A., Serraj, R., Redona, E., Singh, R. K. and Heuer, S. (2009) "Chapter 3 regional vulnerability of climate change impacts on asian rice production and scope for adaptation," in Advances in Agronomy, Elsevier, vol. 102, pp. 91–133 [Online]. DOI: 10.1016/S0065-2113(09)01003-7.

WEF (2025) *The Global Risks Report 2025*, World Economic Forum.

van Westen, R. M. and Baatsen, M. L. J. (2025) "European temperature extremes under different AMOC scenarios in the community earth system model," *Geophysical research letters*, vol. 52, no. 12 [Online]. DOI: 10.1029/2025GL114611.

van Westen, R. M., Kliphuis, M. and Dijkstra, H. A. (2024) "Physics-based early warning signal shows that AMOC is on tipping course.," *Science Advances*, vol. 10, no. 6, p. eadk1189 [Online]. DOI: 10.1126/sciadv.adk1189.

Wheeler, T. and von Braun, J. (2013) "Climate change impacts on global food security.," *Science*, vol. 341, no. 6145, pp. 508–513 [Online]. DOI: 10.1126/science.1239402.

Whitman, E., Parisien, M.-A., Thompson, D. K. and Flannigan, M. D. (2019) "Short-interval wildfire and drought overwhelm boreal forest resilience.," *Scientific Reports*, vol. 9, no. 1, p. 18796 [Online]. DOI: 10.1038/s41598-019-55036-7.

Williamson, M. S., Collins, M., Drijfhout, S. S., Kahana, R., Mecking, J. V. and Lenton, T. M. (2017) "Effect of AMOC collapse on ENSO in a high resolution general circulation model," *Climate dynamics*, vol. 50, pp. 1–16 [Online]. DOI: 10.1007/s00382-017-3756-0.

Winkelmann, R., Dennis, D. P., Donges, J. F., Loriani, S., Klose, A. K., Abrams, J. F., Alvarez-Solas, J., Albrecht, T., Armstrong McKay, D., Bathiany, S., Blasco Navarro, J., Brovkin, V., Burke, E., Danabasoglu, G., Donner, R. V., Drüke, M., Georgievski, G., Goelzer, H., Harper, A. B., Hegerl, G. and Yang, S. (2025) "The Tipping Points Modelling Intercomparison Project (TIPMIP): Assessing tipping point risks in the Earth system," [Online]. DOI: 10.5194/egusphere-2025-1899.

Wood, R. A., Crucifix, M., Lenton, T. M., Mach, K. J., Moore, C., New, M., Sharpe, S., Stocker, T. F. and Sutton, R. T. (2023) "A climate science toolkit for high impact-low likelihood climate risks," *Earth's Future*, vol. 11, no. 4 [Online]. DOI: 10.1029/2022EF003369.

Woollings, T., Gregory, J. M., Pinto, J. G., Reyers, M. and Brayshaw, D. J. (2012) "Response of the North Atlantic storm track to climate change shaped by ocean–atmosphere coupling," *Nature Geoscience*, vol. 5, no. 5, pp. 313–317 [Online]. DOI: 10.1038/ngeo1438.

World Economic Forum (2025) *Over 80% of the world's reefs hit by bleaching event and other nature and climate news* [Online]. Available at https://www.weforum.org/stories/2025/04/reefs-hit-by-bleaching-event-nature-and-climate-news/ (Accessed 28 August 2025).

Wu, R., Trubl, G., Taş, N. and Jansson, J. K. (2022) "Permafrost as a potential pathogen reservoir," *One Earth*, vol. 5, no. 4, pp. 351–360 [Online]. DOI: 10.1016/j.oneear.2022.03.010.

Wunderling, N., Donges, J. F., Kurths, J. and Winkelmann, R. (2021) "Interacting tipping elements increase risk of climate domino effects under global warming," *Earth System Dynamics*, vol. 12, no. 2, pp. 601–619 [Online]. DOI: 10.5194/esd-12-601-2021.

WWF (2009) *The Coral Triangle and climate change: Ecosystem, livelihoods and governance.*, World Wide Fund for Nature.

Yalew, S. G., van Vliet, M. T. H., Gernaat, D. E. H. J., Ludwig, F., Miara, A., Park, C., Byers, E., De Cian, E., Piontek, F., Iyer, G., Mouratiadou, I., Glynn, J., Hejazi, M., Dessens, O., Rochedo, P., Pietzcker, R., Schaeffer, R., Fujimori, S., Dasgupta, S., Mima, S. and van Vuuren, D. P. (2020) "Impacts of climate change on energy systems in global and regional scenarios," *Nature Energy*, vol. 5, no. 10, pp. 794–802 [Online]. DOI: 10.1038/s41560-020-0664-z.

Yang, D., Yang, Y. and Xia, J. (2021) "Hydrological cycle and water resources in a changing world: A review," *Geography and Sustainability*, vol. 2, no. 2, pp. 115–122 [Online]. DOI: 10.1016/j.geosus.2021.05.003.

Yang, Y., Maselli, V., Normandeau, A., Piper, D. J. W., Li, M. Z., Campbell, D. C., Gregory, T. and Gao, S. (2020) "Latitudinal response of storm activity to abrupt climate change during the last 6,500 years," *Geophysical research letters*, vol. 47, no. 19 [Online]. DOI: 10.1029/2020GL089859.

Yang, Z., Yang, D., Sun, D. and Zhong, L. (2023) "Ecological and social poverty traps: Complex interactions moving toward sustainable development," *Sustainable Development*, vol. 31, no. 2, pp. 853–864 [Online]. DOI: 10.1002/sd.2425.

Yin, L., Tao, F., Zhai, R., Chen, Y., Hu, J., Wang, Z. and Fu, B. (2022) "Impacts of future climate change and atmospheric co2 concentration on ecosystem water retention service," Earth's Future, vol. 10, no. 4 [Online]. DOI: 10.1029/2021EF002138.

Zemp, D. C., Schleussner, C. F., Barbosa, H. M. J., van der Ent, R. J., Donges, J. F., Heinke, J., Sampaio, G. and Rammig, A. (2014) "On the importance of cascading moisture recycling in South America," *Atmospheric Chemistry and Physics*, vol. 14, no. 23, pp. 13337–13359 [Online]. DOI: 10.5194/acp-14-13337-2014.

Zemp, D. C., Schleussner, C. F., Barbosa, H. M. J. and Rammig, A. (2017) "Deforestation effects on Amazon forest resilience," *Geophysical Research Letters*, vol. 44, no. 12, pp. 6182–6190 [Online]. DOI: 10.1002/2017GL072955.

Zhang, D., Zhou, G., Li, W., Han, L., Zhang, S., Yao, X. and Duan, H. (2023) "A robust glacial lake outburst susceptibility assessment approach validated by GLOF event in 2020 in the Nidu Zangbo Basin, Tibetan Plateau," CATENA, vol. 220, p. 106734 [Online]. DOI: 10.1016/j.catena.2022.106734.

Zhang, P., Jeong, J.-H., Yoon, J.-H., Kim, H., Wang, S.-Y. S., Linderholm, H. W., Fang, K., Wu, X. and Chen, D. (2020) "Abrupt shift to hotter and drier climate over inner East Asia beyond the tipping point.," *Science*, vol. 370, no. 6520, pp. 1095–1099 [Online]. DOI: 10.1126/science.abb3368.

Zhang, T., Jiang, X., Yang, S., Chen, J. and Li, Z. (2022) "A predictable prospect of the South Asian summer monsoon.," *Nature Communications*, vol. 13, no. 1, p. 7080 [Online]. DOI: 10.1038/s41467-022-34881-7.

Zhang, T., Wang, W., An, B. and Wei, L. (2023) "Enhanced glacial lake activity threatens numerous communities and infrastructure in the Third Pole.," Nature Communications, vol. 14, no. 1, p. 8250 [Online]. DOI: 10.1038/s41467-023-44123-z.

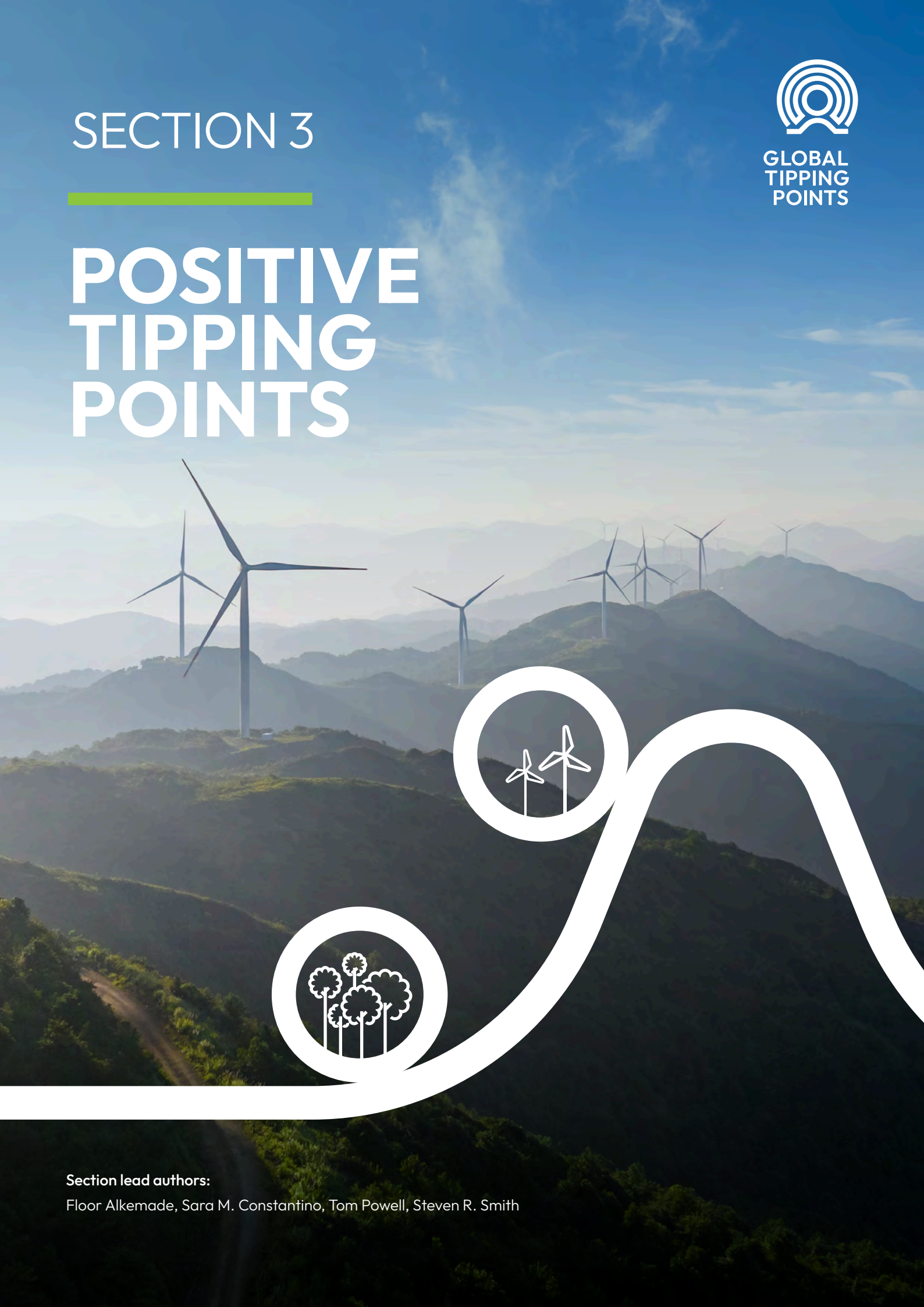
Zhao, J., Cheng, H., Cao, J., Sinha, A., Dong, X., Pan, L., Pérez-Mejías, C., Zhang, H., Li, H., Wang, J., Wang, K., Cui, J. and Yang, Y. (2023) "Orchestrated decline of Asian summer monsoon and Atlantic meridional overturning circulation in global warming period," *The Innovation Geoscience*, vol. 1, no. 1, pp. 1–9 [Online]. DOI: 10.59717/j.xinn-geo.2023.100011.

Zheng, X., Li, A., Wan, S., Jiang, F., Kao, S. J. and Johnson, C. (2014) "ITCZ and ENSO pacing on East Asian winter monsoon variation during the Holocene: Sedimentological evidence from the Okinawa Trough," *Journal of Geophysical Research: Oceans*, vol. 119, no. 7, pp. 4410–4429 [Online]. DOI: 10.1002/2013JC009603.

Zscheischler, J., Westra, S., van den Hurk, B. J. J. M., Seneviratne, S. I., Ward, P. J., Pitman, A., AghaKouchak, A., Bresch, D. N., Leonard, M., Wahl, T. and Zhang, X. (2018) "Future climate risk from compound events," *Nature climate change*, vol. 8, no. 6, pp. 469–477 [Online]. DOI: 10.1038/s41558-018-0156-3.

SECTION 3

POSITIVE TIPPING POINTS



Section lead authors:
Floor Alkemade, Sara M. Constantino, Tom Powell, Steven R. Smith

References 3.1

Allen, C. and Malekpour, S. (2023) 'Unlocking and accelerating transformations to the SDGs: a review of existing knowledge', Sustainability Science, 18(4), pp. 1939–1960. Available at: https://doi.org/10.1007/s11625-023-01342-z.

Ameli, N. et al. (2025) 'Driving sustainability transitions through financial tipping points', Earth System Dynamics, 16(1), pp. 333–345. Available at: https://doi.org/10.5194/esd-16-333-2025.

Behrendt, F. (2018) 'Why cycling matters for electric mobility: towards diverse, active and sustainable e-mobilities', Mobilities, 13(1), pp. 64–80. Available at: https://doi.org/10.1080/17450101.2017.1335463.

BNEF (2025) Bloomberg Electric Vehicle Outlook 2025. Available at: https://about.bnef.com/insights/clean-transport/electric-vehicle-outlook/ (Accessed: 11 September 2025).

Bonvillian, W.B. (2013) 'Advanced Manufacturing Policies and Paradigms for Innovation', Science, 342(6163), pp. 1173–1175. Available at: https://doi.org/10.1126/science.1242210.

Boulton, C.A., Buxton, J.E. and Lenton, T.M. (2025) 'Early opportunity signals of a tipping point in the UK's second-hand electric vehicle market', Earth System Dynamics, 16(2), pp. 411–421. Available at: https://doi.org/10.5194/esd-16-411-2025.

Bury, T.M. et al. (2021) 'Deep learning for early warning signals of tipping points', Proceedings of the National Academy of Sciences, 118(39), p. e2106140118. Available at: https://doi.org/10.1073/pnas.2106140118.

Centola, D. et al. (2018) 'Experimental evidence for tipping points in social convention', Science, 360, pp. 1116–1119.

Centola, D. (2021) Change: how to make big things happen. London: John Murray.

Cherry, C., Verfuerth, C. and Demski, C. (2024) 'Discourses of climate inaction undermine public support for 1.5 °C lifestyles', Global Environmental Change, 87, p. 102875. Available at: https://doi.org/10.1016/j.gloenvcha.2024.102875.

Coan, T.G. et al. (2021) 'Computer-assisted classification of contrarian claims about climate change', Scientific Reports, 11(1), pp. 1–12.

Dunlap, R.E. and McCright, A.M. (2015) 'Challenging Climate Change: The Denial Countermovement', in R.E. Dunlap and R.J. Brulle (eds) Climate Change and Society: Sociological Perspectives. New York, N.Y.: Oxford University Press, pp. 393–442.

Earle, S. (2021) 'The Sordid Story of the Most Successful Political Party in the World', The New Republic [Preprint].

EEIST (2021) The New Economics of Innovation and Transition: Evaluating Opportunities and Risks. Available at: https://eeist.co.uk/eeist-reports/the-new-economics-of-innovation-and-transition-evaluating-opportunities-and-risks/ (Accessed: 18 December 2024).

Eker, S. et al. (2024) 'Cross-system interactions for positive tipping cascades', Earth System Dynamics, 15(3), pp. 789–800. Available at: https://doi.org/10.5194/esd-15-789-2024.

Elbil (2024) 'Norwegian EV Policy', Norway is leading the way for a transition to zero emission in transport. Available at: https://elbil.no/english/norwegian-ev-policy/ (Accessed: 11 September 2025).

Everall, J.P. et al. (2025) 'The Pareto effect in tipping social networks: from minority to majority', Earth System Dynamics, 16(1), pp. 189–214. Available at: https://doi.org/10.5194/esd-16-189-2025.

Geels, F.W. and Ayoub, M. (2023) 'A socio-technical transition perspective on positive tipping points in climate change mitigation: Analysing seven interacting feedback loops in offshore wind and electric vehicles acceleration', Technological Forecasting and Social Change, 193, p. 122639. Available at: https://doi.org/10.1016/j.techfore.2023.122639.

Granovetter, M. (1978) 'Threshold Models of Collective Behavior', American Journal of Sociology, 83(6), pp. 1420–1443. Available at: https://doi.org/10.1086/226707.

Hoekstra, A. and Alkemade, F. (2025) 'Using learning curves to guide the energy transition with the example of heavy electric trucks', Sustainable Mobility and Transport, 2(1), p. 14. Available at: https://doi.org/10.1038/s44333-025-00029-5.

IRENA (2025) Renewable Capacity Statistics. Available at: https://www.ourenergypolicy.org/resources/renewable-capacity-statistics-2025/ (Accessed: 11 September 2025).

Jordan, A.J. and Moore, B. (2020) Durable by Design. Cambridge: Cambridge University Press.

Kuehn, C. (2011) 'A mathematical framework for critical transitions: Bifurcations, fast–slow systems and stochastic dynamics', Physica D: Nonlinear Phenomena, 240(12), pp. 1020–1035. Available at: https://doi.org/10.1016/j.physd.2011.02.012.

Kuhmonen, I. and Siltaoja, M. (2022) 'Farming on the margins: Just transition and the resilience of peripheral farms', Environmental Innovation and Societal Transitions, 43, pp. 343–357. Available at: https://doi.org/10.1016/j.eist.2022.04.011.

Lamb, W.F. et al. (2020) 'Discourses of climate delay', Global Sustainability, 3, p. e17. Available at: https://doi.org/10.1017/sus.2020.13.

Lenton, T.M. et al. (2022) 'Operationalising Positive Tipping Points towards Global Sustainability', Global Sustainability, 5, e1, pp. 1–16.

Lenton, T.M. et al. (2023) The Global Tipping Points Report 2023. The University of Exeter. Available at: https://global-tipping-points.org/.

Lenton, T.M. et al. (2025) 'A method to identify positive tipping points to accelerate low-carbon transitions and actions to trigger them', Sustainability Science [Preprint]. Available at: https://doi.org/10.1007/s11625-025-01704-9.

Lockwood, M. (2015) 'The political dynamics of green transformations: feedback effects and institutional context', in I. Scoones, M. Leach and P. Newell (eds) The Politics of Green Transformations. Abingdon, Oxon: Routledge, pp. 86–101.

Malhotra, A. and Schmidt, T.S. (2020) 'Accelerating Low-Carbon Innovation', Joule, 4(11), pp. 2259–2267. Available at: https://doi.org/10.1016/j.joule.2020.09.004.

Malone, R.E. (2022) 'Tobacco control and the climate emergency', Tobacco Control, 31(3), pp. 395–396. Available at: https://doi.org/10.1136/tobaccocontrol-2022-057412.

Mascia, M.B. and Mills, M. (2018) 'When conservation goes viral: The diffusion of innovative biodiversity conservation policies and practices', Conservation Letters, 11(3), p. e12442. Available at: https://doi.org/10.1111/conl.12442.

McKie, R.E. (2021) 'Obstruction, delay and transnationalism: Examining the online climate change counter-movement', Energy Research & Social Science, 80, p. 102217. Available at: https://doi.org/10.1016/j.erss.2021.102217.

Meldrum, M. et al. (2023) The Breakthrough Effect: How to Trigger a Cascade of Tipping Points to Accelerate the Net Zero Transition. SystemIQ, University of Exeter, Bezos Earth Fund.

Nijsse, F.J.M.M. et al. (2023) 'The momentum of the solar energy transition', Nature Communications, 14(1), p. 6542. Available at: https://doi.org/10.1038/s41467-023-41971-7.

Nisbett, N. et al. (2025) 'Climate action or delay: the dynamics of competing narratives in the UK political sphere and the influence of climate protest', Climate Policy, 25(4), pp. 513–526. Available at: https://doi.org/10.1080/14693062.2024.2398169.

OECD (2025) Leveraging positive tipping points in the race to net zero. Paris: OECD. Available at: https://www.oecd.org/en/publications/leveraging-positive-tipping-points-in-the-race-to-net-zero_50b737f8-en.html (Accessed: 11 September 2025).

Oreskes, N. and Conway, E.M. (2010) Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming. London: Bloomsbury Press.

Pereira, L.M. et al. (2025) 'Beyond tipping points: risks, equity and the ethics of intervention', Earth System Dynamics, 16(4), pp. 1267–1285. Available at: https://doi.org/10.5194/esd-16-1267-2025.

Pollin, R. (2023) 'Fossil Fuel Industry Phase-Out and Just Transition: Designing Policies to Protect Workers' Living Standards', Journal of Human Development and Capabilities, 24(4), pp. 539–568. Available at: https://doi.org/10.1080/19452829.2023.2241840.

Potential Energy (2023) Later is Too Late: A comprehensive analysis of the messaging that accelerates climate action in the G20 and beyond. Potential Energy. Available at: https://potentialenergycoalition.org/later-is-too-late-global-report/.

Raekstad, P. and Gradin, S.S. (2020) Prefigurative Politics. Cambridge: Polity Press.

Rapid Transition Alliance (2021) Is there hope? Available at: https://rapidtransition.org/resources/a-pocket-book-of-hope/ (Accessed: 11 September 2025).

Rogers, E.M. (2003) Diffusion of Innovations, 5th Edition. New York, NY: Simon and Schuster.

Rotmans, J., Kemp, R. and Van Asselt, M. (2001) 'More evolution than revolution: transition management in public policy', Foresight, 3(1), pp. 15–31. Available at: https://doi.org/10.1108/14636680110803003/full/html.

Schilling, T., Wyss, R. and Binder, C.R. (2018) 'The Resilience of Sustainability Transitions', Sustainability, 10(12), p. 4593. Available at: https://doi.org/10.3390/su10124593.

Sharpe, S. and Lenton, T.M. (2021) 'Upward-scaling tipping cascades to meet climate goals: plausible grounds for hope', Climate Policy, 21(4), pp. 421–433.

Tindall, D.B., Stoddart, M.C.J. and Dunlap, R.E. (eds) (2022) Handbook of anti-environmentalism. Cheltenham, UK ; Northampton, MA, USA: Edward Elgar Publishing.

Turnheim, B. and Geels, F.W. (2012) 'Regime destabilisation as the flipside of energy transitions: Lessons from the history of the British coal industry (1913–1997)', Energy Policy, 50, pp. 35–49.

Unruh, G.C. (2000) 'Understanding carbon lock-in', Energy Policy, 28(12), pp. 817–830.

Victor, D.G., Geels, F.W. and Sharpe, S. (2019) 'Accelerating the Low Carbon Transition: The Case for Stronger, More Targeted and Coordinated International Action.'

Wilson, C. et al. (2020) 'Granular technologies to accelerate decarbonization', Science, 368(6486), pp. 36–39. Available at: https://doi.org/10.1126/science.aaz8060.

Yelle, L.E. (1979) 'The Learning Curve: Historical Review and Comprehensive Survey', Decision Sciences, 10(2), pp. 302–328. Available at: https://doi.org/10.1111/j.1540-5915.1979.tb00026.x.

References 3.2

Ameli, N., Chenet, H., Falkenberg, M., Kothari, S., Rickman, J., & Lamperti, F. (2025). Driving sustainability transitions through financial tipping points. Earth System Dynamics, 16(1), 333-345.

Avelino, F., Wijsman, K., Van Steenbergen, F., Jhagroe, S., Wittmayer, J., Akerboom, S., ... & Kalfagianni, A. (2024). Just sustainability transitions: politics, power, and prefiguration in transformative change toward justice and sustainability. Annual Review of Environment and Resources, 49.

Averchenkova, A., Higham, C., Chan, T., & Keuschnigg, I. (2024). Impacts of climate framework laws: Lessons from Germany, Ireland and New Zealand. Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science.

Baumgartner, Frank R., and Bryan D. Jones. Agendas and Instability in American Politics. University of Chicago Press, 1993.

Behn, O., Wichmann, J., Leyer, M., & Schilling, A. (2025). Spillover effects in environmental behaviors: A scoping review about its antecedents, behaviors, and consequences. Current Psychology, 44(5), 3665-3689.

Ben Ayed, R., & Hanana, M. (2021). Artificial intelligence to improve the food and agriculture sector. Journal of Food Quality, 2021(1), 5584754.

Bennett, N. J., Blythe, J., Cisneros-Montemayor, A. M., Singh, G. G., & Sumaila, U. R. (2019). Just transformations to sustainability. Sustainability, 11(14), 3881.

Berditchevskaia, A., & Baeck, P. (2020). The future of minds and machines: How AI can enhance collective intelligence. Nesta. https://media.nesta.org.uk/documents/FINAL_The_future_of_minds_and_machines.pdf

Bergquist, P., Mildenberger, M., & Stokes, L. C. (2020). Combining climate, economic, and social policy builds public support for climate action in the US. Environmental Research Letters, 15(5), 054019.

Biswas, A., Chahout, H., Pigram, T., Dong, H., Williams, H. T., Fung, F., & Xie, H. (2025, July). Evaluating Retrieval Augmented Generation to Communicate UK Climate Change Information. In Proceedings of the 2nd Workshop on Natural Language Processing Meets Climate Change (ClimateNLP 2025) (pp. 126-141).

Bolsen, T., & Shapiro, M. A. (2018). The US news media, polarisation on climate change, and pathways to effective communication. Environmental Communication, 12(2), 149-163.

Bonvillian, W. B., & Weiss, C. (2015). Technological innovation in legacy sectors. Oxford University Press.

Boulton, C. A., Buxton, J. E., & Lenton, T. M. (2023). Early opportunity signals of a tipping point in the UK's second-hand electric vehicle market. EGUsphere, 2023, 1-13.

The British Academy. (2025). Governance to accelerate net zero [Report]. The British Academy. https://www.thebritishacademy.ac.uk/publications/governance-to-accelerate-net-zero/

Caggiano, H., Constantino, S. M., Lees, J., Majumdar, R., & Weber, E. U. (2023). Community-engaged research is best positioned to catalyse systemic change.

Centola, D. (2021). Complex contagions. In Research handbook on analytical sociology (pp. 321-335). Edward Elgar Publishing.

Chaudhary, Y., & Penn, J. (2024). Beware the intention economy: Collection and commodification of intent via large language models. Harvard Data Science Review, (Special Issue 5).

Chenoweth, E., & Stephan, M. J. (2011). Why civil resistance works: The strategic logic of nonviolent conflict. Columbia University Press.

Centola, D., Becker, J., Brackbill, D., & Baronchelli, A. (2018). Experimental evidence for tipping points in social convention. Science, 360(6393), 1116-1119.

Client Earth v. Shell plc and Others [2023] EWHC 1897 (Ch), Available at: https://www.judiciary.uk/wp-content/uploads/2023/07/ClientEarth-v-Shell-judgment-240723.pdf

Coan, T. G., Boussalis, C., Cook, J., & Nanko, M. O. (2021). Computer-assisted classification of contrarian claims about climate change. Scientific reports, 11(1), 22320.

Constantino, S. M., Sparkman, G., Kraft-Todd, G. T., Bicchieri, C., Centola, D., Shell-Duncan, B., ... & Weber, E. U. (2022). Scaling up change: A critical review and practical guide to harnessing social norms for climate action. Psychological science in the public interest, 23(2), 50-97.

Costello, T. H., Pennycook, G., & Rand, D. G. (2024). Durably reducing conspiracy beliefs through dialogues with AI. Science, 385(6714), eadq1814.

Creutzig, F., Roy, J., & Minx, J. (2024). Demand-side climate change mitigation: where do we stand and where do we go?. Environmental Research Letters, 19(4), 040201.

Creutzig, F., Niamir, L., Bai, X., Callaghan, M., Cullen, J., Díaz-José, J., ... & Ürge-Vorsatz, D. (2022). Demand-side solutions to climate change mitigation consistent with high levels of well-being. Nature climate change, 12(1), 36-46.

Curato, N., Dryzek, J. S., Levai, D., Mellier, C., Ross, M., & Wilson, R. (2025). Where next for global climate deliberation: From proof of concept to a role in transformation. Earth System Governance, 25, 100280.

Deloitte & RMI. (2022). Systems change for a sustainable future: Rethinking corporate climate action in an era of rapid disruption. Deloitte. https://www.deloitte.com/content/dam/assets-shared/legacy/docs/analysis/2022/gx-systems-change-for-a-sustainable-future.pdf

Devine-Wright, P., Whitmarsh, L., Gatersleben, B., O'Neill, S., Hartley, S., Burningham, K., ... & Anable, J. (2022). Placing people at the heart of climate action. PLoS Climate, 1(5), e0000035.

D'Arcangelo, F. M., Kruse, T., & Pisu, M. (2024). Identifying and tracking climate change mitigation strategies with a cluster-based assessment. npj Climate Action, 3(1), 86.

Digital Catapult. (n.d.). Critical Minerals NICE: About NICE. Made Smarter Innovation | Digital Supply Chain Hub. https://hub.digitalsupplychainhub.uk/hub/critical-minerals-nice/about-nice

Dougherty, C., Hutchinson, L., Masterson, M., Randol, C., & Emerson, C. (2024, September 18). Clean Energy 101: Demand aggregation. RMI. https://rmi.org/demand-aggregation-101/

Efferson, C., Vogt, S., & Fehr, E. (2020). The promise and the peril of using social influence to reverse harmful traditions. Nature Human Behaviour, 4(1), 55-68.

Eker, S., Lenton, T. M., Powell, T., Scheffran, J., Smith, S. R., Swamy, D., & Zimm, C. (2024). Cross-system interactions for positive tipping cascades. Earth System Dynamics, 15(3), 789-800.

Falkenberg, M., Galeazzi, A., Torricelli, M., Di Marco, N., Larosa, F., Sas, M., ... & Baronchelli, A. (2022). Growing polarisation around climate change on social media. Nature Climate Change, 12(12), 1114-1121.

Farmer, J. D., Hepburn, C., Ives, M. C., Hale, T., Wetzer, T., Mealy, P., ... & Way, R. (2019). Sensitive intervention points in the post-carbon transition. Science, 364(6436), 132-134.

Fesenfeld, L. P., Schmid, N., Finger, R., Mathys, A., & Schmidt, T. S. (2022). The politics of enabling tipping points for sustainable development. One Earth, 5(10), 1100-1108.

Fine, G. A. (2012). Tiny publics: A theory of group action and culture. Russell Sage Foundation.

Foundation to Promote the Fossil-Free Movement v. Royal Airline N.V, Amsterdam Court, C/13/719848/HA ZA 22-524, 2024. Available at: https://climatecasechart.com/wp-content/uploads/non-us-case-documents/2024/20240320_17244_judgment.pdf

Ganz, M. (2009). Why David Sometimes Wins: Leadership, Organisation, and Strategy in the California Farm Worker Movement. Oxford University Press..

Ganz, M. (2010). Leading change: Leadership, organisation, and social movements. In N. Nohria & R. Khurana (Eds.), Handbook of leadership theory and practice (pp. 509–550). Harvard Business School Press.

Ganz, M. (2024). People, Power, Change: Organising for Democratic Renewal. Oxford University Press.

Geels, F. W., & Ayoub, M. (2023). A socio-technical transition perspective on positive tipping points in climate change mitigation: Analysing seven interacting feedback loops in offshore wind and electric vehicles acceleration. Technological Forecasting and Social Change, 193, 122639.

Gilens, M. (2024). The Preference-Policy Link and Representation. For the People?: Democratic Representation in America, 120.

Gillingham, K. T., & Bollinger, B. (2021). Social learning and solar photovoltaic adoption. Management Science, 67(11), 7091-7112.

Giordono, L., Boudet, H., & Gard-Murray, A. (2020). Local adaptation policy responses to extreme weather events. Policy sciences, 53(4), 609-636.

Granovetter, M. (1978). Threshold models of collective behavior. American journal of sociology, 83(6), 1420-1443.

Graziano, M., & Gillingham, K. (2015). Spatial patterns of solar photovoltaic system adoption: the influence of neighbors and the built environment. Journal of Economic Geography, 15(4), 815-839.

Grubb, M., Poncia, A., & Pasqualino, R. (2024). Dynamics of the Energy Transition: Innovation, Transition Economics, Path Dependency, and Decision Making. World Bank Working Paper, 7(11), 2024.

Guenther, G. (2024). The language of climate politics: Fossil-fuel propaganda and how to fight it. Oxford University Press.

Hale, T. (2021). Governing net zero: The conveyor belt. Blavatnik School of Government, University of Oxford.

Hampton, S., & Whitmarsh, L. (2024). Carbon capability revisited: Theoretical developments and empirical evidence. Global Environmental Change, 87, 102895.

Han, H. (2014). How organisations develop activists. Oxford University Press.

Heifetz, R. A. (1994). Leadership without easy answers. Harvard University Press.

Higham, C., Setzer, J., & Bradeen, E. (2022). Challenging government responses to climate change through framework litigation. Grantham Research Institute on Climate Change and the Environment & Centre for Climate Change Economics and Policy, London School of Economics and Political Science.

Hosseini, M. A., Roozbahani, M. H., & Sayyah, A. (2025). AI-driven digital twin architecture for urban bus fleet life-cycle cost analysis in a metaverse environment. Sustainable Cities and Society, 106611.

Intergovernmental Panel on Climate Change (IPCC). (2022). National and Sub-national Policies and Institutions. In: Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; 2023:1355-1450. https://doi.org/10.1017/9781009157926.015

Inter-American Court of Human Rights (IACHR), 2025. Advisory Opinion OC-32/25:

The Climate Emergency and Human Rights.

San José, Costa Rica: Inter-American Court of Human Rights. Available at: https://www.corteidh.or.cr/tablas/OC-32-2025/index-eng.html (Accessed: 1 September 2025).

International Court of Justice (ICJ), 2025. Obligations of States in

Respect of Climate Change (Request for Advisory Opinion). Available at: https://www.icj-cij.org/case/187

International Tribunal for the Law of the Sea (ITLOS), 2024. Request for an Advisory Opinion Submitted by the Commission of Small Island States on Climate Change and International Law. Available at: https://itlos.org/fileadmin/itlos/documents/cases/31/Advisory_Opinion/C31_Adv_Op_21.05.2024_orig.pdf

Jacobs, L. R., & Mettler, S. (2018). When and how new policy creates new politics: Examining the feedback effects of the Affordable Care Act on public opinion. Perspectives on politics, 16(2), 345-363.

Kingdon, J. W. (1995). Agendas, alternatives, and public policies (2nd ed.). HarperCollins College Publishers.

Lamb, W. F., Mattioli, G., Levi, S., Roberts, J. T., Capstick, S., Creutzig, F., ... & Steinberger, J. K. (2020). Discourses of climate delay. Global sustainability, 3, e17.

Lamperti, F., Bosetti, V., Roventini, A., & Tavoni, M. (2019). The public costs of climate-induced financial instability. Nature Climate Change, 9(11), 829-833.

Laybourn-Langton, L. (2020). A NEW POLITICS.

Leghari v. Federation of Pakistan, W.P. No. 25501/201, 2015. Available at: https://climatecasechart.com/non-us-case/ashgar-leghari-v-federation-of-pakistan/

Lenton, T. M., McKay, D. I. A., Loriani, S., Abrams, J. F., Lade, S. J., Donges, J. F., ... & Rockström, J. (2023). The global tipping points report 2023 (Doctoral dissertation, University of Exeter).

Luciano Lliuya v. RWE AG, 5 U 15/17 OLG Hamm / Case No. 2 0 285/15 Essen Regional Court, 2025. Available at: https://climatecasechart.com/non-us-case/lliuya-v-rwe-ag/

Maki, A., Carrico, A. R., Raimi, K. T., Truelove, H. B., Araujo, B., & Yeung, K. L. (2019). Meta-analysis of pro-environmental behaviour spillover. Nature Sustainability, 2(4), 307–315.

Malone, R. E. (2022). Tobacco control and the climate emergency. Tobacco Control, 31(3), 395–396.

Matti, C., Bontoux, L., & Jensen, K. (2025). Strategic foresight framework for addressing agency in sustainability transitions: a co-creation approach. Frontiers in Sustainability, 6, 1507708.

Meadows, D. (2008). Leverage points: places to intervene in a system. 1999. The Sustainability Institute, Hartland, Vermont.

Mealy, P., Barbrook-Johnson, P., Ives, M. C., Srivastav, S., & Hepburn, C. (2023). Sensitive intervention points: a strategic approach to climate action. Oxford Review of Economic Policy, 39(4), 694-710.

Meadowcroft, J., & Rosenbloom, D. (2023). Governing the net-zero transition: Strategy, policy, and politics. Proceedings of the National Academy of Sciences, 120(47), e2207727120.

Meckling, J., Kelsey, N., Biber, E., & Zysman, J. (2015). Winning coalitions for climate policy. Science, 349(6253), 1170–1171.

Meckling, J., & Nahm, J. (2018). When do states disrupt industries? Electric cars and the politics of innovation. Review of International Political Economy, 25(4), 505-529.

Meckling, J., & Trachtman, S. (2024). The home state effect: How subnational governments shape climate coalitions. Governance, 37(3), 887-905.

Meckling, J. (2021). Making industrial policy work for decarbonisation. Global Environmental Politics, 21(4), 134-147.

Meckling, J., Kelsey, N., Biber, E., & Zysman, J. (2015). Winning coalitions for climate policy. Science, 349(6253), 1170-1171.

Meldrum, M., Pinnell, L., Brennan, K., Romani, M., Sharpe, S., & Lenton, T. (2023). The Breakthrough Effect: How to trigger a cascade of tipping points to accelerate the net zero transition.

Mildenberger, M., Lachapelle, E., Harrison, K., & Stadelmann-Steffen, I. (2022). Limited impacts of carbon tax rebate programmes on public support for carbon pricing. Nature Climate Change, 12(2), 141-147.

Mittal, D., Constantino, S. M., & Vasconcelos, V. V. (2024). Anticonformists catalyse societal transitions and facilitate the expression of evolving preferences. PNAS nexus, 3(8), page302.

Montfort, S., Fesenfeld, L., Stadelmann-Steffen, I., & Ingold, K. (2023). Policy sequencing can increase public support for ambitious climate policy. Policy and Society, 42(4), 454-477.

Nielsen, K. S., Nicholas, K. A., Creutzig, F., Dietz, T., & Stern, P. C. (2021). The role of high-socioeconomic-status people in locking in or rapidly reducing energy-driven greenhouse gas emissions. Nature Energy, 6(11), 1011-1016.

Nijsse, F., Sharpe, S., Sahastrabuddhe, R., & Lenton, T. M. (2024, September). A positive tipping cascade in power, transport and heating. Global Tipping Points / Global Systems Institute, University of Exeter & S-Curve Economics.

Noor, D. (2025, June 27). How a new AI tool could amplify doubt in pollution science. The Guardian. https://www.theguardian.com/technology/ng-interactive/2025/jun/27/tony-cox-epidemiology-risk-assessment-chatgpt-ai

Numata, Y., Gorin, A., Speelman, L., Shwisberg, L., & Gulli, C. (2025, July 17). Fast, flexible solutions for data centers. RMI. https://rmi.org/fast-flexible-solutions-for-data-centers/

Nyborg, K., Anderies, J. M., Dannenberg, A., Lindahl, T., Schill, C., Schlüter, M., ... & De Zeeuw, A. (2016). Social norms as solutions. Science, 354(6308), 42-43.

Piggot, G. (2018). The influence of social movements on policies that constrain fossil fuel supply. Climate Policy, 18(7), 942-954.

Organisation for Economic Co-operation and Development. (2025). Fast-tracking net zero by building climate and economic resilience: A summary for policymakers. OECD Publishing. https://doi.org/10.1787/f2c22c96-en

Ong, M. K.-C. F., Blomsma, F., and Lenton, T. M.: Tipping dynamics in packaging systems: How a bottle reuse system was established and then undone, EGUsphere [preprint],

Otto, I. M., Donges, J. F., Cremades, R., Bhowmik, A., Hewitt, R. J., Lucht, W., ... & Schellnhuber, H. J. (2020). Social tipping dynamics for stabilising Earth's climate by 2050. Proceedings of the National Academy of Sciences, 117(5), 2354-2365.

Otto, I. M., Kim, K. M., Dubrovsky, N., & Lucht, W. (2019). Shift the focus from the super-poor to the super-rich. Nature Climate Change, 9(2), 82-84.

Pereira, L. M., Gianelli, I., Achieng, T., Amon, D., Archibald, S., Arif, S., ... & Sumaila, U. R. (2024). Equity and justice should underpin the discourse on tipping points. Earth System Dynamics, 15(2), 341-366.

Pereira, L., Kuiper, J. J., Selomane, O., Aguiar, A. P. D., Asrar, G. R., Bennett, E. M., ... & Ward, J. (2021). Advancing a toolkit of diverse futures approaches for global environmental assessments. Ecosystems and People, 17(1), 191-204.

R (Finch on behalf of Weald Action Group & Others) v. Surrey County Council (& Others) CO/4441/2019 and C1/2021/0261, 2019. Available at: https://climatecasechart.com/non-us-case/r-finch-v-surrey-county-council

Ramirez, R., & Wilkinson, A. (2016). Strategic reframing: The Oxford scenario planning approach. Oxford University Press.

Rayner, C., & Bonnici, F. (2021). The systems work of social change: How to harness connection, context, and power to cultivate deep and enduring change. Oxford University Press.

Ribeiro, J. A., Ribeiro, B. A., Pimenta, F., Tavares, S. M., Zhang, J., & Ahmed, F. (2025). Offshore wind turbine tower design and optimisation: A review and AI-driven future directions. Applied Energy, 397, 126294.

Roberts, C., Geels, F. W., Lockwood, M., Newell, P., Schmitz, H., Turnheim, B., & Jordan, A. (2018). The politics of accelerating low-carbon transitions: Towards a new research agenda. Energy research & social science, 44, 304-311.

Rogers, E. M. (2003). Diffusion of innovations (5th ed.). Free Press.

Rosenbloom, D., Meadowcroft, J., & Cashore, B. (2019). Stability and climate policy? Harnessing insights on path dependence, policy feedback, and transition pathways. Energy Research & Social Science, 50, 168-178.

Ruiu, M. L. (2021). Persistence of scepticism in media reporting on climate change: The case of British newspapers. Environmental Communication, 15(1), 12-26.

Seto, K. C., Davis, S. J., Mitchell, R. B., Stokes, E. C., Unruh, G., & Ürge-Vorsatz, D. (2016). Carbon lock-in: types, causes, and policy implications. Annual review of environment and resources, 41(1), 425-452.

Setzer, J., & Higham, C. (2025). Global trends in climate change litigation: 2025 snapshot. Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science.

Sewerin, S., Fesenfeld, L. P., & Schmidt, T. S. (2023). The role of policy design in policy continuation and ratcheting-up of policy ambition. Policy and Society, 42(4), 478-492.

Scoones, I., Leach, M., & Newell, P. (2015). The politics of green transformations (p. 238). Taylor & Francis.

Sharpe, S., Murphy, A., Geels, F., Pasqualino, R., Vasconcelos, T., & Mercure, J.-F. (2025, February). Analytical tools for innovation and competitiveness in the low carbon transition [Report]. S-Curve Economics.

Sharpe, S., & Lenton, T. M. (2021). Upward-scaling tipping cascades to meet climate goals: Plausible grounds for hope. Climate Policy, 21(4), 421-433.

Spaiser, V., Nisbett, N. Mobilising climate action with moral appeals in a smartphone-based 8-week field experiment. npj Clim. Action 4, 81 (2025). https://doi.org/10.1038/s44168-025-00282-x

State of the Netherlands v. Stichting Urgenda, 2019. Available at: https://uitspraken.rechtspraak.nl/details?id=ECLI:NL:HR:2019:2007

Stechemesser, A., Koch, N., Mark, E., Dilger, E., Klösel, P., Menicacci, L., ... & Wenzel, A. (2024). Climate policies that achieved major emission reductions: Global evidence from two decades. Science, 385(6711), 884-892.

Strowel, A. (2023). ChatGPT and generative AI tools: Theft of intellectual labor?. IIC-International Review of Intellectual Property and Competition Law, 54(4), 491-494.

Thaler, R. H., & Sunstein, C. R. (2009). Nudge: Improving decisions about health, wealth, and happiness. Penguin.

Ukoba, K., Olatunji, K. O., Adeoye, E., Jen, T. C., & Madyira, D. M. (2024). Optimising renewable energy systems through artificial intelligence: Review and future prospects. Energy & Environment, 35(7), 3833-3879.

United Nations Environment Programme. (2025, June 12). UNEP releases guidelines to curb the environmental impact of data centres [Technical highlight]. https://www.unep.org/technical-highlight/unep-releases-guidelines-curb-environmental-impact-data-centres

Vaghefi, S. A., Stammbach, D., Muccione, V., Bingler, J., Ni, J., Kraus, M., ... & Leippold, M. (2023). ChatClimate: Grounding conversational AI in climate science. Communications Earth & Environment, 4(1), 480.

Van der Plas, T. L., Alexander, D. G., & Pocock, M. J. (2025). Monitoring protected areas by integrating machine learning, remote sensing and citizen science. Ecological Solutions and Evidence, 6(2), e70040.

van Tulder, R., & Keen, N. (2018). Capturing collaborative challenges: Designing complexity-sensitive theories of change for cross-sector partnerships. Journal of Business Ethics, 150(2), 315–332.

Vezhnevets, A. S., Agapiou, J. P., Aharon, A., Ziv, R., Matyas, J., Duéñez-Guzmán, E. A., Cunningham, W. A., Osindero, S., Karmon, D., & Leibo, J. Z. (2023, December 6). Generative agent-based modeling with actions grounded in physical, social, or digital space using Concordia [Preprint]. arXiv. https://arxiv.org/abs/2312.03238

Verein KlimaSeniorinnen Schweiz and Others v. Switzerland (GC), 2024. Available at: https://hudoc.echr.coe.int/eng#{%22itemid%22:[%22002-14304%22]}

Walter, D., Bond, K., Butler-Sloss, S., Speelman, L., Numata, Y., & Atkinson, W. (2023, December). X-Change: Batteries — The Battery Domino Effect [Report]. RMI.

Wang, X., Wang, H., Bhandari, B., & Cheng, L. (2024). AI-empowered methods for smart energy consumption: A review of load forecasting, anomaly detection and demand response. International Journal of Precision Engineering and Manufacturing-Green Technology, 11(3), 963-993.

Weible, C. M. (2018). Introduction: The scope and focus of policy process research and theory. In Theories of the policy process (pp.

1-13). Routledge.

Weible, C. M., & Sabatier, P. A. (Eds.). (2018). Theories of the Policy Process (4th ed.). Routledge.

Wewerinke-Singh, M. (2024). Echoes through time: Transforming climate litigation narratives on future generations. Transnational Environmental Law, 13(3), 547-568.

Wewerinke-Singh, M., Ramsay, A. S., & Alo, F. (2024). Echoes through time: Transforming climate litigation narratives on future generations. Transnational Environmental Law, 13(3), 547–568.

World Resources Institute. (2018, November). The ambition loop: How business and government can advance policies that fast-track zero-carbon economic growth. World Resources Institute. https://static1.squarespace.com/static/5bbe243651f4d40801af46d5/t/5c00266c0e2e728a28cee091/1543513751309/The-Ambition-Loop.pdf

Yamagishi, Y. (2024, February 8). AI presenting decarbonised future scenarios: For use in policymaking. Hitachi. https://www.hitachi.com/en/insights/articles/decarbonization-scenario-simulator/ hitachi.com

Juri, S., Marais-Potgieter, A., Achieng, T., Gianelli, I., Kabisa, M., Nkgothoe, B., ... & Pereira, L. (2025). Transforming towards what? A review of futures-thinking applied in the quest for navigating sustainability transformations. Environmental Research Letters.

Young, H. P. (2024). Spontaneous Order: How Norms, Institutions, and Innovations Emerge from the Bottom Up. Oxford University Press.

Zack, E., Smithson-Stanley, L., Booth-Tobin, J., & Han, H. (2023, March 24). Designing resilient coalitions [Report]. P3 Lab / Hahrie Han.

Zhang, J. (2025). The role of Social Media in Promoting Environmental Sustainability. Journal of Lifestyle and SDG's Review, 5, e06586, 1-20. https://doi.org/10.47172/2965-730X.SDGsReview.v5.n05.pe06586

Zuckerman, E. (2020). The Case for Digital Public Infrastructure. Knight First Amendment Institute. Columbia University. https://knightcolumbia.org/content/the-case-for-digital-public-infrastructure

References 3.4

Agnew, S., & Dargusch, P. (2017). Consumer preferences for household-level battery energy storage. Renewable and Sustainable Energy Reviews, 75, 609–617. https://doi.org/10.1016/j.rser.2016.11.030

Akenji, L., M. Bengtsson, V. Toivio, M. Lettenmeier, T. Fawcett, Y. Parag, Y. Saheb, A. Coote, J.H. Spangenberg, S. Capstick, T. Gore, L. Coscieme, M. Wackernagel, D. Kenner. 2021. 1.5-Degree Lifestyles: Towards A Fair Consumption Space for All. Hot or Cool Institute, Berlin. https://hotorcool.org/wp-content/uploads/2021/10/Hot_or_Cool_1_5_lifestyles_FULL_REPORT_AND_ANNEX_B.pdf

Alkemade, F., de Bruin, B., El-Feiaz, A., Pasimeni, F., Niamir, L., & Wade, R. (2024). Social tipping dynamics in the energy system. Earth System Dynamics, 15(2), 485-500. https://esd.copernicus.org/articles/15/485/2024/esd-15-485-2024.html

Breyer, C., Khalili, S., Bogdanov, D., Ram, M., Oyewo, A. S., Aghahosseini, A., Gulagi, A., Solomon, A. A., Keiner, D., Lopez, G., Ostergaard, P. A., Lund, H., Mathiesen, B. V., Jacobson, M. Z., Victoria, M., Teske, S., Pregger, T., Fthenakis, V., Raugei, M., … Sovacool, B. K. (2022). On the History and Future of 100% Renewable Energy Systems Research. IEEE Access, 10, 78176–78218. Scopus. https://doi.org/10.1109/ACCESS.2022.3193402

Breysse J, Jacobs DE, Weber W, et al. Health Outcomes and Green Renovation of Affordable Housing. Public Health Reports®. 2011;126(1_suppl):64-75. doi:10.1177/00333549111260S110

Campfens, J. K., Duygan, M., & Binder, C. R. (2025). Initiating social tipping dynamics in energy transitions: A novel analytical approach for exploring feedback loops and intervention points. Environmental Innovation and Societal Transitions, 56, 100973.

Carbon brief (2025) https://www.carbonbrief.org/analysis-clean-energy-just-put-chinas-co2-emissions-into-reverse-for-first-time/

Draghi, M. (2024). The future of European competitiveness https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en

Ember 2025. https://ember-energy.org/latest-insights/the-long-march-of-electrification/

Ember 2025 Wiatros-Motyka, M., Fulghum, N., & Jones, D. (2024). Global electricity review 2024.https://ember-energy.org/app/uploads/2024/05/Report-Global-Electricity-Review-2024.pdf

EIA (n.d.) https://www.eia.gov/energyexplained/natural-gas/use-of-natural-gas.php

European Commission, Joint Research Centre, Toleikyte, A., Lecomte, E., Volt, J., Lyons, L., Roca Reina, J.C., Georgakaki, A., Letout, S., Mountraki, A., Wegener, M., Schmitz, A., Clean Energy Technology Observatory: Heat Pumps in the European Union - 2024 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2024, https://data.europa.eu/doi/10.2760/7205477, JRC139377.

Galletti, A., Pasimeni, F., Melideo, D., Desideri, U., & Alkemade, F. (2025). Learning in green hydrogen production: Insights from a novel European dataset. International Journal of Hydrogen Energy, 148, 149812. https://doi.org/10.1016/j.ijhydene.2025.06.002

Hoekstra, A., Alkemade, F. Using learning curves to guide the energy transition with the example of heavy electric trucks. npj. Sustain. Mobil. Transp. 2, 14 (2025). https://doi.org/10.1038/s44333-025-00029-5

IEA (2022), Annual heat pump installations in the European Union, 2021-2030, IEA, Paris https://www.iea.org/data-and-statistics/charts/annual-heat-pump-installations-in-the-european-union-2021-2030

IEA (2024), World Energy Outlook 2024, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2024, Licence: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A) https://www.iea.org/reports/world-energy-outlook-2024

IEA (2024), Global EV Outlook 2024, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2024, Licence: CC BY 4.0

IRENA (2024), World Energy Transitions Outlook 2024: 1.5°C Pathway, International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Nov/IRENA_World_energy_transitions_outlook_2024.pdf

Ivanova, D., Barrett, J., Wiedenhofer, D., Macura, B., Callaghan, M., & Creutzig, F. (2020). Quantifying the potential for climate change mitigation of consumption options. Environmental Research Letters, 15(9), 093001. https://doi.org/10.1088/1748-9326/ab8589

Jarvis, D., Chinn, S., Luczynska, C., & Burney, P. (1996). Association of respiratory symptoms and lung function in young adults with use of domestic gas appliances. The Lancet, 347(8999), 426-431.

Kern, F., Rogge, K. S., & Howlett, M. (2019). Policy mixes for sustainability transitions: New approaches and insights through bridging innovation and policy studies. Research Policy, 48(10), 103832.

Liang, J., Qiu, Y. (Lucy), & Xing, B. (2022). Impacts of the co-adoption of electric vehicles and solar panel systems: Empirical evidence of changes in electricity demand and consumer behaviors from household smart meter data. Energy Economics, 112, 106170. https://doi.org/10.1016/j.eneco.2022.106170

Nijsse, F.J.M.M., Mercure, JF., Ameli, N. et al. The momentum of the solar energy transition. Nat Commun 14, 6542 (2023). https://doi.org/10.1038/s41467-023-41971-7

Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow, W. R., III, Zhou, N., Elliott, N., Dell, R., Heeren, N., Huckestein, B., Cresko, J., Miller, S. A., Roy, J., Fennell, P., Cremmins, B., Koch Blank, T., Hone, D., Williams, E. D., de la Rue du Can, S., … Helseth, J. (2020). Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. Applied Energy, 266. Scopus. https://doi.org/10.1016/j.apenergy.2020.114848

Pang, M., Meirelles, J., Moreau, V., & Binder, C. (2019). Urban carbon footprints: a consumption-based approach for Swiss households. Environmental Research Communications, 2(1), 011003.

Plananska, J., & Gamma, K. (2022). Product bundling for accelerating electric vehicle adoption: A mixed-method empirical analysis of Swiss customers. Renewable and Sustainable Energy Reviews, 154, 111760. https://doi.org/10.1016/j.rser.2021.111760

Priessner, A., & Hampl, N. (2020). Can product bundling increase the joint adoption of electric vehicles, solar panels and battery storage? Explorative evidence from a choice-based conjoint study in Austria. Ecological Economics, 167, 106381. https://doi.org/10.1016/j.ecolecon.2019.106381

Reinders, M. J., Frambach, R. T., & Schoormans, J. P. L. (2010). Using Product Bundling to Facilitate the Adoption Process of Radical Innovations. Journal of Product Innovation Management, 27(7), 1127–1140. https://doi.org/10.1111/j.1540-5885.2010.00775.x

Shen, X., Qiu, Y. L., Bo, X., Patwardhan, A., Hultman, N., & Dong, B. (2023). The impact of co-adopting electric vehicles, solar photovoltaics, and battery storage on electricity consumption patterns: Empirical evidence from Arizona. Resources, Conservation and Recycling, 192, 106914. https://doi.org/10.1016/j.resconrec.2023.106914

Stauch, A. (2021). Does solar power add value to electric vehicles? An investigation of car-buyers' willingness to buy product-bundles in Germany. Energy Research & Social Science, 75, 102006. https://doi.org/10.1016/j.erss.2021.102006

Stremersch, S., & Tellis, G. J. (2002). Strategic Bundling of Products and Prices: A New Synthesis for Marketing. Journal of Marketing, 66(1), 55–72. https://doi.org/10.1509/jmkg.66.1.55.18455

References 3.5

Baker, D.J. et al. (2025) 'Aligning strategic and participatory approaches to agri-environment scheme design and implementation to enhance nature recovery outcomes', People and Nature, 7(2), pp. 329–345. Available at: https://doi.org/10.1002/pan3.10785.

BBC (2021) 'COP26: Supermarkets promise to halve environmental impact by 2030', BBC News, 6 November. Available at: https://www.bbc.com/news/uk-59184278 (Accessed: 3 September 2025).

Benkwitt, C.E. et al. (2023) 'Seabirds boost coral reef resilience', Science Advances, 9(49), p. eadj0390. Available at: https://doi.org/10.1126/sciadv.adj0390.

Blöcker, A.M. et al. (2023) 'Regime shift dynamics, tipping points and the success of fisheries management', Scientific Reports, 13(1), p. 289. Available at: https://doi.org/10.1038/s41598-022-27104-y.

Boers, N. et al. (2017) 'A deforestation-induced tipping point for the South American monsoon system', Scientific Reports, 7(1), p. 41489. Available at: https://doi.org/10.1038/srep41489.

Boulton, C.A., Lenton, T.M. and Boers, N. (2022) 'Pronounced loss of Amazon rainforest resilience since the early 2000s', Nature Climate Change, 12(3), pp. 271–278. Available at: https://doi.org/10.1038/s41558-022-01287-8.

Brando, P.M. et al. (2025) 'Tipping Points of Amazonian Forests: Beyond Myths and Toward Solutions'. Available at: https://doi.org/10.1146/annurev-environ-111522-112804.

Buxton, J. et al. (2021) 'Community-driven tree planting greens the neighbouring landscape', Scientific Reports, 11(1), p. 18239. Available at: https://doi.org/10.1038/s41598-021-96973-6.

Castilla-Rho, J.C. et al. (2017) 'Social tipping points in global groundwater management', Nature Human Behaviour, 1(9), pp. 640–649. Available at: https://doi.org/10.1038/s41562-017-0181-7.

Cesar de Oliveira, S.E.M. et al. (2024) 'The European Union and United Kingdom's deforestation-free supply chains regulations: Implications for Brazil', Ecological Economics, 217, p. 108053. Available at: https://doi.org/10.1016/j.ecolecon.2023.108053.

Chin, A.Z. et al. (2020) 'Malaria elimination in Malaysia and the rising threat of Plasmodium knowlesi', Journal of Physiological Anthropology, 39(1), p. 36. Available at: https://doi.org/10.1186/s40101-020-00247-5.

Clark, M. et al. (2024) 'Forecasting adoption with epidemiological models can enable adaptively scaling out conservation', One Earth, 7(10), pp. 1820–1832. Available at: https://doi.org/10.1016/j.oneear.2024.08.017.

Convention on Biological Diversity (2022) Kunming-Montreal Global Biodiversity Framework, Convention on Biological Diversity. Available at: https://www.cbd.int/ (Accessed: 7 September 2025).

Crippa, M. et al. (2021) 'Food systems are responsible for a third of global anthropogenic GHG emissions', Nature Food, 2(3), pp. 198–209. Available at: https://doi.org/10.1038/s43016-021-00225-9.

Dagevos, H. (2021) 'Finding flexitarians: Current studies on meat eaters and meat reducers', Trends in Food Science & Technology, 114, pp. 530–539. Available at: https://doi.org/10.1016/j.tifs.2021.06.021.

Di Lorenzo, M. et al. (2020) 'Assessing spillover from marine protected areas and its drivers: A meta-analytical approach', Fish and Fisheries, 21(5), pp. 906–915. Available at: https://doi.org/10.1111/faf.12469.

Emenyu, A.P. et al. (2023) 'Positive tipping points for accelerating adoption of regenerative practices in African smallholder farming systems: What sustains adoption?', EGUsphere, pp. 1–19. Available at: https://doi.org/10.5194/egusphere-2023-2531.

van der Ent, R.J. et al. (2010) 'Origin and fate of atmospheric moisture over continents', Water Resources Research, 46(9). Available at: https://doi.org/10.1029/2010WR009127.

Everard, M. (2015) 'Community-based groundwater and ecosystem restoration in semi-arid north Rajasthan (1): Socio-economic progress and lessons for groundwater-dependent areas', Ecosystem Services, 16, pp. 125–135. Available at: https://doi.org/10.1016/j.ecoser.2015.10.011.

Fesenfeld, L.P. et al. (2022) 'The politics of enabling tipping points for sustainable development', One Earth, 5(10), pp. 1100–1108. Available at: https://doi.org/10.1016/j.oneear.2022.09.004.

Flores, B.M. et al. (2024) 'Critical transitions in the Amazon forest system', Nature, 626(7999), pp. 555–564. Available at: https://doi.org/10.1038/s41586-023-06970-0.

Giua, C., Materia, V.C. and Camanzi, L. (2022) 'Smart farming technologies adoption: Which factors play a role in the digital transition?', Technology in Society, 68, p. 101869. Available at: https://doi.org/10.1016/j.techsoc.2022.101869.

Graham, N.A. et al. (2013) 'Managing resilience to reverse phase shifts in coral reefs', Frontiers in Ecology and the Environment, 11(10), pp. 541–548. Available at: https://doi.org/10.1890/120305.

Graham, N.A.J. et al. (2015) 'Predicting climate-driven regime shifts versus rebound potential in coral reefs', Nature, 518(7537), pp. 94–97. Available at: https://doi.org/10.1038/nature14140.

Groom, B., Palmer, C. and Sileci, L. (2022) 'Carbon emissions reductions from Indonesia's moratorium on forest concessions are cost-effective yet contribute little to Paris pledges', Proceedings of the National Academy of Sciences, 119(5), p. e2102613119. Available at: https://doi.org/10.1073/pnas.2102613119.

Hilmi, Y.S. et al. (2024) 'Farmers' resilience to climate change through the circular economy and sustainable agriculture: a review from developed and developing countries', Renewable Agriculture and Food Systems, 39, p. e15. Available at: https://doi.org/10.1017/S1742170524000097.

HLPE (2019) 'Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome'.

Holbrook, S.J. et al. (2016) 'Coral Reef Resilience, Tipping Points and the Strength of Herbivory', Scientific Reports, 6(1), p. 35817. Available at: https://doi.org/10.1038/srep35817.

Jeppesen, E. et al. (2007) 'Restoration of shallow lakes by nutrient control and biomanipulation—the successful strategy varies with lake size and climate', Hydrobiologia, 581(1), pp. 269–285. Available at: https://doi.org/10.1007/s10750-006-0507-3.

Kassam, A., Friedrich, T. and Derpsch, R. (2019) 'Global spread of Conservation Agriculture', International Journal of Environmental Studies, 76(1), pp. 29–51. Available at: https://doi.org/10.1080/00207233.2018.1494927.

Kassam, A., Friedrich, T. and Derpsch, R. (2022) 'Successful Experiences and Lessons from Conservation Agriculture Worldwide', Agronomy, 12(4), p. 769. Available at: https://doi.org/10.3390/agronomy12040769.

Lambin, E.F. and Furumo, P.R. (2023) 'Deforestation-Free Commodity Supply Chains: Myth or Reality?', Annual Review of Environment and Resources, 48(Volume 48, 2023), pp. 237–261. Available at: https://doi.org/10.1146/annurev-environ-112321-121436.

Leclère, D. et al. (2020) 'Bending the curve of terrestrial biodiversity needs an integrated strategy', Nature, 585(7826), pp. 551–556. Available at: https://doi.org/10.1038/s41586-020-2705-y.

Li, C. et al. (2023) 'Shorebirds-driven trophic cascade helps restore coastal wetland multifunctionality', Nature Communications, 14(1), p. 8076. Available at: https://doi.org/10.1038/s41467-023-43951-3.

Li, Y. et al. (2023) 'Contribution of Tibetan Plateau ecosystems to local and remote precipitation through moisture recycling', Global Change Biology, 29(3), pp. 702–718. Available at: https://doi.org/10.1111/gcb.16495.

Long, T.B., Blok, V. and Coninx, I. (2016) 'Barriers to the adoption and diffusion of technological innovations for climate-smart agriculture in Europe: evidence from the Netherlands, France, Switzerland and Italy', Journal of Cleaner Production, 112, pp. 9–21. Available at: https://doi.org/10.1016/j.jclepro.2015.06.044.

Mascia, M.B. and Mills, M. (2018) 'When conservation goes viral: The diffusion of innovative biodiversity conservation policies and practices', Conservation Letters, 11(3), p. e12442. Available at: https://doi.org/10.1111/conl.12442.

Mennig, P. (2024) 'A never-ending story of reforms: on the wicked nature of the Common Agricultural Policy', npj Sustainable Agriculture, 2(1), p. 20. Available at: https://doi.org/10.1038/s44264-024-00027-z.

Morand, S. and Lajaunie, C. (2021) 'Outbreaks of Vector-Borne and Zoonotic Diseases Are Associated With Changes in Forest Cover and Oil Palm Expansion at Global Scale', Frontiers in Veterinary Science, 8. Available at: https://doi.org/10.3389/fvets.2021.661063.

Nyasulu, M.K. et al. (2024) 'African rainforest moisture contribution to continental agricultural water consumption', Agricultural and Forest Meteorology, 346, p. 109867. Available at: https://doi.org/10.1016/j.agrformet.2023.109867.

Olabanji, M.F. and Chitakira, M. (2025) 'The Adoption and Scaling of Climate-Smart Agriculture Innovation by Smallholder Farmers in South Africa: A Review of Institutional Mechanisms, Policy Frameworks and Market Dynamics', World, 6(2), p. 51. Available at: https://doi.org/10.3390/world6020051.

Oliveira, G.M. et al. (2024) 'Blind spots in the EU's Regulation on Deforestation-free products', Nature Ecology & Evolution, 8(8), pp. 1382–1383. Available at: https://doi.org/10.1038/s41559-024-02465-x.

Participation, E. (2021) Environment Act 2021. Statute Law Database. Available at: https://www.legislation.gov.uk/ukpga/2021/30/schedule/17 (Accessed: 3 September 2025).

Pendrill, F. et al. (2022) 'Disentangling the numbers behind agriculture-driven tropical deforestation', Science, 377(6611), p. eabm9267. Available at: https://doi.org/10.1126/science.abm9267.

Perino, A. et al. (2019) 'Rewilding complex ecosystems', Science, 364(6438), p. eaav5570. Available at: https://doi.org/10.1126/science.aav5570.

Rajão, R. et al. (2020) 'The rotten apples of Brazil's agribusiness', Science, 369(6501), pp. 246–248. Available at: https://doi.org/10.1126/science.aba6646.

Reddington, C.L. et al. (2025) 'Tropical deforestation is associated with considerable heat-related mortality', Nature Climate Change, pp. 1–8. Available at: https://doi.org/10.1038/s41558-025-02411-0.

Reusch, T.B.H. et al. (2018) 'The Baltic Sea as a time machine for the future coastal ocean', Science Advances, 4(5), p. eaar8195. Available at: https://doi.org/10.1126/sciadv.aar8195.

Ripple, W.J. et al. (2025) 'The strength of the Yellowstone trophic cascade after wolf reintroduction', Global Ecology and Conservation, 58, p. e03428. Available at: https://doi.org/10.1016/j.gecco.2025.e03428.

Ritchie, H. and Roser, M. (2019) 'Half of the world's habitable land is used for agriculture', Our World in Data [Preprint]. Available at: https://ourworldindata.org/global-land-for-agriculture (Accessed: 3 September 2025).

Rosenfeld, D.L., Rothgerber, H. and Tomiyama, A.J. (2020) 'Mostly Vegetarian, But Flexible About It: Investigating How Meat-Reducers Express Social Identity Around Their Diets', Social Psychological and Personality Science, 11(3), pp. 406–415. Available at: https://doi.org/10.1177/1948550619869619.

Russ, G.R. et al. (2004) 'Marine Reserve Benefits Local Fisheries', Ecological Applications, 14(2), pp. 597–606. Available at: https://doi.org/10.1890/03-5076.

Scheffer, M. et al. (1993) 'Alternative equilibria in shallow lakes', Trends in Ecology & Evolution, 8(8), pp. 275–279. Available at: https://doi.org/10.1016/0169-5347(93)90254-M.

Selkoe, K.A. et al. (2015) 'Principles for managing marine ecosystems prone to tipping points', Ecosystem Health and Sustainability, 1(5), pp. 1–18. Available at: https://doi.org/10.1890/EHS14-0024.1.

Sewerin, S., Fesenfeld, L.P. and Schmidt, T.S. (2023) 'The role of policy design in policy continuation and ratcheting-up of policy ambition', Policy and Society, 42(4), pp. 478–492. Available at: https://doi.org/10.1093/polsoc/puad027.

Sguotti, C. et al. (2019) 'Catastrophic dynamics limit Atlantic cod recovery', Proceedings of the Royal Society B: Biological Sciences, 286(1898), p. 20182877. Available at: https://doi.org/10.1098/rspb.2018.2877.

Shang, L. et al. (2021) 'Adoption and diffusion of digital farming technologies - integrating farm-level evidence and system interaction', Agricultural Systems, 190, p. 103074. Available at: https://doi.org/10.1016/j.agsy.2021.103074.

Silliman, B.R. et al. (2015) 'Facilitation shifts paradigms and can amplify coastal restoration efforts', Proceedings of the National Academy of Sciences, 112(46), pp. 14295–14300. Available at: https://doi.org/10.1073/pnas.1515297112.

Spurk, C. et al. (2025) 'Farmers' innovativeness and positive affirmation as main drivers of adoption of soil fertility management practices – evidence across sites in Africa', The Journal of Agricultural Education and Extension, 31(1), pp. 4–28. Available at: https://doi.org/10.1080/1389224X.2023.2281909.

Suykerbuyk, W. et al. (2012) 'Suppressing antagonistic bioengineering feedbacks doubles restoration success', Ecological Applications, 22(4), pp. 1224–1231. Available at: https://doi.org/10.1890/11-1625.1.

Temmink, R.J.M. et al. (2023) 'Restoration ecology meets design-engineering: Mimicking emergent traits to restore feedback-driven ecosystems', Science of The Total Environment, 902, p. 166460. Available at: https://doi.org/10.1016/j.scitotenv.2023.166460.

The National Archives (2021). Available at: https://webarchive.nationalarchives.gov.uk/ukgwa/20230418175226/https://ukcop26.org/glasgow-leaders-declaration-on-forests-and-land-use/ (Accessed: 26 August 2025).

Varjopuro, R. et al. (2014) 'Coping with persistent environmental problems: systemic delays in reducing eutrophication of the Baltic Sea', Ecology and Society, 19(4). Available at: https://doi.org/10.5751/ES-06938-190448.

Whitton, C. et al. (2021) 'Are We Approaching Peak Meat Consumption? Analysis of Meat Consumption from 2000 to 2019 in 35 Countries and Its Relationship to Gross Domestic Product', Animals : an Open Access Journal from MDPI, 11(12), p. 3466. Available at: https://doi.org/10.3390/ani11123466.

Worden, S. et al. (2021) 'Where Does Moisture Come From Over the Congo Basin?', Journal of Geophysical Research: Biogeosciences, 126(8), p. e2020JG006024. Available at: https://doi.org/10.1029/2020JG006024.

Wunderling, N. et al. (2022) 'Recurrent droughts increase risk of cascading tipping events by outpacing adaptive capacities in the Amazon rainforest', Proceedings of the National Academy of Sciences, 119(32), p. e2120777119. Available at: https://doi.org/10.1073/pnas.2120777119.

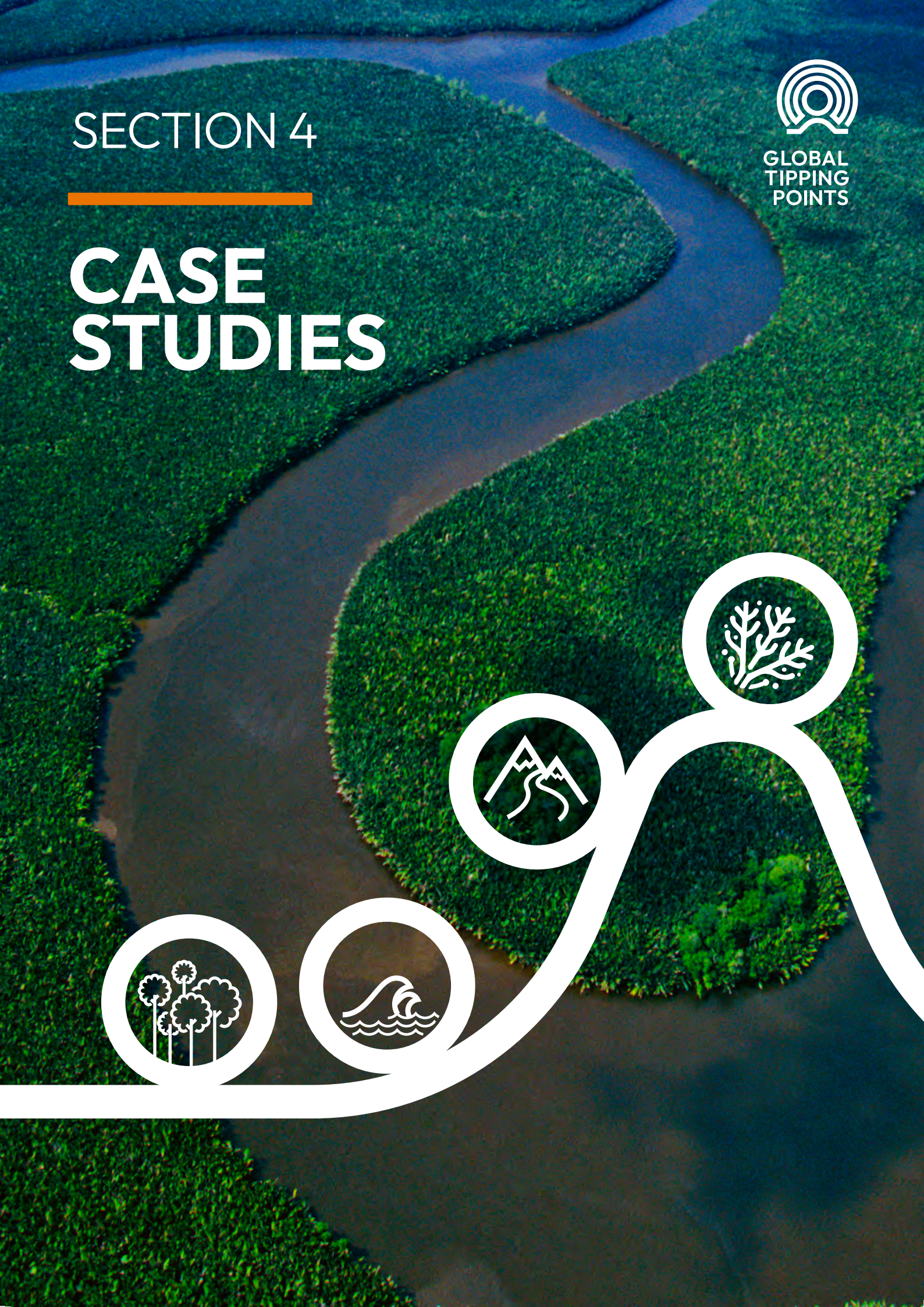
Wuyts, B. and Sieber, J. (2023) 'Emergent structure and dynamics of tropical forest-grassland landscapes', Proceedings of the National Academy of Sciences, 120(45), p. e2211853120. Available at: https://doi.org/10.1073/pnas.2211853120.

Xu, C. et al. (2023) 'Herbivory limits success of vegetation restoration globally', Science, 382(6670), pp. 589–594. Available at: https://doi.org/10.1126/science.add2814.

Zemp, D.C. et al. (2014) 'On the importance of cascading moisture recycling in South America', Atmospheric Chemistry and Physics, 14(23), pp. 13337–13359. Available at: https://doi.org/10.5194/acp-14-13337-2014.

SECTION 4

CASE STUDIES



References 4.1

Akabane, T.K., Chiessi, C.M., Hirota, M., Bouimetarhan, I., Prange, M., Mulitza, S., Bertassoli Jr, D.J., Häggi, C., Staal, A., Lohmann, G., Boers, N., Daniau, A.L., Oliveira, R.S., Campos, M.C., Shi, X. and De Oliveira, P.E. (2024) 'Weaker Atlantic overturning circulation increases the vulnerability of northern Amazon forests', Nature Geoscience, 17(12), pp. 1284-1290. doi: 10.1038/s41561-024-01578-z

Almada, H.K., Macedo, M.N., Lenza, E., Maracahipes, L. and Silvério, D.V. (2024) 'Indigenous lands and conservation units slow down non-GHG climate change in the Cerrado-Amazon ecotone', Perspectives in Ecology and Conservation, 22(2), pp. 177-185. doi: 10.1016/j.pecon.2024.03.002

Aragão, L.E.O.C., Anderson, L.O., Fonseca, M.G., Rosan, T.M., Vedovato, L.B., Wagner, F.H., Silva, C.V.J., Silva Junior, C.H.L., Arai, E., Aguiar, A.P., Barlow, J., Berenguer, E., Deeter, M.N., Domingues, L.G., Gatti, L., Gloor, M., Malhi, Y., Marengo, J.A., Miller, J.B., Phillips, O.L. and Saatchi, S. (2018) '21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions', Nature Communications, 9(1), p. 536. doi: 10.1038/s41467-017-02771-y

Armstrong McKay, D.I., Staal, A., Abrams, J.F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S.E., Rockström, J. and Lenton, T.M. (2022) 'Exceeding 1.5°C global warming could trigger multiple climate tipping points', Science, 377(6611), p. eabn7950. doi: 10.1126/science.abn7950

Barichivich, J., Gloor, E., Peylin, P., Brienen, R.J.W., Schöngart, J., Espinoza, J.C. and Pattnayak, K.C. (2018) 'Recent intensification of Amazon flooding extremes driven by strengthened Walker circulation', Science Advances, 4(9), p. eaat8785. doi: doi:10.1126/sciadv.aat8785

Barlow, J., França, F., Gardner, T.A., Hicks, C.C., Lennox, G.D., Berenguer, E., Castello, L., Economo, E.P., Ferreira, J., Guénard, B., Gontijo Leal, C., Isaac, V., Lees, A.C., Parr, C.L., Wilson, S.K., Young, P.J. and Graham, N.A.J. (2018) 'The future of hyperdiverse tropical ecosystems', Nature, 559(7715), pp. 517-526. doi: 10.1038/s41586-018-0301-1

Barlow, J., Sist, P., Almeida, R., Arantes, C., Berenguer, E., Caron, P., Cuesta, F., Doria, C., Ferreira, J., Flecker, A., Heilpern, S., Kalamandeen, M., Lees, A.L., Nascimento, N., Peña-Claros, M., Piponiot, C., Pompeu, P.S., Souza, C. and Valentin, J.F. (2021a) 'Chapter 28: Restoration Options for the Amazon', in Nobre C., Encalada A., Anderson E., Roca Alcazar F. H., Bustamante M., Mena C., Peña-Claros M., Poveda G., Rodriguez J. P., Saleska S., Trumbore S., Val A. L., Villa Nova L., Abramovay R., Alencar A., Rodríguez Alzza C., Armenteras D., Artaxo P., Athayde S., Barretto Filho H. T., Barlow J., Berenguer E., Bortolotto F., Costa F. A., Costa M. H., Cuvi N., Fearnside P. M., Ferreira J., Flores B. M., Frieri S., Gatti L. V., Guayasamin J. M., Hecht S., Hirota M., Hoorn C., Josse C., Lapola D. M., Larrea C., Larrea-Alcazar D. M., Lehm Ardaya Z., Malhi Y., Marengo J. A., Melack J., Moraes R. M., Moutinho P., Murmis M. R., Neves E. G., Paez B., Painter L., Ramos A., Rosero-Peña M. C., Schmink M., Sist P., Ter Steege H., Val P., Van Der Voort H., Varese M. and Z.-R. G. (eds.) Amazon Assessment Report 2021. United Nations Sustainable Development Solutions Network, New York, USA. doi: 10.55161/OSPD2912

Barlow, J., Sist, P., Almeida, R., Arantes, C., Berenguer, E., Caron, P., Cuesta, F., Doria, C., Ferreira, J., Flecker, A., Heilpern, S., Kalamandeen, M., Lees, A.L., Nascimento, N., Peña-Claros, M., Piponiot, C., Pompeu, P.S., Souza, C. and Valentin, J.F. (2021b) 'Chapter 29: Restoration Priorities and Benefits within Landscapes and Catchments and Across the Amazon Basin', in Nobre C., Encalada A., Anderson E., Roca Alcazar F. H., Bustamante M., Mena C., Peña-Claros M., Poveda G., Rodriguez J. P., Saleska S., Trumbore S., Val A. L., Villa Nova L., Abramovay R., Alencar A., Rodríguez Alzza C., Armenteras D., Artaxo P., Athayde S., Barretto Filho H. T., Barlow J., Berenguer E., Bortolotto F., Costa F. A., Costa M. H., Cuvi N., Fearnside P. M., Ferreira J., Flores B. M., Frieri S., Gatti L. V., Guayasamin J. M., Hecht S., Hirota M., Hoorn C., Josse C., Lapola D. M., Larrea C., Larrea-Alcazar D. M., Lehm Ardaya Z., Malhi Y., Marengo J. A., Melack J., Moraes R. M., Moutinho P., Murmis M. R., Neves E. G., Paez B., Painter L., Ramos A., Rosero-Peña M. C., Schmink M., Sist P., Ter Steege H., Val P., Van Der Voort H., Varese M. and Z.-R. G. (eds.) Amazon Assessment Report 2021. United Nations Sustainable Development Solutions Network, New York, USA. doi: 10.55161/GGIR9016

Batistella, M., Bolfe, É.L. and Moran, E.F. (2013) 'Agroforestry in Tomé-Açu: An Alternative to Pasture in the Amazon', in E. S. Brondízio and E. F. Moran (eds.) Human-Environment Interactions: Current and Future Directions. Dordrecht: Springer Netherlands, pp. 321-342. doi: 10.1007/978-94-007-4780-7_14.

Begazo-Curie, K. and Vranken, L. (2025) 'Forests' contribution to rural livelihoods and food security: Insights from a study case in the Peruvian Amazon', Food Security, 17(2), pp. 387-403. doi: 10.1007/s12571-025-01521-z

Beguería, S., Vicente-Serrano, S.M. and Angulo-Martínez, M. (2010) 'A Multiscalar Global Drought Dataset: The SPEIbase: A New Gridded Product for the Analysis of Drought Variability and Impacts', Bulletin of the American Meteorological Society, 91(10), pp. 1351-1356. doi: 10.1175/2010BAMS2988.1

Bergamo, D., Zerbini, O., Pinho, P. and Moutinho, P. (2022) 'The Amazon bioeconomy: Beyond the use of forest products', Ecological Economics, 199, p. 107448. doi: 10.1016/j.ecolecon.2022.107448

Betts, R.A., Cox, P.M., Collins, M., Harris, P.P., Huntingford, C. and Jones, C.D. (2004) 'The role of ecosystem-atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global climate warming', Theoretical and Applied Climatology, 78(1), pp. 157-175. doi: 10.1007/s00704-004-0050-y

Beveridge, C.F., Espinoza, J.-C., Athayde, S., Correa, S.B., Couto, T.B.A., Heilpern, S.A., Jenkins, C.N., Piland, N.C., Utsunomiya, R., Wongchuig, S. and Anderson, E.P. (2024) 'The Andes–Amazon–Atlantic pathway: A foundational hydroclimate system for social–ecological system sustainability', Proceedings of the National Academy of Sciences, 121(22), p. e2306229121. doi: 10.1073/pnas.2306229121

Birkmann, J., Liwenga, E., Pandey, R., Boyd, E., Djalante, R., Gemenne, F., Leal Filho, W., Pinho, P.F., Stringer, L. and Wrathall, D. (2022) 'Chapter 8: Poverty, Livelihoods and Sustainable Development', in H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama (eds.) Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1171–1274. doi: 10.1017/9781009325844.010.

Boers, N., Marwan, N., Barbosa, H.M.J. and Kurths, J. (2017) 'A deforestation-induced tipping point for the South American monsoon system', Scientific Reports, 7(1), p. 41489. doi: 10.1038/srep41489

Bowman, K.W., Dale, S.A., Dhanani, S., Nehru, J. and Rabishaw, B.T. (2021) 'Environmental degradation of indigenous protected areas of the Amazon as a slow onset event', Current Opinion in Environmental Sustainability, 50, pp. 260-271. doi: 10.1016/j.cosust.2021.04.012

Brando, P.M., Balch, J.K., Nepstad, D.C., Morton, D.C., Putz, F.E., Coe, M.T., Silvério, D., Macedo, M.N., Davidson, E.A., Nóbrega, C.C., Alencar, A. and Soares-Filho, B.S. (2014) 'Abrupt increases in Amazonian tree mortality due to drought–fire interactions', Proceedings of the National Academy of Sciences, 111(17), pp. 6347-6352. doi: doi:10.1073/pnas.1305499111

Brando, P.M., Barlow, J., Macedo, M.N., Silvério, D.V., Ferreira, J.N., Maracahipes, L., Anderson, L., Morton, D.C., Alencar, A., Paolucci, L.N., Jacobs, S., Stouter, H., Randerson, J., Flores, B.M., Starinchak, B., Coe, M., Pires, M.M., Rattis, L., Armenteras, D., Artaxo, P., Ordway, E.M., Trumbore, S., Staver, C., Berenguer, E., Menor, I.O., Maracahipes-Santos, L., Potter, N., Spracklen, D.V. and Uribe, M. (2025) 'Tipping Points of Amazonian Forests: Beyond Myths and Toward Solutions', Annual Review of Environment and Resources, doi: 10.1146/annurev-environ-111522-112804

Brando, P.M., Paolucci, L., Ummenhofer, C.C., Ordway, E.M., Hartmann, H., Cattau, M.E., Rattis, L., Medjibe, V., Coe, M.T. and Balch, J. (2019) 'Droughts, Wildfires, and Forest Carbon Cycling: A Pantropical Synthesis', Annual Review of Earth and Planetary Sciences, 47(Volume 47, 2019), pp. 555-581. doi: 10.1146/annurev-earth-082517-010235

Brondizio, E.S. (2025) 'The entangled Indigenous, rural, and urban realities in Amazônia's governance', Ambio, 54(6), pp. 923-931. doi: 10.1007/s13280-025-02183-z

Brondizio, E.S., Andersson, K., de Castro, F., Futemma, C., Salk, C., Tengö, M., Londres, M., Tourne, D.C.M., Gonzalez, T.S., Molina-Garzón, A., Russo Lopes, G. and Siani, S.M.O. (2021) 'Making place-based sustainability initiatives visible in the Brazilian Amazon', Current Opinion in Environmental Sustainability, 49, pp. 66-78. doi: 10.1016/j.cosust.2021.03.007

Brondízio, E.S., de Lima, A.C.B., Schramski, S. and Adams, C. (2016) 'Social and health dimensions of climate change in the Amazon', Annals of Human Biology, 43(4), pp. 405-414. doi: 10.1080/03014460.2016.1193222

Brondizio, E.S., Giroux, S.A., Valliant, J.C.D., Blekking, J., Dickinson, S. and Henschel, B. (2023) 'Millions of jobs in food production are disappearing — a change in mindset would help to keep them', Nature, 620(7972), pp. 33–36. doi: 10.1038/d41586-023-02447-2

Bullock, E.L., Woodcock, C.E., Souza Jr., C. and Olofsson, P. (2020) 'Satellite-based estimates reveal widespread forest degradation in the Amazon', Global Change Biology, 26(5), pp. 2956-2969. doi: 10.1111/gcb.15029

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G. and Saba, V. (2018) 'Observed fingerprint of a weakening Atlantic Ocean overturning circulation', Nature, 556(7700), pp. 191-196. doi: 10.1038/s41586-018-0006-5

Campanharo, W.A., Lopes, A.P., Anderson, L.O., da Silva, T.F.M.R. and Aragão, L.E.O.C. (2019) 'Translating Fire Impacts in Southwestern Amazonia into Economic Costs', Remote Sensing, 11(7), p. 764. doi: 10.3390/rs11070764

Campos-Silva, J.V., Peres, C.A., Hawes, J.E., Haugaasen, T., Freitas, C.T., Ladle, R.J. and Lopes, P.F.M. (2021) 'Sustainable-use protected areas catalyze enhanced livelihoods in rural Amazonia', Proceedings of the National Academy of Sciences, 118(40), p. e2105480118. doi: doi:10.1073/pnas.2105480118

Ciemer, C., Winkelmann, R., Kurths, J. and Boers, N. (2021) 'Impact of an AMOC weakening on the stability of the southern Amazon rainforest', The European Physical Journal Special Topics, 230(14), pp. 3065-3073. doi: 10.1140/epjs/s11734-021-00186-x

Costa, F. and Marengo, J.A. (2023) 'Statement on the 2023 Amazon drought and its unforeseen consequences', The Amazon We Want. Science Panel for Amazon. Available at: https://eng-other-pub.sp-amazon.org/231208%20Statement%20on%20the%202023%20Amazon%20Drought%20(English).pdf

Cox, P.M., Betts, R.A., Collins, M., Harris, P.P., Huntingford, C. and Jones, C.D. (2004) 'Amazonian forest dieback under climate-carbon cycle projections for the 21st century', Theoretical and Applied Climatology, 78(1-3), pp. 137-156. doi: 10.1007/s00704-004-0049-4

de Carvalho, T. (2025) 'The cascading effects of climate change on children: extreme floods, family mobility and child well-being in Amazonia', Climate and Development, 17(3), pp. 191-199. doi: 10.1080/17565529.2024.2345331

De Longueville, F., Ozer, P., Gemenne, F., Henry, S., Mertz, O. and Nielsen, J.Ø. (2020) 'Comparing climate change perceptions and meteorological data in rural West Africa to improve the understanding of household decisions to migrate', Climatic Change, 160(1), pp. 123-141. doi: 10.1007/s10584-020-02704-7

Flores, B.M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R.A., Levis, C., Lapola, D.M., Esquível-Muelbert, A., Jakovac, C., Nobre, C.A., Oliveira, R.S., Borma, L.S., Nian, D., Boers, N., Hecht, S.B., ter Steege, H., Arieira, J., Lucas, I.L., Berenguer, E., Marengo, J.A., Gatti, L.V., Mattos, C.R.C. and Hirota, M. (2024) 'Critical transitions in the Amazon forest system', Nature, 626(7999), pp. 555-564. doi: 10.1038/s41586-023-06970-0

Fu, R., Yin, L., Li, W., Arias, P.A., Dickinson, R.E., Huang, L., Chakraborty, S., Fernandes, K., Liebmann, B., Fisher, R. and Myneni, R.B. (2013) 'Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection', Proceedings of the National Academy of Sciences, 110(45), pp. 18110-18115. doi: doi:10.1073/pnas.1302584110

Garcia, B.N., Libonati, R. and Nunes, A.M.B. (2018) 'Extreme Drought Events over the Amazon Basin: The Perspective from the Reconstruction of South American Hydroclimate', Water, 10(11), p. 1594. doi: 10.3390/w10111594

Garnett, S.T., Burgess, N.D., Fa, J.E., Fernández-Llamazares, Á., Molnár, Z., Robinson, C.J., Watson, J.E.M., Zander, K.K., Austin, B., Brondizio, E.S., Collier, N.F., Duncan, T., Ellis, E., Geyle, H., Jackson, M.V., Jonas, H., Malmer, P., McGowan, B., Sivongxay, A. and Leiper, I. (2018) 'A spatial overview of the global importance of Indigenous lands for conservation', Nature Sustainability, 1(7), pp. 369-374. doi: 10.1038/s41893-018-0100-6

Garrett, R.D., Cammelli, F., Ferreira, J., Levy, S.A., Valentim, J. and Vieira, I. (2021) 'Forests and Sustainable Development in the Brazilian Amazon: History, Trends, and Future Prospects', Annual Review of Environment and Resources, 46(Volume 46, 2021), pp. 625-652. doi: 10.1146/annurev-environ-012220-010228

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

Gatti, L.V., Cunha, C.L., Marani, L., Cassol, H.L.G., Messias, C.G., Arai, E., Denning, A.S., Soler, L.S., Almeida, C., Setzer, A., Domingues, L.G., Basso, L.S., Miller, J.B., Gloor, M., Correia, C.S.C., Tejada, G., Neves, R.A.L., Rajao, R., Nunes, F., Filho, B.S.S., Schmitt, J., Nobre, C., Corrêa, S.M., Sanches, A.H., Aragão, L.E.O.C., Anderson, L., Von Randow, C., Crispim, S.P., Silva, F.M. and Machado, G.B.M. (2023) 'Increased Amazon carbon emissions mainly from decline in law enforcement', Nature, 621(7978), pp. 318-323. doi: 10.1038/s41586-023-06390-0

Gueiros, C., Jodoin, S., & McDermott, C. L. (2023). Jurisdictional approaches to reducing emissions from deforestation and forest degradation in Brazil: Why do states adopt jurisdictional policies? Land Use Policy, 127, 106582. https://doi.10.1016/j.landusepol.2023.106582.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. and Townshend, J.R.G. (2013) 'High-Resolution Global Maps of 21st-Century Forest Cover Change', Science, 342(6160), pp. 850-853. doi: 10.1126/science.1244693

Harris, M. (1998) 'The Rhythm of Life on the Amazon Floodplain: Seasonality and Sociality in a Riverine Village', The Journal of the Royal Anthropological Institute, 4(1), pp. 65-82. doi: 10.2307/3034428

Heinrich, V.H.A., Dalagnol, R., Cassol, H.L.G., Rosan, T.M., de Almeida, C.T., Silva Junior, C.H.L., Campanharo, W.A., House, J.I., Sitch, S., Hales, T.C., Adami, M., Anderson, L.O. and Aragão, L.E.O.C. (2021) 'Large carbon sink potential of secondary forests in the Brazilian Amazon to mitigate climate change', Nature Communications, 12(1), p. 1785. doi: 10.1038/s41467-021-22050-1

Higgins, S.I., Bond, W.J. and Trollope, W.S.W. (2000) 'Fire, resprouting and variability: a recipe for grass–tree coexistence in savanna', Journal of Ecology, 88(2), pp. 213-229. doi: 10.1046/j.1365-2745.2000.00435.x

Hirota, M., Holmgren, M., Van Nes, E.H. and Scheffer, M. (2011) 'Global Resilience of Tropical Forest and Savanna to Critical Transitions', Science, 334(6053), pp. 232-235. doi: 10.1126/science.1210657

Jakovac, C.C., Nascimento, N., Gallegos, S.C., Celentano, D., Vieira D. L. M., Fernandes, C.C., Brienza Junior, S. and Pellicciotti, A.S. (2024) Strategies for implementing and scaling up forest restoration in the Amazon, Policy Brief. Science Panel for the Amazon, United Nations Sustainable Development Solutions Network, New York, USA. Available from https://www.theamazonwewant.org/spa-reports/.

Jiménez-Muñoz, J.C., Mattar, C., Barichivich, J., Santamaría-Artigas, A., Takahashi, K., Malhi, Y., Sobrino, J.A. and Schrier, G.v.d. (2016) 'Record-breaking warming and extreme drought in the Amazon rainforest during the course of El Niño 2015–2016', Scientific Reports, 6(1), p. 33130. doi: 10.1038/srep33130

Josse, C., Tupinambá, R., Viscarra, F.E., Armenteras, D., Barreto Filho, H.T., Guzmán León, A., Cípio Aureliano, I., Martins Machado, A., Heilpern S., Begotti, R.A. and Kambeba, M.W. (2024) Protected Areas and Indigenous Territories: Pillars for Achieving Conservation Goals in the Amazon. Policy Brief. Science Panel for the Amazon, United Nations Sustainable Development Solutions Network, New York, USA. Available from https://www.theamazonwewant.org/spa-reports/.

Kelly, B. and Gratten, S. (2023) 'In Brazil's Amazon, drought affects locals' access to food and water', Reuters. Available at: https://www.reuters.com/world/americas/brazils-amazon-drought-affects-locals-access-food-water-2023-09-28/ (Accessed: 2025-09-04).

Kreibich, H., Van Loon, A.F., Schröter, K., Ward, P.J., Mazzoleni, M., Sairam, N., Abeshu, G.W., Agafonova, S., AghaKouchak, A., Aksoy, H., Alvarez-Garreton, C., Aznar, B., Balkhi, L., Barendrecht, M.H., Biancamaria, S., Bos-Burgering, L., Bradley, C., Budiyono, Y., Buytaert, W., Capewell, L., Carlson, H., Cavus, Y., Couasnon, A., Coxon, G., Daliakopoulos, I., de Ruiter, M.C., Delus, C., Erfurt, M., Esposito, G., François, D., Frappart, F., Freer, J., Frolova, N., Gain, A.K., Grillakis, M., Grima, J.O., Guzmán, D.A., Huning, L.S., Ionita, M., Kharlamov, M., Khoi, D.N., Kieboom, N., Kireeva, M., Koutroulis, A., Lavado-Casimiro, W., Li, H.-Y., Llasat, M.C., Macdonald, D., Mård, J., Mathew-Richards, H., McKenzie, A., Mejia, A., Mendiondo, E.M., Mens, M., Mobini, S., Mohor, G.S., Nagavciuc, V., Ngo-Duc, T., Thao Nguyen Huynh, T., Nhi, P.T.T., Petrucci, O., Nguyen, H.Q., Quintana-Seguí, P., Razavi, S., Ridolfi, E., Riegel, J., Sadik, M.S., Savelli, E., Sazonov, A., Sharma, S., Sörensen, J., Arguello Souza, F.A., Stahl, K., Steinhausen, M., Stoelzle, M., Szalińska, W., Tang, Q., Tian, F., Tokarczyk, T., Tovar, C., Tran, T.V.T., Van Huijgevoort, M.H.J., van Vliet, M.T.H., Vorogushyn, S., Wagener, T., Wang, Y., Wendt, D.E., Wickham, E., Yang, L., Zambrano-Bigiarini, M., Blöschl, G. and Di Baldassarre, G. (2022) 'The challenge of unprecedented floods and droughts in risk management', Nature, 608(7921), pp. 80-86. doi: 10.1038/s41586-022-04917-5

Kruid, S., Macedo, M.N., Gorelik, S.R., Walker, W., Moutinho, P., Brando, P.M., Castanho, A., Alencar, A., Baccini, A. and Coe, M.T. (2021) 'Beyond Deforestation: Carbon Emissions From Land Grabbing and Forest Degradation in the Brazilian Amazon', Frontiers in Forests and Global Change, Volume 4 - 2021 doi: 10.3389/ffgc.2021.645282

Lapola, D.M., Pinho, P., Barlow, J., Aragão, L.E.O.C., Berenguer, E., Carmenta, R., Liddy, H.M., Seixas, H., Silva, C.V.J., Silva-Junior, C.H.L., Alencar, A.A.C., Anderson, L.O., Armenteras, D., Brovkin, V., Calders, K., Chambers, J., Chini, L., Costa, M.H., Faria, B.L., Fearnside, P.M., Ferreira, J., Gatti, L., Gutierrez-Velez, V.H., Han, Z., Hibbard, K., Koven, C., Lawrence, P., Pongratz, J., Portela, B.T.T., Rounsevell, M., Ruane, A.C., Schaldach, R., da Silva, S.S., von Randow, C. and Walker, W.S. (2023) 'The drivers and impacts of Amazon forest degradation', Science, 379(6630), p. eabp8622. doi: 10.1126/science.abp8622

Lapola, D.M., Pinho, P., Quesada, C.A., Strassburg, B.B.N., Rammig, A., Kruijt, B., Brown, F., Ometto, J.P.H.B., Premebida, A., Marengo, J.A., Vergara, W. and Nobre, C.A. (2018) 'Limiting the high impacts of Amazon forest dieback with no-regrets science and policy action', Proceedings of the National Academy of Sciences, 115(46), pp. 11671-11679. doi: 10.1073/pnas.1721770115

Laybourn, L., Abrams, J.F., Benton, D., Brown, K., Evans, J., Elliott, J., Swingedouw, D., Lenton, T.M. and Dyke, J.G. (2024) The security blind spot: Cascading climate impacts and tipping points threaten national security. IPPR. Available from: http://www.ippr.org/articles/security-blind-spot.

Lenton, T.M., Armstrong McKay, D.I., Loriani, S., Abrams, J.F., Lade, S.J., Donges, J.F., Milkoreit, M., Powell, T., Smith, S.R., Zimm, C., Buxton, J.E., Bailey, E., Laybourn, L., Ghadiali, A. and Dyke, J.G. (2023) The Global Tipping Points Report 2023. University of Exeter, Exeter, UK.

Lenton, T.M., Benson, S., Smith, T., Ewer, T., Lanel, V., Petykowski, E., Powell, T.W.R., Abrams, J.F., Blomsma, F. and Sharpe, S. (2022) 'Operationalising positive tipping points towards global sustainability', Global Sustainability, 5, p. e1. article number e1. doi: 10.1017/sus.2021.30

Levis, C., Flores, B.M., Campos-Silva, J.V., Peroni, N., Staal, A., Padgurschi, M.C.G., Dorshow, W., Moraes, B., Schmidt, M., Kuikuro, T.W., Kuikuro, H., Wauja, K., Kuikuro, K., Kuikuro, A., Fausto, C., Franchetto, B., Watling, J., Lima, H., Heckenberger, M. and Clement, C.R. (2024) 'Contributions of human cultures to biodiversity and ecosystem conservation', Nature Ecology & Evolution, 8(5), pp. 866-879. doi: 10.1038/s41559-024-02356-1

Lovejoy, T.E. and Nobre, C. (2018) 'Amazon Tipping Point', Science Advances, 4(2), p. eaat2340. doi: 10.1126/sciadv.aat2340

Machado-Silva, F., Libonati, R., Melo de Lima, T.F., Bittencourt Peixoto, R., de Almeida França, J.R., de Avelar Figueiredo Mafra Magalhães, M., Lemos Maia Santos, F., Abrantes Rodrigues, J. and DaCamara, C.C. (2020) 'Drought and fires influence the respiratory diseases hospitalizations in the Amazon', Ecological Indicators, 109, p. 105817. doi: 10.1016/j.ecolind.2019.105817

Malhi Y., Melack J., Gatti L. V., Ometto J., Kesselmeier J., Wolff S., Aragão L. E. O., Costa M., Saleska S., Pangala S. R., Basso L. S., Rizzo L., Araùjo A. C., Restrepo-Coupe N. and S., J.C.H.L. (2021) 'Chapter 6: Biogeochemical Cycles of the Amazon', in Nobre C., Encalada A., Anderson E., Roca Alcazar F. H., Bustamante M., Mena C., Peña-Claros M., Poveda G., Rodriguez J. P., Saleska S., Trumbore S., Val A. L., Villa Nova L., Abramovay R., Alencar A., Rodríguez Alzza C., Armenteras D., Artaxo P., Athayde S., Barretto Filho H. T., Barlow J., Berenguer E., Bortolotto F., Costa F. A., Costa M. H., Cuvi N., Fearnside P. M., Ferreira J., Flores B. M., Frieri S., Gatti L. V., Guayasamin J. M., Hecht S., Hirota M., Hoorn C., Josse C., Lapola D. M., Larrea C., Larrea-Alcazar D. M., Lehm Ardaya Z., Malhi Y., Marengo J. A., Melack J., Moraes R. M., Moutinho P., Murmis M. R., Neves E. G., Paez B., Painter L., Ramos A., Rosero-Peña M. C., Schmink M., Sist P., Ter Steege H., Val P., Van Der Voort H., Varese M. and Z.-R. G. (eds.) Amazon Assessment Report 2021. https://www.theamazonwewant.org/spa-reports/: United Nations Sustainable Development Solutions Network, New York, USA. doi: 10.55161/TAKR3454.

Marengo, J.A., Espinoza, J.-C., Fu, R., Jimenez Muñoz, J.C., Alves, L.M., Da Rocha, H.R. and Schöngart, J. (2024) 'Long-term variability, extremes and changes in temperature and hydrometeorology in the Amazon region: A review', Acta Amazonica, 54(spe1) doi: 10.1590/1809-4392202200980

Marengo, J.A., Espinoza, J.-C., Fu, R., Jimenez Muñoz, J.C., Muniz Alves, L., Ribeiro da Rocha, H. and Schongart, J. (2021) 'Chapter 22: Long-term variability, extremes, and changes in temperature and hydro meteorology', in Nobre C., Encalada A., Anderson E., Roca Alcazar F. H., Bustamante M., Mena C., Peña-Claros M., Poveda G., Rodriguez J. P., Saleska S., Trumbore S., Val A. L., Villa Nova L., Abramovay R., Alencar A., Rodríguez Alzza C., Armenteras D., Artaxo P., Athayde S., Barretto Filho H. T., Barlow J., Berenguer E., Bortolotto F., Costa F. A., Costa M. H., Cuvi N., Fearnside P. M., Ferreira J., Flores B. M., Frieri S., Gatti L. V., Guayasamin J. M., Hecht S., Hirota M., Hoorn C., Josse C., Lapola D. M., Larrea C., Larrea-Alcazar D. M., Lehm Ardaya Z., Malhi Y., Marengo J. A., Melack J., Moraes R. M., Moutinho P., Murmis M. R., Neves E. G., Paez B., Painter L., Ramos A., Rosero-Peña M. C., Schmink M., Sist P., Ter Steege H., Val P., Van Der Voort H., Varese M. and Z.-R. G. (eds.) Amazon Assessment Report 2021. United Nations Sustainable Development Solutions Network, New York, USA. doi: 10.55161/ZGJG8060.

Marengo, J.A., Nobre, C.A., Tomasella, J., Oyama, M.D., Sampaio de Oliveira, G., De Oliveira, R., Camargo, H., Alves, L.M. and Brown, I.F. (2008) 'The drought of Amazonia in 2005', Journal of Climate, 21(3), pp. 495-516. doi: 10.1175/2007JCLI1600.1

Maru, Y.T., Stafford Smith, M., Sparrow, A., Pinho, P.F. and Dube, O.P. (2014) 'A linked vulnerability and resilience framework for adaptation pathways in remote disadvantaged communities', Global Environmental Change, 28, pp. 337-350. doi: 10.1016/j.gloenvcha.2013.12.007

Monteverde, C., Quandt, A., Gilberto de Souza Ribeiro, J. and De Sales, F. (2024) 'Changing climates, changing lives: Voices of a Brazilian Amazon farming community in a time of climate crisis', PLOS Climate, 3(11), p. e0000522. doi: 10.1371/journal.pclm.0000522

Moutinho, P. and Azevedo-Ramos, C. (2023) 'Untitled public forestlands threaten Amazon conservation', Nature Communications, 14(1), p. 1152. doi: 10.1038/s41467-023-36427-x

Nepstad, D., McGrath, D., Stickler, C., Alencar, A., Azevedo, A., Swette, B., Bezerra, T., DiGiano, M., Shimada, J., Seroa da Motta, R., Armijo, E., Castello, L., Brando, P., Hansen, M.C., McGrath-Horn, M., Carvalho, O. and Hess, L. (2014) 'Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains', Science, 344(6188), pp. 1118-1123. doi: 10.1126/science.1248525

Neves, E.G., Furquim, L.P., Levis, C., Rocha, B.C., Waitling, J.G., Ozorio de Almeida, F., Jaimes Betancourt, C., Junqueira, A.B., Moraes, C.P., Morcote-Rios, G., Shock, M.P. and Tamanaha, E.K. (2021) 'Chapter 8: Peoples of the Amazon before European Colonization', in Nobre C., Encalada A., Anderson E., Roca Alcazar F. H., Bustamante M., Mena C., Peña-Claros M., Poveda G., Rodriguez J. P., Saleska S., Trumbore S., Val A. L., Villa Nova L., Abramovay R., Alencar A., Rodríguez Alzza C., Armenteras D., Artaxo P., Athayde S., Barretto Filho H. T., Barlow J., Berenguer E., Bortolotto F., Costa F. A., Costa M. H., Cuvi N., Fearnside P. M., Ferreira J., Flores B. M., Frieri S., Gatti L. V., Guayasamin J. M., Hecht S., Hirota M., Hoorn C., Josse C., Lapola D. M., Larrea C., Larrea-Alcazar D. M., Lehm Ardaya Z., Malhi Y., Marengo J. A., Melack J., Moraes R. M., Moutinho P., Murmis M. R., Neves E. G., Paez B., Painter L., Ramos A., Rosero-Peña M. C., Schmink M., Sist P., Ter Steege H., Val P., Van Der Voort H., Varese M. and Z.-R. G. (eds.) Amazon Assessment Report 2021. United Nations Sustainable Development Solutions Network, New York, USA. doi: 10.55161/LXIT5573.

Nian, D., Bathiany, S., Ben-Yami, M., Blaschke, L.L., Hirota, M., Rodrigues, R.R. and Boers, N. (2023) 'A potential collapse of the Atlantic Meridional Overturning Circulation may stabilise eastern Amazonian rainforests', Communications Earth & Environment, 4(1), p. 470. doi: 10.1038/s43247-023-01123-7

Nobre, C.A., Peña-Claros, M., Arieira, J., Brandão, D.O. and Viscarra Riveros, F. (2025) 'Climate Change and Sustainability in Amazonia', Oxford Research Encyclopedias: Climate Science, doi: 10.1093/acrefore/9780190228620.013.978

Nolte, C., Agrawal, A., Silvius, K.M. and Soares-Filho, B.S. (2013) 'Governance regime and location influence avoided deforestation success of protected areas in the Brazilian Amazon', Proceedings of the National Academy of Sciences, 110(13), pp. 4956-4961. doi: 10.1073/pnas.1214786110

O'Neill, B., van Aalst, M., Zaiton Ibrahim, Z., Berrang Ford, L., Bhadwal, S., Buhaug, H., Diaz, D., Frieler, K., Garschagen, M., Magnan, A., Midgley, G., Mirzabaev, A., Thomas, A. and Warren, R. (2023) 'Key Risks across Sectors and Regions', in C. Intergovernmental Panel on Climate (ed.) Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, pp. 2411-2538. doi: 10.1017/9781009325844.025.

Padilha, J., Azevedo-Silva, Claudio E., Parente, C., Kasper, D., Dorneles, P., Coelho-Souza, S., Paiva, T., Azeredo, A., Bastos, W. and Sousa, R. (2025) 'Worsening Drought and the Bleak Future for Biodiversity and Ecosystem Services in the Amazon Basin', Aquatic Conservation: Marine and Freshwater Ecosystems, 35(3), p. e70101. doi: 10.1002/aqc.70101

Parry, L., Davies, G., Almeida, O., Frausin, G., de Moraés, A., Rivero, S., Filizola, N. and Torres, P. (2017) 'Social Vulnerability to Climatic Shocks Is Shaped by Urban Accessibility', Annals of the American Association of Geographers, 108(1), pp. 125-143. doi: 10.1080/24694452.2017.1325726

Pearson, J., Jackson, G. and McNamara, K.E. (2023) 'Climate-driven losses to knowledge systems and cultural heritage: A literature review exploring the impacts on Indigenous and local cultures', The Anthropocene Review, 10(2), pp. 343-366. doi: 10.1177/20530196211005482

Pereira, L.M., Gianelli, I., Achieng, T., Amon, D., Archibald, S., Arif, S., Castro, A., Chimbadzwa, T.P., Coetzer, K., Field, T.L., Selomane, O., Sitas, N., Stevens, N., Villasante, S., Armani, M., Kimuyu, D.M., Adewumi, I.J., Lapola, D.M., Obura, D., Pinho, P., Roa-Clavijo, F., Rocha, J. and Sumaila, U.R. (2024) 'Equity and justice should underpin the discourse on tipping points', Earth Syst. Dynam., 15(2), pp. 341-366. doi: 10.5194/esd-15-341-2024

Pessôa, A.C.M., Morello R.S, T.F., Silva-Junior, C.H.L., Doblas, J., Carvalho, N.S., Aragão, L.E.O.C. and Anderson, L.O. (2023) 'Protected areas are effective on curbing fires in the Amazon', Ecological Economics, 214, p. 107983. doi: 10.1016/j.ecolecon.2023.107983

Pinho, P.F., Marengo, J.A. and Smith, M.S. (2015) 'Complex socio-ecological dynamics driven by extreme events in the Amazon', Regional Environmental Change, 15(4), pp. 643-655. doi: 10.1007/s10113-014-0659-z

Pinho, P.F., Patenaude, G., Ometto, J.P., Meir, P., Toledo, P.M., Coelho, A. and Young, C.E.F. (2014) 'Ecosystem protection and poverty alleviation in the tropics: Perspective from a historical evolution of policy-making in the Brazilian Amazon', Ecosystem Services, 8, pp. 97-109. doi: 10.1016/j.ecoser.2014.03.002

Prist, P.R., Sangermano, F., Bailey, A., Bugni, V., Villalobos-Segura, M.d.C., Pimiento-Quiroga, N., Daszak, P. and Zambrana-Torrelio, C. (2023) 'Protecting Brazilian Amazon Indigenous territories reduces atmospheric particulates and avoids associated health impacts and costs', Communications Earth & Environment, 4(1), p. 34. doi: 10.1038/s43247-023-00704-w

Pueyo, S., De Alencastro Graça, P.M.L., Barbosa, R.I., Cots, R., Cardona, E. and Fearnside, P.M. (2010) 'Testing for criticality in ecosystem dynamics: the case of Amazonian rainforest and savanna fire', Ecology Letters, 13(7), pp. 793-802. doi: 10.1111/j.1461-0248.2010.01497.x

Reuters (2024) 'Deforestation in Brazil's Amazon down by 50% to five-year low in 2023', Reuters. Available at: https://www.reuters.com/world/americas/deforestation-brazils-amazon-down-by-50-five-year-low-2023-2024-01-12/ (Accessed: 2025-09-08).

Salati, E., Dall'Olio, A., Matsui, E. and Gat, J.R. (1979) 'Recycling of water in the Amazon Basin: An isotopic study', Water Resources Research, 15(5), pp. 1250-1258. doi: 10.1029/WR015i005p01250

Santos de Lima, L., Silva, F.E.O.e., Dorio Anastácio, P.R., Kolanski, M.M.d.P., Pires Pereira, A.C., Menezes, M.S.R., Cunha, E.L.T.P. and Macedo, M.N. (2024) 'Severe droughts reduce river navigability and isolate communities in the Brazilian Amazon', Communications Earth & Environment, 5(1), p. 370. doi: 10.1038/s43247-024-01530-4

Simpson, N.P., Mach, K.J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R.J., Muccione, V., Mackey, B., New, M.G., O'Neill, B., Otto, F., Pörtner, H.-O., Reisinger, A., Roberts, D., Schmidt, D.N., Seneviratne, S., Strongin, S., van Aalst, M., Totin, E. and Trisos, C.H. (2021) 'A framework for complex climate change risk assessment', One Earth, 4(4), pp. 489-501. doi: 10.1016/j.oneear.2021.03.005

Siqueira-Gay, J., Sonter, L.J. and Sánchez, L.E. (2020) 'Exploring potential impacts of mining on forest loss and fragmentation within a biodiverse region of Brazil's northeastern Amazon', Resources Policy, 67, p. 101662.

Spaiser, V., Juhola, S., Constantino, S.M., Guo, W., Watson, T., Sillmann, J., Craparo, A., Basel, A., Bruun, J.T., Krishnamurthy, K., Scheffran, J., Pinho, P., Okpara, U.T., Donges, J.F., Bhowmik, A., Yasseri, T., Safra de Campos, R., Cumming, G.S., Chenet, H., Krampe, F., Abrams, J.F., Dyke, J.G., Rynders, S., Aksenov, Y. and Spears, B.M. (2024) 'Negative social tipping dynamics resulting from and reinforcing Earth system destabilization', Earth Syst. Dynam., 15(5), pp. 1179-1206. doi: 10.5194/esd-15-1179-2024

Staal, A., Tuinenburg, O.A., Bosmans, J.H.C., Holmgren, M., van Nes, E.H., Scheffer, M., Zemp, D.C. and Dekker, S.C. (2018) 'Forest-rainfall cascades buffer against drought across the Amazon', Nature Climate Change, 8(6), pp. 539-543. doi: 10.1038/s41558-018-0177-y

Sultana, F. (2022) 'Critical climate justice', The Geographical Journal, 188(1), pp. 118-124. doi: 10.1111/geoj.12417

Thompson, D.A., Glenn, D.E., Trethewey, L.L., Blackett, P. and Logan, T.M. (2024) 'Capturing cascading consequences is required to reflect risk from climate change and natural hazards', Climate Risk Management, 44, p. 100613. doi: 10.1016/j.crm.2024.100613

Urrutia-Pereira, M., Varanda Rizzo, L.V., Chong-Neto, H.J. and Solé, D. (2021) 'Impact of exposure to smoke from biomass burning in the Amazon rain forest on human health', J Bras Pneumol., 47(5), p. e20210219. doi: 10.36416/1806-3756/e20210219

Urzedo, D. and Chatterjee, P. (2022) 'The Colonial Reproduction of Deforestation in the Brazilian Amazon: Violence Against Indigenous Peoples for Land Development', in D. Short and M. Crook (eds.) The Genocide-Ecocide Nexus. Routledge, London. doi: 10.4324/9781003253983.

Walker, W.S., Gorelik, S.R., Baccini, A., Aragon-Osejo, J.L., Josse, C., Meyer, C., Macedo, M.N., Augusto, C., Rios, S., Katan, T., de Souza, A.A., Cuellar, S., Llanos, A., Zager, I., Mirabal, G.D., Solvik, K.K., Farina, M.K., Moutinho, P. and Schwartzman, S. (2020) 'The role of forest conversion, degradation, and disturbance in the carbon dynamics of Amazon indigenous territories and protected areas', Proceedings of the National Academy of Sciences, 117(6), pp. 3015-3025. doi: 10.1073/pnas.1913321117

Whyte, K. (2020) 'Too late for indigenous climate justice: Ecological and relational tipping points', WIREs Climate Change, 11(1), p. e603. doi: 10.1002/wcc.603

Wunderling, N., Sakschewski, B., Rockström, J., Flores, B., Hirota, M. and Staal, A. (2025) 'Pinpointing Amazon forest tipping in global warming and deforestation pathways', In Review, doi: 10.21203/rs.3.rs-5840795/v1

Wunderling, N., Staal, A., Sakschewski, B., Hirota, M., Tuinenburg, O.A., Donges, J.F., Barbosa, H.M.J. and Winkelmann, R. (2022) 'Recurrent droughts increase risk of cascading tipping events by outpacing adaptive capacities in the Amazon rainforest', Proceedings of the National Academy of Sciences, 119(32), p. e2120777119. doi: 10.1073/pnas.2120777119

Yoon, A. and Hohenegger, C. (2025) 'Muted Amazon Rainfall Response to Deforestation in a Global Storm-Resolving Model', Geophysical Research Letters, 52(4), p. e2024GL110503. doi: 10.1029/2024GL110503

Zemp, D.C., Schleussner, C.-F., Barbosa, H.M.J., Hirota, M., Montade, V., Sampaio, G., Staal, A., Wang-Erlandsson, L. and Rammig, A. (2017a) 'Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks', Nature Communications, 8(1), p. 14681. doi: 10.1038/ncomms14681

Zemp, D.C., Schleussner, C.-F., Barbosa, H.M.J. and Rammig, A. (2017b) 'Deforestation effects on Amazon forest resilience', Geophysical Research Letters, 44(12), pp. 6182-6190. doi: 10.1002/2017GL072955

Zimbres, B., Shimbo, J., Lenti, F., Brandão, A., Souza, E., Azevedo, T. and Alencar, A. (2024) 'Improving estimations of GHG emissions and removals from land use change and forests in Brazil', Environmental Research Letters, 19(9), p. 094024. doi: 10.1088/1748-9326/ad64ea

References 4.2

Alkhayuon, H., Ashwin, P., Jackson, L. C., Quinn, C. and Wood. R. A. (2019) 'Basin bifurcations, oscillatory instability and rate-induced thresholds for Atlantic meridional overturning circulation in a global oceanic box model', Proc. R. Soc. A. 475, 20190051. https://doi.org/10.1098/rspa.2019.0051

Arellano-Nava, B., Halloran, P. R., Boulton, C. A., Scourse, J., Butler, P. G., Reynolds, D. J., and Lenton, T. M. (2022) 'Destabilisation of the Subpolar North Atlantic prior to the Little Ice Age', Nature Communications, 13(1), 5008. https://doi.org/10.1038/s41467-022-32653-x

Armstrong, E., Valdes, P., House, J. et al. (2019) 'Investigating the feedbacks between CO2, vegetation and the AMOC in a coupled climate model', Clim. Dyn. 53, pp. 2485–2500. https://doi.org/10.1007/s00382-019-04634-2

Årthun, M., Asbjørnsen, H., Chafik, L., Johnson, H. L. and Våge, K. (2023) 'Future strengthening of the Nordic Seas overturning circulation', Nature Communications, 14(1), 2065. https://doi.org/10.1038/s41467-023-37846-6

Arumí-Planas, C., Dong, S., Perez, R., Harrison, M. J., Farneti, R. and Hernández-Guerra, A. (2024) 'A multi-data set analysis of the freshwater transport by the Atlantic meridional overturning circulation at nominally 34.5°S'. Journal of Geophysical Research: Oceans, 129, e2023JC020558. https://doi.org/10.1029/2023JC020558

Asch, R.G., Stock, C.A. and Sarmiento J.L. (2019) 'Climate change impacts on mismatches between phytoplankton blooms and fish spawning phenology', Glob. Change Biol. 25: pp. 2544–2559. https://doi.org/10.1111/gcb.14650

Bakker, P., et al. (2016) 'Fate of the Atlantic Meridional Overturning Circulation: Strong decline under continued warming and Greenland melting', Geophys. Res. Lett., 43, pp. 12,252–12,260 (2016). https://doi.org/10.1002/2016GL070457

Baker, J.A., Bell, M.J., Jackson, L.C. et al. (2025) 'Continued Atlantic overturning circulation even under climate extremes', Nature 638, pp. 987–994. https://doi.org/10.1038/s41586-024-08544-0

Barton, A.D., Irwin, A.J., Finkel, Z.V. and Stock, C.A. (2016) 'Anthropogenic climate change drives shift and shuffle in North Atlantic phytoplankton communities', Proc. Natl. Acad. Sci. U.S.A. 113 (11) pp. 2964-2969. https://doi.org/10.1073/pnas.1519080113

Beaugrand, G., Edwards, M., Brander, K., Luczak, C. and Ibanez, F. (2008) 'Causes and projections of abrupt climate-driven ecosystem shifts in the North Atlantic', Ecology Letters, 11, pp. 1157-1168. https://doi.org/10.1111/j.1461-0248.2008.01218.x

Bellomo, K., Angeloni, M., Corti, S. et al. (2021) 'Future climate change shaped by inter-model differences in Atlantic meridional overturning circulation response', Nature Communications 12, 3659. https://doi.org/10.1038/s41467-021-24015-w

Bellomo, K., Meccia, V.L., D'Agostino, R. et al. (2023) 'Impacts of a weakened AMOC on precipitation over the Euro-Atlantic region in the EC-Earth3 climate model', Climate Dynamics, 61, pp. 3397–3416. https://doi.org/10.1007/s00382-023-06754-2

Bellomo, K. and Mehling, O. (2024) 'Impacts and state-dependence of AMOC weakening in a warming climate', Geophysical Research Letters, 51, e2023GL107624. https://doi.org/10.1029/2023GL107624

Ben-Yami, M. et al. (2024a) 'Uncertainties too large to predict tipping times of major earth system components from historical data', Science Advances, 10 (31), eadl4841. https://doi.org/10.1126/sciadv.adl4841

Ben-Yami, M., Good, P., Jackson, L. C., Crucifix, M., Hu, A., Saenko, O., et al. (2024b) 'Impacts of AMOC collapse on monsoon rainfall: A multi-model comparison', Earth's Future, 12, e2023EF003959. https://doi.org/10.1029/2023EF003959

Biesbroek, R., Haasnoot, M., Mach, K.J. and Petersen, A.C., (2025) 'Adaptation planning in the context of a weakening and possibly collapsing Atlantic Meridional Overturning Circulation (AMOC)', Regional Environmental Change, 25, 93. https://doi.org/10.1007/s10113-025-02434-5

Bishop, S.P et al. (2016) 'Southern Ocean overturning compensation in an eddy-resolving climate simulation', J. Phys. Oceanogr., 46, pp. 1575-1592. https://doi.org/10.1175/JPO-D-15-0177.1

Bode A. (2024) 'Synchronised multidecadal trends and regime shifts in North Atlantic plankton populations', ICES Journal of Marine Science, 81 (3), pp. 575-586. https://doi.org/10.1093/icesjms/fsad095

Boers, N. (2021) 'Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation', Nature Climate Change, 11, pp. 680–688. https://doi.org/10.1038/s41558-021-01097-4

Bonan, D. B., Thompson, A. F., Newsom, E. R., Sun, S. and Rugenstein, M. (2022) 'Transient and Equilibrium Responses of the Atlantic Overturning Circulation to Warming in Coupled Climate Models: The Role of Temperature and Salinity', J. Climate, 35, 5173–5193. https://doi.org/10.1175/JCLI-D-21-0912.1.

Bonnet, R. et al. (2021) 'Increased risk of near term global warming due to a recent AMOC weakening', Nat Communications, 12, 6108. https://doi.org/10.1038/s41467-021-26370-0

Boot, A. A., Steenbeek, J., Coll, M., von der Heydt, A. S. and Dijkstra, H. A. (2025) 'Global marine ecosystem response to a strong AMOC weakening under low and high future emission scenarios', Earth's Future, 13, e2024EF004741. https://doi.org/10.1029/2024EF004741

Boot, A.A., von der Heydt, A.S. and Dijkstra, H.A. (2024) 'Response of atmospheric pCO2 to a strong AMOC weakening under low and high emission scenarios', Climate Dynamics, 62, pp. 7559–7574. https://doi.org/10.1007/s00382-024-07295-y

Boot, A.A., von der Heydt, A.S. and Dijkstra, H.A. (2023) 'Effect of Plankton Composiiton Shifts in the North Atlantic on Atmospheric pCO2', Geophysical Research Letters, 50, e2022GL100230. https://doi.org/10.1029/2022GL100230

Born, A. and Stocker, T. F. (2014) 'Two stable equilibria of the Atlantic subpolar gyre', J. Phys. Oceanography, 44, pp. 246–264 (2014). https://doi.org/10.1175/JPO-D-13-073.1

Born, A. and Mignot, J. (2012) 'Dynamics of decadal variability in the Atlantic subpolar gyre: a stochastically forced oscillator', Climate Dynamics, 39, pp. 461-474. https://doi.org/10.1007/s00382-011-1180-4

Born, A., Stocker, T. F., and Sandø, A. B. (2016) 'Transport of salt and freshwater in the Atlantic Subpolar Gyre', Ocean Dynamics, 66, pp. 1051-1064. https://doi.org/10.1007/s10236-016-0970-y

Bosch, T., Thornton, F. and Vinke, K. (2025) 'Climate Change Is Affecting Geopolitics - Not Just the Other Way Around. DGAP Memo', German Council on Foreign Relations e.V. https://dgap.org/system/files/article_pdfs/18_Memo_Geopolitics.pdf

Brodeau, L. and Koenigk, T. (2016) 'Extinction of the northern oceanic deep convection in an ensemble of climate model simulations of the 20th and 21st centuries', Climate Dynamics, 46, pp. 2863–2882. https://doi.org/10.1007/s00382-015-2736-5

Caesar, L., McCarthy G.D., Thornalley,, D.J.R., Cahill, N. and Rahmstorf, S. (2021) 'Current Atlantic Meridional Overturning Circulation weakest in last millennium', Nature Geoscience, 14(3), pp. 118–120. https://doi.org/10.1038/s41561-021-00699-z

Caesar, L., Rahmstorf. S., Robinson, A., Feulner, G. and Saba, V. (2018) 'Observed fingerprint of a weakening Atlantic Ocean overturning circulation', Nature 556, pp. 191–196. https://doi.org/10.1038/s41586-018-0006-5

Castellana, D., Baars, S., Wubs, F,W. and Dijkstra, H.A. (2019) 'Transition Probabilities of Noise-induced Transitions of the Atlantic Ocean Circulation', Scientific Reports 9(1), 20284. https://doi.org/10.1038/s41598-019-56435-6

Chapman, R.R., Ashwin, P., Baker, J. and Wood, R.A. (2024) 'Quantifying risk of a noise-induced AMOC collapse from northern and tropical Atlantic Ocean variability', Environmental Research Communications, 6(11), 111003. https://doi.org/10.1088/2515-7620/ad8f98

Cini, M., Zappa, G., Ragone, F. and Corti, S. (2024) 'Simulating AMOC tipping driven by internal climate variability with a rare event algorithm'. npj Climate and Atmospheric Science 7(1), 31. https://doi.org/10.1038/s41612-024-00568-7

Cyr, F., Lewis, K., Bélanger, D., Regular, P., Clay, S. and Devred, E. (2024) 'Physical controls and ecological implications of the timing of the spring phytoplankton bloom on the Newfoundland and Labrador shelf', Limnol. Oceanogr. Lett, 9, pp. 191-198. https://doi.org/10.1002/lol2.10347

Danabasoglu, G., Yeager, S.G., Bailey, D., Behrens, E., Bentsen, M., Bi, D., Biastoch, A. et al. (2014) 'North Atlantic simulations in coordinated ocean-ice reference experiments phase II (CORE-II). Part I: mean states', Ocean Modelling, 73, pp. 76-107. https://doi.org/10.1016/j.ocemod.2013.10.005.

Devilliers, M., Swingedouw, D., Mignot, J. et al. (2021) 'A realistic Greenland ice sheet and surrounding glaciers and ice caps melting in a coupled climate model', Climate Dynamics, 57, 2467–2489. https://doi.org/10.1007/s00382-021-05816-7.

Devilliers, M., Yang, S., Drews, A. et al. (2024) 'Ocean response to a century of observation-based freshwater forcing around Greenland in EC-Earth3'. Climate Dynamics, 62, pp. 4905–4923. https://doi.org/10.1007/s00382-024-07142-0.

Dima, M,. and Lohmann, G. (2010) 'Evidence for two Distinct Modes of Large-Scale Ocean Circulation Changes over the Last Century'., J Climate 23, pp. 5-16. https://doi.org/10.1175/2009JCLI2867.1

Ditlevsen, P. and Ditlevsen, S. (2023) 'Warning of a forthcoming collapse of the Atlantic meridional overturning circulation', Nature Communications, 14 (1), 4254. https://doi.org/10.1038/s41467-023-39810-w

Drijfhout, S., Van Oldenborgh, G. J., and Cimatoribus, A. (2012) 'Is a decline of AMOC causing the warming hole above the North Atlantic in observed and modeled warming patterns?' Journal of Climate, 25, pp. 8373–8379. https://doi.org/10.1175/jcli-d-12-00490.1

Drijfhout, S. Angevaare, J., Mecking, J., van Westen, R. and Rahmstorf, S. (2025) 'Shutdown of northern Atlantic overturning after 2100 following deep mixing collapse in CMIP6 projections, Environmental Research Letters, 20 094062. https://doi.org/10.1088/1748-9326/adfa3b

Drijfhout, S.S. (2015a) 'Competition between global warming and an abrupt collapse of the AMOC in Earth's energy imbalance', Scientific Reports, 5, 14877. https://doi.org/10.1038/srep14877

Drijfhout, S.S.(2015b) 'Global radiative adjustment after a collapse of the Atlantic meridional overturning circulation', Climate Dynamics, 45, pp. 1789–1799.https://doi.org/10.1007/s00382-014-2433-9

Dunstone, N.J., Smith, D.M. and Eade, R. (2011) 'Multi-year predictability of the tropical Atlantic atmosphere driven by the high latitude North Atlantic Ocean', Geophys. Res. Lett., 38, L14701. https://doi.org/10.1029/2011GL047949.

Falkena, S., Dijkstra, H.A. and Von der Heydt, A.S., (2025) 'Causal Mechanisms of Subpolar Gyre Variability in CMIP6 Models', Earth System Dynamics, in press, https://doi.org/10.48550/arXiv.2408.16541

Fedorov, A. M., et al. (2023) 'Deep convection in the Subpolar Gyre: Do we have enough data to estimate its intensity?', Dynamics of Atmospheres and Oceans, 101, 101338. https://doi.org/10.1016/j.dynatmoce.2022.101338.

Fraser, N. J. and Cunningham, S. A. (2021) '120 years of AMOC variability reconstructed from observations using the Bernoulli inverse'. Geophys. Res. Lett. 48, e2021GL093893. https://doi.org/10.1029/2021GL093893

Futerman, G., Adhikari, M., Duffey, A., Fan, Y., Gurevitch, J., Irvine, P., and Wieners, C. (2025) 'The interaction of solar radiation modification with Earth system tipping elements', Earth Syst. Dynam., 16, pp. 939–978. https://doi.org/10.5194/esd-16-939-2025.

Gajewski, Ł., Hinge, M. and Denkenberger, D. (2025) 'Quantitative, Data-driven Network Model for Global Cascading Financial Failure', Preprint arXiv, https://doi.org/10.48550/arXiv.2502.12980

Gelderloos, R., Katsman, C. A. and Drijfhout, S. S. (2011) 'Assessing the roles of three eddy types in restratifying the Labrador Sea after deep convection', Journal of Physical Oceanography, 41(11), pp. 2102-2119. https://doi.org/10.1175/JPO-D-11-054.1

Georgiou, S., van der Boog, C. G., Brüggemann, N., Ypma, S. L., Pietrzak, J. D. and Katsman, C. A. (2019) 'On the interplay between downwelling, deep convection and mesoscale eddies in the Labrador Sea'. Ocean Modelling, 135, pp. 56-70. https://doi.org/10.1016/j.ocemod.2019.02.004.

Greene C. H. et al. (2013) 'Remote climate forcing of decadal-scale regime shifts in Northwest Atlantic shelf ecosystems', Limnology and Oceanography, 58, https://doi.org/10.4319/lo.2013.58.3.0803.

Haarsma, R. J., Selten, F. M. and Drijfhout, S. S. (2015) 'Decelerating Atlantic meridional overturning circulation main cause of future west European summer atmospheric circulation changes', Environmental Research Letters, 10, 094007. https://doi.org/10.1088/1748-9326/10/9/094007

Haustein, K. and Rayer, Q. (2023) 'Water Cycle Changes in a Warming World: The Scientific Background'. In: Gramlich, D., Walker, T., Michaeli, M., Esme Frank, C. (eds) Water Risk Modeling. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-031-23811-6_2

Hirasawa, H., Hingmire, D., Sigh, H., Rasch, P.J. and Mitra, P., (2023) 'Effect of Regional Marine Cloud Brightening Interventions on Climate Tipping Elements', Geophys. Res. Letters, 50, e2023GL104314. https://doi.org/10.1029/2023GL104314

Howard, T., et al. (2024) 'Storm surge changes around the UK under a weakened Atlantic meridional overturning circulation', Environ. Res. Commun. 6, 035026. https://doi.org/10.1088/2515-7620/ad3368

Hunt, J.D. and Byers, E. (2019) 'Reducing sea level rise with submerged barriers and dams in Greenland', Mitig Adapt Strateg Glob Change, 24, pp. 779-794. https://doi.org/10.1007/s11027-018-9831-y

Jackson, L.C., Schaller, N., Smith, R.S. et al. (2014) 'Response of the Atlantic meridional overturning circulation to a reversal of greenhouse gas increases', Climate Dynamics, 42, pp. 3323–3336. https://doi.org/10.1007/s00382-013-1842-5

Jackson, L.C. et al. (2015) 'Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM', Climate Dynamics, 45 (11), pp. 3299 – 3316. https://doi.org/10.1007/s00382-015-2540-2

Jackson, J. (2025) 'The Climate-Changing Context of Inflation: Fossilflation, Climateflation, and the Environmental Politics of Green Central Banks', Global Environmental Politics, 24(4), 1-9. https://doi.org/10.1162/glep_a_00762

Jackson, L. C., et al. (2025) 'Toward Improving Representation of the Atlantic Meridional Overturning Circulation in Climate Models', Bulletin of the American Meteorological Society 106 (6), pp. E1032-E1036. https://doi.org/10.1175/BAMS-D-25-0078.1

Jones, A.; Bridle, S.; Denby, K.; Bhunnoo, R.; Morton, D.; Stanbrough, L.; Coupe, B.; Pilley, V.; Benton, T.; Falloon, P. et al. (2023) 'Scoping Potential Routes to UK Civil Unrest via the Food System: Results of a Structured Expert Elicitation', Sustainability 15, 14783. https://doi.org/10.3390/su152014783

Keefer, B., Wolovick, M. and Moore, J.C., (2023) 'Feasibility of ice sheet conservation using seabed anchored curtains', PNAS Nexus, pgad053. https://doi.org/10.1093/pnasnexus/pgad053

Kelly, S.J., Popova, E.E., Yool, A., Jebri, F., Oliver, S. and Srokosz, M. (2025) 'Abrupt Changes in the Timing and Magnitude of the North Atlantic Bloom Over the 21st Century', Journal of Geophysical Research: Oceans. 130, e2024JC022284. https://doi.org/10.1029/2024JC022284

Kleppin, H., Jochum, M., Otto-Bliesner, B., Shields, C. A. and Yeager, S. (2015) 'Stochastic atmospheric forcing as a cause of Greenland climate transitions', Journal of Climate, 28(19), pp. 7741-7763. https://doi.org/10.1175/JCLI-D-14-00728.1

Klose, A. K., Donges, J. F., Feudel, U., and Winkelmann, R. (2024) 'Rate-induced tipping cascades arising from interactions between the Greenland Ice Sheet and the Atlantic Meridional Overturning Circulation', Earth System Dynamics, 15, pp. 635–652, https://doi.org/10.5194/esd-15-635-2024.

Latif, M., Sun, J., Visbeck, M. and Bordbar, M. H. (2022) 'Natural variability has dominated Atlantic Meridional Overturning Circulation since 1900'. Nat Clim Change, 12, pp. 455–460. https://doi.org/10.1038/s41558-022-01342-4

Lawrence, M., Homer-Dixon, T., Janzwood, S., Rockström J., Renn, O., Donges, J.F. (2024) 'Global polycrisis: the causal mechanisms of crisis entanglement', Global Sustainability, 7:e6. doi:10.1017/sus.2024.1

Laybourn, L. et al. (2024) 'The Blind Spot. Cascading Climate Impacts and Tipping Points Threaten National Security. Institute for Public Policy Research', URL: https://ippr-org.files.svdcdn.com/production/Downloads/The-security-blind-spot-October-24_2024-10-14-121035_uryr.pdf

Lehner, F., Born, A., Raible, C. C. and Stocker, T. F. (2013) 'Amplified inception of European Little Ice Age by sea ice–ocean–atmosphere feedbacks'. Journal of Climate, 26(19), pp. 7586-7602. https://doi.org/10.1175/JCLI-D-12-00690.1

Lenton, T. et al. (2023) 'Global Tipping Points Report', https://report-2023.global-tipping-points.org/

Levermann, A., et al. (2005) 'Dynamic sea level changes following changes in the thermohaline circulation', Climate Dynamics, 24, pp. 347–354. https://doi.org/10.1007/s00382-004-0505-y

Li, C. and Born, A. (2019) 'Coupled atmosphere-ice-ocean dynamics in Dansgaard-Oeschger events'. Quaternary Science Reviews, 203, pp. 1-20. https://doi.org/10.1016/j.quascirev.2018.10.031.

Li, K.Y. and Liu, W. (2025) 'Weakened Atlantic Meridional Overturning Circulation causes the historical North Atlantic Warming Hole', Commun Earth Environ 6, 416. https://doi.org/10.1038/s43247-025-02403-0

Lin, P. et al. (2023) 'Recent state transition of the Arctic Ocean's Beaufort Gyre', Nat. Geosci. 16, pp. 485–491. https://doi.org/10.1038/s41561-023-01184-5

Liu, W., et al. (2020) 'Climate impacts of a weakened Atlantic Meridional Overturning Circulation in a warming climate', Science Advances, 6, eaaz4876. https://doi.org/10.1126/sciadv.aaz4876

Lohmann, J., Dijkstra, H. A., Jochum, M., Lucarini, V., and Ditlevsen, P. D. (2024) 'Multistability and intermediate tipping of the Atlantic Ocean circulation'. Science Advances, 10(12), eadi4253. https://doi.org/ 10.1126/sciadv.adi4253

Lohmann, J., et al. (2025) 'The role of edge states for early warning of tipping points', Proceedings of the Royal Society A, 481, 2024.0753. https://doi.org/10.1098/rspa.2024.0753

Loriani, S. et al. (2025) 'Tipping points in ocean and atmosphere circulations', Earth System Dynamics, in press. https://doi.org/10.5194/egusphere-2023-2589.

Mandal, G., Hettiarachchi, A. I., and Ekka, S. V. (2024) 'The North Atlantic subpolar ocean dynamics during the past 21,000 years', Dynamics of Atmospheres and Oceans, 106, 101462. https://doi.org/10.1016/j.dynatmoce.2024.101462.

Marshall, J. and Schott, F. (1999) 'Open ocean deep convection: observations, models and theory', Reviews of Geophysics, 37, pp. 1–64. https://doi.org/10.1029/98RG02739

Martin, T. and Biastoch, A. (2023) 'On the ocean's response to enhanced Greenland runoff in model experiments: relevance of mesoscale dynamics and atmospheric coupling', Ocean Science, 19(1), pp. 141-167. https://doi.org/10.5194/os-19-141-2023

McLaren, D. (2023) 'Governing emerging solar geoengineering: a role for risk-risk evaluation?', Georgetown Journal of International Affairs, 24(2), pp. 234-243. https://doi.org/ 10.1353/gia.2023.a913651

McLaren, D.P. (2025) 'Reconstructing Risk–Risk Analysis to Support Effective Governance of High-Risk Climate Interventions', European Journal of Risk Regulation, pp.1-17. https://doi.org/doi:10.1017/err.2025.10019

Meccia, V. et al. (2024): Extreme cold events in Europe under a reduced AMOC. Environmental Research Letters, 19 (1), 014054. https://doi.org/10.1088/1748-9326/ad14b0

Menary, M. B. et al. (2021) 'Skillful decadal predictions of subpolar North Atlantic SSTs using CMIP model-analogues', Environ. Res. Lett., 16, 064090. https://doi.org/ 10.1088/1748-9326/ac06fb

Merikanto, J. et al. (2024) 'The Significance of Climate Tipping Points for Finland: Latest Information on the Possible Shutdown of the Atlantic Meridional Overturning Circulation (AMOC) and Preventive Climate Actions', Policy Brief, https://www.acccflagship.fi/wp-content/uploads/Tipping_points_Policy_Brief_english.pdf

Moffa-Sánchez, P., Born, A., Hall, I. R., Thornalley, D. J. and Barker, S. (2014) 'Solar forcing of North Atlantic surface temperature and salinity over the past millennium', Nature Geoscience, 7(4), pp. 275-278. https://doi.org/10.1038/ngeo2094

Moreno-Chamarro, E., Zanchettin, D., Lohmann, K., and Jungclaus, J. H. (2015) 'Internally generated decadal cold events in the northern North Atlantic and their possible implications for the demise of the Norse settlements in Greenland', Geophysical Research Letters, 42(3), 908-915. https://doi.org/10.1002/2014GL062741

Munday, D.R., Johnson, H.L. and Marshall, D.P. (2013) 'Eddy saturation of equilibrated circumpolar currents', J. Phys. Oceanogr., 43, pp. 507-532, https://doi.org/10.1175/JPO-D-12-095.1

OECD (2021) 'Managing Climate Risks, Facing up to Losses and Damages', https://www.oecd.org/content/dam/oecd/en/publications/reports/2021/11/managing-climate-risks-facing-up-to-losses-and-damages_928fe20d/55ea1cc9-en.pdf

OECD (2022) 'Climate Tipping Points. Insights for Effective Policy Action', https://www.oecd.org/content/dam/oecd/en/publications/reports/2022/12/climate-tipping-points_9994de90/abc5a69e-en.pdf

Orbe, C., et al. (2023) 'Atmospheric response to a collapse of the North Atlantic circulation under a mid-range future climate scenario: A regime shift in Northern Hemisphere dynamics', J. Climate, 36, pp. 6669-6693. https://doi.org/10.1175/JCLI-D-22-0841.1

Orihuela-Pinto et al. (2022) 'Interbasin and interhemispheric impacts of a collapsed atlantic overturning circulation', Nature Climate Change, 12 (6), pp. 558–565. https://doi.org/10.1038/s41558-022-01380-y

Osman, M.B., Das, S.B., Trusel, L.D. et al. (2019) 'Industrial-era decline in subarctic Atlantic productivity', Nature 569, pp. 551–555. https://doi.org/10.1038/s41586-019-1181-8

Pflüger, D., Wieners, C.E., van Kampenhout, L., Wijngaard, R.R. and Dijkstra, H.A., (2024) 'Flawed Emergency Intervention: Slow Ocean Response to Abrupt Stratospheric Aerosol Injection', Geophysical Research Letters, 51, e2023GL106132. https://doi.org/10.1029/2023GL106132

Pontes, G.M. and Menviel, L. (2024) 'Weakening of the Atlantic Meridional Overturning Circulation driven by subarctic freshening since the mid-twentieth century'. Nature Geoscience, 17, pp. 1291–1298. https://doi.org/10.1038/s41561-024-01568-1

Rahmstorf, S., et al. (2015) 'Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation'. Nature Climate Change, 5, pp. 475–480. https://doi.org/10.1038/nclimate2554

Rahmstorf, S. (2001) 'A simple model of seasonal open-ocean convection. Part I: Theory', Ocean Dynamics, 52, pp. 26-35. https://doi.org/10.1007/s10236-001-8174-4

Rahmstorf, S. (2024) 'Is the Atlantic overturning circulation approaching a tipping point?', Oceanography, 37 (3), pp. 16–29. https://doi.org/10.5670/oceanog.2024.501

Riahi et al. (2017) 'The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview', Global Environmental Change 42, pp. 153–168 (2017). https://doi.org/ 10.1016/j.gloenvcha.2016.05.009

Ritchie, P. et al. (2020) 'Shifts in national land use and food production in Great Britain after a climate tipping point', Nature Food, 1, pp. 76-83. https://doi.org/10.1038/s43016-019-0011-3

Ritchie, P. D. L., Alkhayuon, H., Cox, P. M. and Wieczorek, S. (2023) 'Rate-induced tipping in natural and human systems', Earth Syst. Dyn. 14, pp. 669–683. https://doi.org/10.5194/esd-14-669-2023

Roman Cuesta, R.M., Dentener, F., Galmarini, S., Milkoreit, M., Armstrong McKay, D., De Groeve, T., Dennis, D.P., Janssens-Maenhout, G., Loriani, S. And Ruiz Moreno, A. (2025) 'Earth System Tipping Points are a threat to Europe', European Commission, Ispra, JRC140827.

Romanou, A. et al. (2023) 'Stochastic Bifurcation of the North Atlantic Circulation under a Midrange Future Climate Scenario with the NASA-GISS ModelE', J. Climate, 36, pp. 6141–6161. https://doi.org/10.1175/JCLI-D-22-0536.1

Rossby, T., Palter, J. and Donohue, K. (2022) 'What can hydrography between the New England slope, Bermuda and Africa tell us about the strength of the AMOC over the last 90 years?', Geophys. Res. Lett. 49, e2022GL099173. https://doi.org/10.1029/2022GL099173

Sadatzki, H. et al. (2019) 'Sea ice variability in the southern Norwegian Sea during glacial Dansgaard-Oeschger climate cycles', Science Advances 5, eaau6174. https://doi.org/10.1126/sciadv.aau6174

Saini, H. et al. (2025) 'Australasian Hydroclimate Response to the Collapse of the Atlantic Meridional Overturning Circulation Under Pre-Industrial and Last Interglacial Climates', Paleocanography and Paleoclimatology. 40, e2024PA004967. https://doi.org/10.1029/2024PA004967

Schweizer, P-J. and Juhola, S. (2024) 'Navigating systemic risks: governance of and for systemic risks'. Global Sustainability, 7:e38. https://doi.org/10.1017/sus.2024.30

Schwinger, J., Asaadi, A., Goris, N and Lee, H. (2022) 'Possibility for strong northern hemisphere high-latitude cooling under negative emissions', Nature Communications, 13, 1095. https://doi.org/10.1038/s41467-022-28573-5

Sgubin, G. et al. (2015) 'Multimodel analysis on the response of the AMOC under an increase of radiative forcing and its symmetrical reversal'. Climate Dynamics, 45, pp. 1429–1450. https://doi.org/10.1007/s00382-014-2391-2

Sgubin, G., Swingedouw, D., Drijfhout, S. et al. (2017) 'Abrupt cooling over the North Atlantic in modern climate models', Nature Communications, 8, 14375. https://doi.org/10.1038/ncomms14375.

Shakou, L.M., Wybo, J.-L., Reniers, G. and Boustras, G. (2019) 'Developing an innovative framework for enhancing the resilience of critical infrastructure to climate change', Safety Science, 118, pp. 364-378. https://doi.org/10.1016/j.ssci.2019.05.019.

Shan, Xuan, et al. (2024) 'Role of the Labrador Current in the Atlantic Meridional Overturning Circulation response to greenhouse warming', Nature Communications 15 (1), 7361. https://doi.org/10.1038/s41467-024-51449-9

Simpson, N.P et al. (2021) 'A framework for complex climate change risk assessment', One Earth, 4(4), https://doi.org/10.1016/j.oneear.2021.03.005.

Sovacool, B. K., Baum, C. M., and Low, S. (2023) 'Risk–risk governance in a low-carbon future: Exploring institutional, technological, and behavioral tradeoffs in climate geoengineering pathways', Risk Analysis, 43(4), pp. 838-859. https://doi.org/10.1111/risa.13932

Spaiser, V. et al. (2024) 'Negative social tipping dynamics resulting from and reinforcing Earth system destabilization', Earth System Dynamics, 15, pp. 1179–1206. https://doi.org/10.5194/esd-15-1179-2024

Spall, M. A. (2004) 'Boundary currents and watermass transformation in marginal seas', Journal of Physical Oceanography, 34(5), pp. 1197-1213. https://doi.org/10.1175/1520-0485(2004)034<1197:BCAWTI>2.0.CO;2

Steinsland, K., Grant, D. M., Ninnemann, U. S., Fahl, K., Stein, R., and De Schepper, S. (2023) 'Sea ice variability in the North Atlantic subpolar gyre throughout the last interglacial', Quaternary Science Reviews, 313, 108198. https://doi.org/10.1016/j.quascirev.2023.108198

Sterl, M. F. and de Jong, M. F. (2022) 'Restratification structure and processes in the Irminger Sea', Journal of Geophysical Research: Oceans, 127(12), e2022JC019126. https://doi.org/10.1029/2022JC019126

Straneo, F. (2006) 'On the connection between dense water formation, overturning, and poleward heat transport in a convective basin', Journal of Physical Oceanography, 36(9), pp. 1822-1840. https://doi.org/10.1175/JPO2932.1

Stommel H. (1961) 'Thermohaline convection with two stable regimes of flow', Tellus 13(2), pp. 224–230. https://doi.org/10.1111/j.2153-3490.1961.tb00079.x

Swingedouw, D., Bily, A., Esquerdo, C., Borchert, L. F., Sgubin, G., Mignot, J., and Menary, M. (2021) 'On the risk of abrupt changes in the North Atlantic subpolar gyre in CMIP6 models', Annals of the New York Academy of Sciences, 1504(1), pp. 187-201. https://doi.org/ 10.1111/nyas.14659

Terhaar, J., Vogt, L. and Foukal, N.P. (2025) 'Atlantic overturning inferred from air-sea heat fluxes indicates no decline since the 1960s', Nature Communications 16, 222. https://doi.org/10.1038/s41467-024-55297-5

Ureta, C., Ramírez-Barahona, S., Calderón-Bustamante, Ó. et al. (2022) 'Evaluation of animal and plant diversity suggests Greenland's thaw hastens the biodiversity crisis', Commun Biol 5, 985. https://doi.org/10.1038/s42003-022-03943-3

van Westen, R.M. and Dijkstra, H.A. (2023) 'Asymmetry of AMOC Hysteresis in a State-Of-The-Art Global Climate Model', Geophysical Research Letters, 50 (22), e2023GL106088. https://doi.org/10.1029/2023GL106088

van Westen, R.M. and Dijkstra, H.A. (2024) 'Persistent climate model biases in the Atlantic ocean's freshwater transport', Ocean Science, 20 (2), pp. 549–567. https://doi.org/10.5194/os-20-549-2024

van Westen, R. M., Kliphuis, M. and Dijkstra, H.A. (2024) 'Physics-based early warning signal shows that AMOC is on tipping course', Science Advances,10, eadk1189. https://doi.org/10.1126/sciadv.adk1189

van Westen, R.M. and Baatsen, M. (2025) 'European Temperature Extremes Under Different AMOC Scenarios in the Community Earth System Model', Geophysical Research Letters, 52, e2025GL114611. https://doi.org/10.1029/2025GL114611

van Westen, R.M., Kliphuis, M. and Dijkstra, H.A. (2025a) 'Collapse of the Atlantic Meridional Overturning Circulation in a Strongly Eddying Ocean-Only Model', Geophysical Research Letters, 52, e2024GL114532. https://doi.org/10.1029/2024GL114532

van Westen, R.M., Vanderborght, E., Kliphuis, M. and Dijkstra, H.A. (2025b) 'Physics-Based Indicators for the Onset of an AMOC Collapse Under Climate Change'. J. Geophys. Res. Oceans, 130, e2025JC022651. https://doi.org/10.1029/2025JC022651

van Westen, R. M. et al. (2025c) 'Changing European Hydroclimate under a Collapsed AMOC in the Community Earth System Model', preprint HESS, https://doi.org/10.5194/egusphere-2025-1440

Velasco, J.A., Estrada, F., Calderón-Bustamante, O. et al. (2021) 'Synergistic impacts of global warming and thermohaline circulation collapse on amphibians'. Commun. Biol. 4, 141. . https://doi.org/10.1038/s42003-021-01665-6

Vellinga, M. and Wood, R.A. (2008) 'Impacts of thermohaline circulation shutdown in the twenty-first century'. Climatic Change, 91, pp. 43–63. https://doi.org/10.1007/s10584-006-9146-yvan

Velay-Vitow, J., Chandan, D. and Peltier, W.R. (2024) 'Into the Holocene, anatomy of the Younger Dryas cold reversal and preboreal oscillation', Scientific Reports, 14, 3134. https://doi.org/10.1038/s41598-024-53591-2

Volkov, D.L., et al. (2023) 'Atlantic meridional overturning circulation increases flood risk along the United States southeast coast'. Nature Communications, 14, 5095. https://doi.org/10.1038/s41467-023-40848-z

Wei, X. and Zhang, R. (2024) 'Weakening of the AMOC and strengthening of Labrador Sea deep convection in response to external freshwater forcing', Nature Communications, 15(1), 10357. https://doi.org/10.1038/s41467-024-54756-3

Weijer, W., Cheng, W., Garuba, O.A., Hu, A. and Nadiga, B.T. (2020) 'CMIP6 Models Predict Significant 21st Century Decline of the Atlantic Meridional Overturning Circulation', Geophysical Research Letters, 47, e2019GL086075. https://doi.org/10.1029/2019GL086075

White, S., Collet, D., Alcoberro, A. et al. (2025) 'Climate, peace, and conflict—past and present: Bridging insights from historical sciences and contemporary research'. Ambio, 54, pp. 774-792. https://doi.org/10.1007/s13280-024-02109-1

Williamson, M.S., et al. (2018) 'Effect of AMOC collapse on ENSO in a high resolution general circulation model', Climate Dynamics, 50, pp. 2537–2552. https://doi.org/10.1007/s00382-017-3756-0

Woillez, M.-N., Kageyama, M., Combourieu-Nebout, N., and Krinner, G. (2013) 'Simulating the vegetation response in western Europe to abrupt climate changes under glacial background conditions', Biogeosciences, 10, pp. 1561–1582, https://doi.org/10.5194/bg-10-1561-2013

Wolovick, M.J. and Moore, J.C. (2020) 'Stopping the flood: could we use targeted geoengineering to mitigate sea level rise?', The Cryosphere, 12, pp. 2955–2967. https://doi.org/10.5194/tc-12-2955-2018

Woollings, T., et al. (2012) 'Response of the North Atlantic storm track to climate change shaped by ocean–atmosphere coupling', Nature Geoscience, 5, pp. 313–317. https://doi.org/10.1038/ngeo1438

Worthington, E. L. et al. (2021) 'A 30-year reconstruction of the Atlantic Meridional Overturning Circulation shows no decline'. Ocean Science, 17, pp. 285–299. https://doi.org/10.5194/os-17-285-2021

Yashayaev, I. (2024) 'Intensification and shutdown of deep convection in the Labrador Sea were caused by changes in atmospheric and freshwater dynamics', Communications Earth and Environment, 5, 156. https://doi.org/10.1038/s43247-024-01296-9

Yool, A., Popova, E. E. and Coward, A. C. (2015) 'Future change in ocean productivity: Is the Arctic the new Atlantic?', J. Geophys. Res. Oceans, 120, pp. 7771–7790, https://doi.org/10.1002/2015JC011167.

Zhai, Z.M., Moradi, M., Panahi, S., Wang, Z.H. and Lai, Y.C. (2024) 'Machine-learning nowcasting of the Atlantic Meridional Overturning Circulation', APL Machine Learning, 2 (3): 036103. https://doi.org/10.1063/5.0207539

Zhu, C., et al. (2023) 'Likely accelerated weakening of Atlantic overturning circulation emerges in optimal salinity fingerprint', Nat Communications, 14, 1245. https://doi.org/10.1038/s41467-023-36288-4

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References 4.3

Abraham, J., Cheng, L., Mann, M.E., Trenberth, K. and von Schuckmann, K. (2022). 'The ocean response to climate change guides both adaptation and mitigation efforts'. Atmospheric and Oceanic Science Letters, 15(4), p.100221. https://doi.org/10.1016/j.aosl.2022.100221

AIMS LTMP (2025) https://doi.org/10.25845/CS9T-0K11

Agostini, S., Harvey, B. P., Milazzo, M., Wada, S., Kon, K., Floc'h, N., Komatsu, K., Kuroyama, M., & Hall-Spencer, J. M. (2021). 'Simplification, not "tropicalization", of temperate marine ecosystems under ocean warming and acidification'. Global Change Biology, 27, 4771–4784. https://doi.org/10.1111/gcb.15749

Allan, R.P. and Merchant, C.J. (2025). 'Reconciling Earth's growing energy imbalance with ocean warming'. Environmental Research Letters, 20(4), p.044002. https://doi.org/10.1088/1748-9326/adb448

Alvarez-Filip, L., González-Barrios, F.J., Pérez-Cervantes, E., Molina-Hernández, A. and Estrada-Saldívar, N. (2022). 'Stony coral tissue loss disease decimated Caribbean coral populations and reshaped reef functionality'. Communications Biology, 5(1), p.440. https://doi.org/10.1038/s42003-022-03398-6

Aronson, R.B. and Precht, W.F. (2006). 'Conservation, precaution, and Caribbean reefs'. Coral reefs, 25(3), pp.441-450.. https://doi.org/10.1007/s00338-006-0122-9

Barrera-Falcon, E., Rioja-Nieto, R., Hernández-Landa, R.C. and Torres-Irineo, E. (2021). 'Comparison of standard Caribbean coral reef monitoring protocols and underwater digital photogrammetry to characterize hard coral species composition, abundance and cover'. Frontiers in Marine Science, 8, p.722569. https://doi.org/10.3389/fmars.2021.722569

Bevacqua, E., Schleussner, C.F. and Zscheischler, J. (2025). 'A year above 1.5° C signals that Earth is most probably within the 20-year period that will reach the Paris Agreement limit'. Nature Climate Change, 15(3), pp.262-265. https://doi.org/10.1038/s41558-025-02246-9

Birkart, Lara Virginia and Alvarez-Filip, Lorenzo and Administrator, Sneak Peek, 2023 Global Heatwave Causes Mass Mortality of a Keystone Coral on Shallow Western Atlantic Reefs. ISCIENCE-D-25-06898, Available at SSRN: https://ssrn.com/abstract=5253072 or http://dx.doi.org/10.2139/ssrn.5253072

Boström-Einarsson, L., Babcock, R.C., Bayraktarov, E., Ceccarelli, D., Cook, N., Ferse, S.C., Hancock, B., Harrison, P., Hein, M., Shaver, E. and Smith, A. (2020). 'Coral restoration–A systematic review of current methods, successes, failures and future directions'. PloS one, 15(1), p.e0226631. https://doi.org/10.1371/journal.pone.0226631

Burke, L. and Sugg, Z., (2006). 'Hydrologic modeling of watersheds discharging adjacent to the Mesoamerican Reef'. World Resources Institute, Washington, DC. https://www.wri.org/research/watershed-analysis-mesoamerican-reef

Byrne, M., Waller, A., Clements, M., Kelly, A.S., Kingsford, M.J., Liu, B., Reymond, C.E., Vila-Concejo, A., Webb, M., Whitton, K. and Foo, S.A. (2025). 'Catastrophic bleaching in protected reefs of the Southern Great Barrier Reef'. Limnology and Oceanography Letters, 10(3), pp.340-348. https://doi.org/10.1002/lol2.10456

Capotondi, A., Rodrigues, R.R., Sen Gupta, A. et al. A global overview of marine heatwaves in a changing climate. Commun Earth Environ 5, 701 (2024). https://doi.org/10.1038/s43247-024-01806-9

Carlson, R.R., Evans, L.J., Foo, S.A., Grady, B.W., Li, J., Seeley, M., Xu, Y. and Asner, G.P. (2021). 'Synergistic benefits of conserving land-sea ecosystems'. Global Ecology and Conservation, 28, p.e01684. https://doi.org/10.1016/j.gecco.2021.e01684 .

Cheng, L., Abraham, J., Trenberth, K.E., Boyer, T., Mann, M.E., Zhu, J., Wang, F., Yu, F., Locarnini, R., Fasullo, J. and Zheng, F. (2024). 'New record ocean temperatures and related climate indicators in 2023'. Advances in Atmospheric Sciences, 41(6), pp.1068-1082. https://doi.org/10.1007/s00376-024-3378-5

Cheng, L., Abraham, J., Trenberth, K.E., Reagan, J., Zhang, H.M., Storto, A., Von Schuckmann, K., Pan, Y., Zhu, Y., Mann, M.E. and Zhu, J. (2025). 'Record high temperatures in the ocean in 2024'. Advances in Atmospheric Sciences, 42(6), pp.1092-1109. https://doi.org/10.1007/s00376-025-4541-3

Cheng, L., von Schuckmann, K., Abraham, J.P., Trenberth, K.E., Mann, M.E., Zanna, L., England, M.H., Zika, J.D., Fasullo, J.T., Yu, Y. and Pan, Y. (2022). 'Past and future ocean warming'. Nature Reviews Earth & Environment, 3(11), pp.776-794. https://doi.org/10.1038/s43017-022-00345-1

Cinner, J.E., Huchery, C., MacNeil, M.A., Graham, N.A., McClanahan, T.R., Maina, J., Maire, E., Kittinger, J.N., Hicks, C.C., Mora, C. and Allison, E.H. (2016). 'Bright spots among the world's coral reefs'. Nature, 535(7612), pp.416-419. https://doi.org/10.1038/nature18607.

Copernicus (2025) Climate Change Service. Climate Indicators. Temperature. https://climate.copernicus.eu/copernicus-january-2025-was-warmest-record-globally-despite-emerging-la-nina

Cornwall, C.E., Comeau, S., Donner, S.D., Perry, C., Dunne, J., van Hooidonk, R., Ryan, J.S. and Logan, C.A., 2023. Coral adaptive capacity insufficient to halt global transition of coral reefs into net erosion under climate change. Global change biology, 29(11), pp.3010-3018 https://onlinelibrary.wiley.com/doi/10.1111/gcb.16647

Cornwall, C.E., Comeau, S. and Harvey, B.P. (2024). 'Are physiological and ecosystem-level tipping points caused by ocean acidification? A critical evaluation'. Earth System Dynamics, 15(3), pp.671-687. https://doi.org/10.5194/esd-15-671-2024

Costanza, R., De Groot, R., Sutton, P., Van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S. and Turner, R.K. (2014). 'Changes in the global value of ecosystem services'. Global environmental change, 26, pp.152-158. https://doi.org/10.1016/j.gloenvcha.2014.04.002

Cramer, K.L., Jackson, J.B., Donovan, M.K., Greenstein, B.J., Korpanty, C.A., Cook, G.M. and Pandolfi, J.M. (2020). 'Widespread loss of Caribbean acroporid corals was underway before coral bleaching and disease outbreaks'. Science Advances, 6(17), p.eaax9395. https://doi.org/10.1126/sciadv.aax9395

Cramer, K.L., Donovan, M.K., Jackson, J.B., Greenstein, B.J., Korpanty, C.A., Cook, G.M. and Pandolfi, J.M. (2021). 'The transformation of Caribbean coral communities since humans'. Ecology and Evolution, 11(15), pp.10098-10118. https://doi.org/10.1002/ece3.7808

Darling, E.S., McClanahan, T.R., Maina, J. et al. Social–environmental drivers inform strategic management of coral reefs in the Anthropocene. Nat Ecol Evol 3, 1341–1350 (2019). https://doi.org/10.1038/s41559-019-0953-8

Dixon, A.M., Forster, P.M., Heron, S.F., Stoner, A.M. and Beger, M. (2022). 'Future loss of local-scale thermal refugia in coral reef ecosystems'. PLoS Climate, 1(2), p.e0000004. https://doi.org/10.1371/journal.pclm.0000004

Dobbelaere, T., Holstein, D.M., Gramer, L.J., McEachron, L. and Hanert, E. (2024). 'Investigating the link between the Port of Miami dredging and the onset of the stony coral tissue loss disease epidemics'. Marine Pollution Bulletin, 207, p.116886. https://doi.org/10.1016/j.marpolbul.2024.116886

Eakin, C.M., Sweatman, H.P. and Brainard, R.E. (2019). 'The 2014–2017 global-scale coral bleaching event: insights and impacts'. Coral Reefs, 38(4), pp.539-545. https://link.springer.com/article/10.1007/s00338-019-01844-2

Eddy, T.D., Lam, V.W., Reygondeau, G., Cisneros-Montemayor, A.M., Greer, K., Palomares, M.L.D., Bruno, J.F., Ota, Y. and Cheung, W.W. (2021). 'Global decline in capacity of coral reefs to provide ecosystem services'. One Earth, 4(9), pp.1278-1285. https://doi.org/10.1016/j.oneear.2021.08.016.

Fabricius, K.E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Marine pollution bulletin, 50(2), pp.125-146. https://doi.org/10.1016/j.marpolbul.2004.11.028

Ferrario, F., Beck, M.W., Storlazzi, C.D., Micheli, F., Shepard, C.C. and Airoldi, L. (2014). 'The effectiveness of coral reefs for coastal hazard risk reduction and adaptation'. Nature communications, 5(1), p.3794. https://doi.org/10.1038/ncomms4794

Fisher, R., O'Leary, R.A., Low-Choy, S., Mengersen, K., Knowlton, N., Brainard, R.E. and Caley, M.J. (2015). 'Species richness on coral reefs and the pursuit of convergent global estimates'. Current Biology, 25(4), pp.500-505. https://doi.org/10.1016/j.cub.2014.12.022

Forster, P.M., Smith, C., Walsh, T., Lamb, W.F., Lamboll, R., Cassou, C., Hauser, M., Hausfather, Z., Lee, J.Y., Palmer, M.D. and von Schuckmann, K. (2025). 'Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence'. Earth System Science Data Discussions, 2025, pp.1-72. https://doi.org/10.5194/essd-17-2641-2025.

Fuchs, Y.H., Edgar, G.J., Bates, A.E., Waldock, C. and Stuart-Smith, R.D., 2024. Limited net poleward movement of reef species over a decade of climate extremes. Nature Climate Change, 14(10), pp.1087-1092. https://doi.org/10.1038/s41558-024-02116-w

Gardner, T.A., Côté, I.M., Gill, J.A., Grant, A. and Watkinson, A.R. (2003). 'Long-term region-wide declines in Caribbean corals'. Science, 301(5635), pp.958-960. https://doi.org/10.1126/science.1086050

GCRMN-Caribbean (2025). 'Global Coral Reef Monitoring Centre. SPAW-RAC. Preliminary results of the Status and Trends of Caribbean Coral Reef: 1970-2024 GCRMN report'. Poster presented at the third United Nations Ocean Conference (UNOC), in Nice, France. 2025-06-11. Poster GCRMN-Caribbean

Goreau, T.J. and Hayes, R.L. (2024). '2023 Record marine heat waves: Coral reef bleaching HotSpot maps reveal global sea surface temperature extremes, coral mortality, and ocean circulation changes'. Oxford Open Climate Change, 4(1), p.kgae005. https://doi.org/10.1093/oxfclm/kgaf006

Graham, N.A. (2014). 'Habitat complexity: coral structural loss leads to fisheries declines'. Current Biology, 24(9), pp.R359-R361. https://www.cell.com/current-biology/fulltext/S0960-9822(14)00391-1

Graham, N.A., Jennings, S., MacNeil, M.A., Mouillot, D. and Wilson, S.K. (2015). 'Predicting climate-driven regime shifts versus rebound potential in coral reefs'. Nature, 518(7537), pp.94-97. https://doi.org/10.1038/nature14140

Hansen, J.E., Kharecha, P., Sato, M., Tselioudis, G., Kelly, J., Bauer, S.E., Ruedy, R., Jeong, E., Jin, Q., Rignot, E. and Velicogna, I. (2025). 'Global warming has accelerated: are the united nations and the public well-informed?'. Environment: Science and Policy for Sustainable Development, 67(1), pp.6-44. https://doi.org/10.1080/00139157.2025.2434494

Hansen, J., Nazarenko, L., Ruedy, R., Sato, M., Willis, J., Del Genio, A., Koch, D., Lacis, A., Lo, K., Menon, S. and Novakov, T. (2005). 'Earth's energy imbalance: Confirmation and implications'. Science, 308(5727), pp.1431-1435. https://doi.org/10.1126/science.1110252

Henley, B. J., McGregor, H. V., King, A. D., Hoegh-Guldberg, O., Arzey, A. K., Karoly, D. J., Lough, J. M., DeCarlo, T. M., & Linsley, B. K. (2024). Highest ocean heat in four centuries places Great Barrier Reef in danger. Nature, 632, 320–326) https://doi.org/10.1038/s41586-024-07672-x

Heron, S.F., Maynard, J.A., Van Hooidonk, R. and Eakin, C.M. (2016). 'Warming trends and bleaching stress of the world's coral reefs 1985–2012'. Scientific reports, 6(1), p.38402. https://doi.org/10.1038/srep38402

Hoegh-Guldberg, O., Poloczanska, E.S., Skirving, W. and Dove, S. (2017). 'Coral reef ecosystems under climate change and ocean acidification'. Frontiers in marine science, 4, p.252954. https://doi.org/10.3389/fmars.2017.00158

Hoegh-Guldberg, O., Jacob, D., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K., Engelbrecht, F., Guiot, J. and Hijioka, Y. (2018). 'Impacts of 1.5 C global warming on natural and human systems'. In Global warming of 1.5 C.: An IPCC Special Report (pp. 175-311). IPCC Secretariat. https://doi.org/10.1017/9781009157940.005

Hoegh-Guldberg, O., Skirving, W., Dove, S.G., Spady, B.L., Norrie, A., Geiger, E.F., Liu, G., De La Cour, J.L. and Manzello, D.P. (2023). 'Coral reefs in peril in a record-breaking year'. Science, 382(6676), pp.1238-1240. https://doi.org/10.1126/science.adk4532

Hughes, T.P., Kerry, J.T., Baird, A.H., Connolly, S.R., Dietzel, A., Eakin, C.M., Heron, S.F., Hoey, A.S., Hoogenboom, M.O., Liu, G. and McWilliam, M.J. (2018). 'Global warming transforms coral reef assemblages'. Nature, 556(7702), pp.492-496. https://doi.org/10.1038/s41586-018-0041-2

Hughes, T.P., Baird, A.H., Morrison, T.H. and Torda, G. (2023). 'Principles for coral reef restoration in the anthropocene'. One Earth, 6(6), pp.656-665. https://doi.org/10.1016/j.oneear.2023.04.008

IPCC (2022) 'Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change'. Cambridge University Press; 2023. https://doi.org/10.1017/9781009325844.

Jackson, J., Donovan, M., Cramer, K. and Lam, V. (2014). 'Status and trends of Caribbean coral reefs: 1970-2012'. Gland, Switzerland: Global Coral Reef Monitoring Network; International Union for the Conservation of Nature (IUCN). https://iucn.org/sites/default/files/import/downloads/caribbean_coral_reefs___status_report_1970_2012.pdf

Jury, C.P. and Toonen, R.J. (2024). 'Widespread scope for coral adaptation under combined ocean warming and acidification'. Proceedings of the Royal Society B, 291(2031), p.20241161. https://doi.org/10.1098/rspb.2024.1161

Kalmus, P., Ekanayaka, A., Kang, E., Baird, M. and Gierach, M. (2022). 'Past the precipice? Projected coral habitability under global heating'. Earth's Future, 10(5), p.e2021EF002608. https://doi.org/10.1029/2021EF002608

Kaufhold, C., Willeit, M., Talento, S., Ganopolski, A. and Rockström, J. (2025). 'Interplay between climate and carbon cycle feedbacks could substantially enhance future warming'. Environmental Research Letters, 20(4), p.044027. https://doi.org/10.1088/1748-9326/adb6be

Ke, P., Ciais, P., Sitch, S., Li, W., Bastos, A., Liu, Z., Xu, Y., Gui, X., Bian, J., Goll, D.S. and Xi, Y. (2024). 'Low latency carbon budget analysis reveals a large decline of the land carbon sink in 2023'. National Science Review, 11(12), p.nwae367. https://doi.org/10.1093/nsr/nwae367

Kenyon, T.M., Doropoulos, C., Wolfe, K., Webb, G.E., Dove, S., Harris, D. and Mumby, P.J. (2023). 'Coral rubble dynamics in the Anthropocene and implications for reef recovery'. Limnology and Oceanography, 68(1), pp.110-147. https://doi.org/10.1002/lno.12254

Kopecky, K.L., Stier, A.C., Schmitt, R.J., Holbrook, S.J. and Moeller, H.V. (2023). 'Material legacies can degrade resilience: Structure-retaining disturbances promote regime shifts on coral reefs'. Ecology, 104(4), p.e4006. https://esajournals.onlinelibrary.wiley.com/doi/10.1002/ecy.4006

Kramer, P.A. (2003). 'Synthesis of coral reef health indicators for the western Atlantic: Results of the AGRRA program(1997-2000)'. Atoll Research Bulletin, 496(3), pp.1-57. https://agrra.org/wp-content/uploads/2016/08/synthesis.pdf

Lachs, L., Donner, S.D., Mumby, P.J., Bythell, J.C., Humanes, A., East, H.K. and Guest, J.R., 2023. Emergent increase in coral thermal tolerance reduces mass bleaching under climate change. Nature Communications, 14(1), p.4939.https://doi.org/10.1038/s41467-023-40601-6

Lachs, L., Bozec, Y.M., Bythell, J.C., Donner, S.D., East, H.K., Edwards, A.J., Golbuu, Y., Gouezo, M., Guest, J.R., Humanes, A. and Riginos, C. (2024). 'Natural selection could determine whether Acropora corals persist under expected climate change'. Science, 386(6727), pp.1289-1294. https://doi.org/10.1126/science.adl6480

Laffoley, D. and Baxter, J.M. eds. (2016). 'Explaining Ocean Warming: Causes, scale, effects and consequences'. Gland, Switzerland: IUCN. http://dx.doi.org/10.2305/IUCN.CH.2016.08.en

Lenton, T.M., McKay, D.I.A., Loriani, S., Abrams, J.F., Lade, S.J., Donges, J.F., Buxton, J.E., Milkoreit, M., Powell, T., Smith, S.R. and Constantino, S. (2023). 'The global tipping points report 2023 (University of Exeter)'. https://report-2023.global-tipping-points.org/.

Logan, C.A., Dunne, J.P., Ryan, J.S., Baskett, M.L. and Donner, S.D. (2021). 'Quantifying global potential for coral evolutionary response to climate change'. Nature Climate Change, 11(6), pp.537-542. https://doi.org/10.1038/s41558-021-01037-2

Marcos, M., Amores, A., Agulles, M., Robson, J. and Feng, X. (2025). 'Global warming drives a threefold increase in persistence and 1° C rise in intensity of marine heatwaves'. Proceedings of the National Academy of Sciences, 122(16), p.e2413505122. https://www.pnas.org/doi/10.1073/pnas.2413505122

Mauritsen, T., Tsushima, Y., Meyssignac, B., Loeb, N.G., Hakuba, M., Pilewskie, P., Cole, J., Suzuki, K., Ackerman, T.P., Allan, R.P. and Andrews, T. (2025). 'Earth's energy imbalance more than doubled in recent decades'. AGU Advances, 6(3), p.e2024AV001636. https://doi.org/10.1029/2024AV001636

McWilliam, M., Hoogenboom, M.O., Baird, A.H., Kuo, C.Y., Madin, J.S. and Hughes, T.P. (2018). 'Biogeographical disparity in the functional diversity and redundancy of corals'. Proceedings of the National Academy of Sciences, 115(12), pp.3084-3089. https://www.pnas.org/doi/10.1073/pnas.1716643115

Merchant, C.J., Allan, R.P. and Embury, O. (2025). 'Quantifying the acceleration of multidecadal global sea surface warming driven by Earth's energy imbalance'. Environmental Research Letters, 20(2), p.024037. https://iopscience.iop.org/article/10.1088/1748-9326/adaa8a

Meyer, A.L., Bentley, J., Odoulami, R.C., Pigot, A.L. and Trisos, C.H. (2022). 'Risks to biodiversity from temperature overshoot pathways'. Philosophical Transactions of the Royal Society B, 377(1857), p.20210394. http://doi.org/10.1098/rstb.2021.0394

Miloslavich, P., Díaz, J.M., Klein, E., Alvarado, J.J., Díaz, C., Gobin, J., Escobar-Briones, E., Cruz-Motta, J.J., Weil, E., Cortes, J. and Bastidas, A.C. (2010). 'Marine biodiversity in the Caribbean: regional estimates and distribution patterns'. PloS one, 5(8), p.e11916. http://doi.org/10.1371/journal.pone.0011916

Möller, T., Högner, A.E., Schleussner, C.F., Bien, S., Kitzmann, N.H., Lamboll, R.D., Rogelj, J., Donges, J.F., Rockström, J. and Wunderling, N. (2024). 'Achieving net zero greenhouse gas emissions critical to limit climate tipping risks'. Nature Communications, 15(1), p.6192. https://www.nature.com/articles/s41467-024-49863-0

Mulà, C., Bradshaw, C.J.A., Cabeza, M. et al. Restoration cannot be scaled up globally to save reefs from loss and degradation. Nat Ecol Evol 9, 822–832 (2025). https://doi.org/10.1038/s41559-025-02667-x

Muñiz-Castillo, A.I., Rivera-Sosa, A., Chollett, I., Eakin, C.M., Andrade-Gómez, L., McField, M. and Arias-González, J.E. (2019). 'Three decades of heat stress exposure in Caribbean coral reefs: a new regional delineation to enhance conservation'. Scientific reports, 9(1), p.11013. https://www.nature.com/articles/s41598-019-47307-0

Muñiz-Castillo, A.I., Rivera-Sosa, A., McField, M., Chollett, I., Eakin, C.M., Enríquez, S., Giró, A., Drysdale, I., Rueda, M., Soto, M. and Craig, N. (2024). 'Underlying drivers of coral reef vulnerability to bleaching in the Mesoamerican Reef'. Communications Biology, 7(1), p.1452. https://www.nature.com/articles/s42003-024-07128-y

Mycoo, M., Wairiu, M., Campbell, D., Duvat, V., Golbuu, Y., Maharaj, S., Nalau, J., Nunn, P., Pinnegar, J. and Warrick, O. (2022). 'Small Islands. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change'. Climate Change 2022: Impacts, Adaptation and Vulnerability. https://doi.org/10.1017/9781009325844.017

Myhre, G., Hodnebrog, Ø., Loeb, N. and Forster, P.M. (2025). 'Observed trend in Earth energy imbalance may provide a constraint for low climate sensitivity models'. Science, 388(6752), pp.1210-1213. https://www.science.org/doi/10.1126/science.adt0647

Neely KL, Nowicki RJ, Dobler MA, Chaparro AA, Miller SM and Toth KA (2024) Too hot to handle? The impact of the 2023 marine heatwave on Florida Keys coral. Front. Mar. Sci. 11:1489273. doi: 10.3389/fmars.2024.1489273

NOAA National Environmental Satellite, Data, and Information Service (2025). Coral Reef Watch. https://www.coralreefwatch.noaa.gov/satellite/research/coral_bleaching_report.php

Oziel, L., Gürses, Ö., Torres-Valdés, S., Hoppe, C.J., Rost, B., Karakuş, O., Danek, C., Koch, B.P., Nissen, C., Koldunov, N. and Wang, Q. (2025). 'Climate change and terrigenous inputs decrease the efficiency of the future Arctic Ocean's biological carbon pump'. Nature Climate Change, 15(2), pp.171-179. https://doi.org/10.1038/s41558-024-02233-6

Pearce-Kelly, P., Altieri, A.H., Bruno, J.F., Cornwall, C.E., McField, M., Muñiz-Castillo, A.I., Rocha, J., Setter, R.O., Sheppard, C., Roman-Cuesta, R.M. and Yesson, C. (2025). 'Considerations for determining warm-water coral reef tipping points'. Earth System Dynamics, 16(1), pp.275-292. https://doi.org/10.5194/esd-2023-35

Pendleton, L., Comte, A., Langdon, C., Ekstrom, J.A., Cooley, S.R., Suatoni, L., Beck, M.W., Brander, L.M., Burke, L., Cinner, J.E. and Doherty, C. (2016). 'Coral reefs and people in a high-CO2 world: where can science make a difference to people?' PloS one, 11(11), p.e0164699. Doi: https://doi.org/10.1371/journal.pone.0164699

Perry, C.T., Alvarez-Filip, L., Graham, N.A., Mumby, P.J., Wilson, S.K., Kench, P.S., Manzello, D.P., Morgan, K.M., Slangen, A.B., Thomson, D.P. and Januchowski-Hartley, F. (2018). 'Loss of coral reef growth capacity to track future increases in sea level'. Nature, 558(7710), pp.396-400. https://doi.org/10.1038/s41586-018-0194-z

Perry, C.T. and Alvarez-Filip, L. (2019). 'Changing geo-ecological functions of coral reefs in the Anthropocene'. Functional Ecology, 33(6), pp.976-988. https://doi.org/10.1111/1365-2435.13247

Plaisance, L., Caley, M.J., Brainard, R.E. and Knowlton, N. (2011). 'The diversity of coral reefs: what are we missing?' PloS one, 6(10), p.e25026. https://doi.org/10.1371/journal.pone.0025026

Precht, W.F., Aronson, R.B., Gardner, T.A., Gill, J.A., Hawkins, J.P., Hernández-Delgado, E.A., Jaap, W.C., McClanahan, T.R., McField, M.D., Murdoch, T.J. and Nugues, M.M. (2020). 'The timing and causality of ecological shifts on Caribbean reefs'. In Advances in marine biology (Vol. 87, No. 1, pp. 331-360). Academic Press. https://doi.org/10.1016/bs.amb.2020.08.008

Randazzo-Eisemann, Á., Arias-González, J.E., Velez, L., McField, M. and Mouillot, D. (2021). 'The last hotspots of structural complexity as conservation targets in the Mesoamerican Coral Reef'. Biological Conservation, 256, p.109021. https://doi.org/10.1016/j.biocon.2021.109021.

Raoult, V., Joyce, K., Li, J.Y., Roff, G., Carlin, G. and Williamson, J.E. (2025). 'Coral bleaching and mass mortality at Lizard Island revealed by drone imagery'. Coral Reefs, pp.1-10. https://doi.org/10.1007/s00338-025-02695-w

Reimer, J.D., Peixoto, R.S., Davies, S.W., Traylor-Knowles, N., Short, M.L., Cabral-Tena, R.A., Burt, J.A., Pessoa, I., Banaszak, A.T., Winters, R.S. and Moore, T. (2024). 'The fourth global coral bleaching event: where do we go from here?' Coral Reefs, 43(4), pp.1121-1125. https://doi.org/10.1007/s00338-024-02504-w

Reisinger, A., Fuglestvedt, J.S., Pirani, A., Geden, O., Jones, C.D., Maharaj, S., Poloczanska, E.S., Morelli, A., Johansen, T.G., Adler, C. and Betts, R.A. (2025). 'Overshoot: A Conceptual Review of Exceeding and Returning to Global Warming of 1.5° C'. Annual Review of Environment and Resources, 50. https://doi.org/10.1146/annurev-environ-111523-102029

Richards, Z.T. (2024). 'Conservation: Corals in an extinction vortex'. Current Biology, 34(21), pp.R1090-R1093. https://doi.org/10.1016/j.cub.2024.09.081

Richards, Z.T., Haines, L., Ross, C., Preston, S., Matthews, T., Terriaca, A., Black, E., Lewis, Y., Mannolini, J., Dean, P. and Middleton, V., 2024. Deoxygenation following coral spawning and low-level thermal stress trigger mass coral mortality at Coral Bay, Ningaloo Reef. Coral Reefs, 43(2), pp.443-453.https://doi.org/10.1007/s00338-024-02476-x

Richie et al (2025). 'Overshooting tipping point thresholds in a changing climate'. Nature, 592(7855), pp.517-523. https://doi.org/10.1038/s41586-021-03263-2

Rodrigues, R.R., Artana, C., Neto, A.G., Frölicher, T.L., Keenlyside, N., Hobday, A.J., Burger, F.A., Bernardo, P.S. and Araújo, J. (2025a). 'Extreme compound events in the equatorial and South Atlantic'. Nature Communications, 16(1), p.3183. https://www.nature.com/articles/s41467-025-58238-y.pdf

Rocha, L.A., Pinheiro, H.T., Shepherd, B., Papastamatiou, Y.P., Luiz, O.J., Pyle, R.L. and Bongaerts, P., 2018. Mesophotic coral ecosystems are threatened and ecologically distinct from shallow water reefs. Science, 361(6399), pp.281-284.https://www.science.org/doi/10.1126/science.aaq1614

Rodrigues, R.R., Gonçalves Neto, A.H., Vieira, E.A. and Longo, G.O. (2025b). 'The severe 2020 coral bleaching event in the tropical Atlantic linked to marine heatwaves'. Communications Earth & Environment, 6(1), p.208. https://www.nature.com/articles/s43247-025-02195-3.pdf

Santana-Falcón, Y., Yamamoto, A., Lenton, A., Jones, C.D., Burger, F.A., John, J.G., Tjiputra, J., Schwinger, J., Kawamiya, M., Frölicher, T.L. and Ziehn, T. (2023). 'Irreversible loss in marine ecosystem habitability after a temperature overshoot'. Communications Earth & Environment, 4(1), p.343. https://doi.org/10.1038/s43247-023-01002-1

Schleussner, C.F., Ganti, G., Lejeune, Q., Zhu, B., Pfleiderer, P., Prütz, R., Ciais, P., Frölicher, T.L., Fuss, S., Gasser, T. and Gidden, M.J. (2024). 'Overconfidence in climate overshoot'. Nature, 634(8033), pp.366-373. https://doi.org/10.1038/s41586-024-08020-9

Setter, R.O., Franklin, E.C. and Mora, C. (2022). 'Co-occurring anthropogenic stressors reduce the timeframe of environmental viability for the world's coral reefs'. PLoS Biology, 20(10), p.e3001821. https://doi.org/10.1371/journal.pbio.3001821

Sheppard, C., Sheppard, A. and Fenner, D. (2020). 'Coral mass mortalities in the Chagos Archipelago over 40 years: regional species and assemblage extinctions and indications of positive feedbacks'. Marine Pollution Bulletin, 154, p.111075. https://doi.org/10.1016/j.marpolbul.2020.111075.

Skirving, W.J., Heron, S.F., Marsh, B.L., Liu, G., De La Cour, J.L., Geiger, E.F. and Eakin, C.M. (2019). 'The relentless march of mass coral bleaching: a global perspective of changing heat stress'. Coral reefs, 38(4), pp.547-557. https://doi.org/10.1007/s00338-019-01799-4

Smith, K.E., Aubin, M., Burrows, M.T., Filbee-Dexter, K., Hobday, A.J., Holbrook, N.J., King, N.G., Moore, P.J., Sen Gupta, A., Thomsen, M. and Wernberg, T. (2024). 'Global impacts of marine heatwaves on coastal foundation species'. Nature Communications, 15(1), p.5052. https://doi.org/10.1038/s41467-024-49307-9

Smith, K.E., Burrows, M.T., Hobday, A.J., King, N.G., Moore, P.J., Sen Gupta, A., Thomsen, M.S., Wernberg, T. and Smale, D.A. (2023). 'Biological impacts of marine heatwaves'. Annual review of marine science, 15(1), pp.119-145. https://doi.org/10.1146/annurev-marine-032122-121437

Smith, K.E., Sen Gupta, A., Burrows, M.T., Filbee-Dexter, K., Hobday, A.J., Holbrook, N.J., Malan, N., Moore, P.J., Oliver, E.C., Thomsen, M.S. and Wernberg, T. (2025). 'Ocean extremes as a stress test for marine ecosystems and society'. Nature Climate Change, pp.1-5. https://doi.org/10.1038/s41558-025-02269-2

Souter, D., Planes, S., Wicquart, J., Logan, M., Obura, D., Staub, F. (eds) (2021). 'Status of coral reefs of the world: 2020 report'. Global Coral Reef Monitoring Network (GCRMN) and International Coral Reef Initiative (ICRI). https://doi.org/10.59387/WOTJ9184

Statista (2022). 'Caribbean economies most dependent on tourism 2022'.| https://www.statista.com/statistics/789517/caribbean-direct-contribution-travel-tourism-gdp-country/

Stokes, C.R., Bamber, J.L., Dutton, A. and DeConto, R.M. (2025). 'Warming of+ 1.5° C is too high for polar ice sheets'. Communications Earth & Environment, 6(1), p.351. https://doi.org/10.1038/s43247-025-02299-w

Storlazzi, C.D., Reguero, B.G., Yates, K.K., Cumming, K.A., Cole, A., Shope, J.B., Gaido, C., Zawada, D.G., Arsenault, S.R., Fehr, Z.W. and Nickel, B.A. (2021). 'Rigorously valuing the impact of projected coral reef degradation on coastal hazard risk in Florida (No. 2021-1055)'. US Geological Survey. https://doi.org/10.3133/ofr20211055

Tachiiri, K., Herran, D.S., Su, X. and Kawamiya, M. (2019). 'Effect on the Earth system of realizing a 1.5 C warming climate target after overshooting to the 2 C level'. Environmental Research Letters, 14(12), p.124063. https://doi.org/10.1088/1748-9326/ab5199

Thompson, A.M., Stathakopoulos, A., Hollister, K.J. et al. Acute heat stress and the extirpation of a threatened coral species from a remote, subtropical reef system. Coral Reefs 44, 1023–1030 (2025). https://doi.org/10.1007/s00338-025-02653-6

Venegas, R.M., Acevedo, J. and Treml, E.A. (2023). 'Three decades of ocean warming impacts on marine ecosystems: A review and perspective'. Deep Sea Research Part II: Topical Studies in Oceanography, 212, p.105318. https://doi.org/10.1016/j.dsr2.2023.105318.

Vercelloni, J., Caley, M.J. and Mengersen, K.L. (2020). 'Thresholds of coral cover that support coral reef biodiversity'. In Case Studies in Applied Bayesian Data Science: CIRM Jean-Morlet Chair, Fall 2018 (pp. 385-398). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-42553-1_16

Virkkala, A.M., Rogers, B.M., Watts, J.D., Arndt, K.A., Potter, S., Wargowsky, I., Schuur, E.A., See, C.R., Mauritz, M., Boike, J. and Bret-Harte, M.S. (2025). 'Wildfires offset the increasing but spatially heterogeneous Arctic–boreal CO2 uptake'. Nature Climate Change, 15(2), pp.188-195. https://doi.org/10.1038/s41558-024-02234-5

Vogt-Vincent, N.S., Pringle, J.M., Cornwall, C.E. and McManus, L.C. (2025). 'Anthropogenic climate change will likely outpace coral range expansion'. Science Advances, 11(23), p.eadr2545. https://doi.org/10.1126/sciadv.adr2545

von Schuckmann, K., Moreira, L., Cancet, M., Gues, F., Autret, E., Baker, J., Bricaud, C., Bourdalle-Badie, R., Castrillo, L., Cheng, L. and Chevallier, F. (2024). 'The state of the global ocean'. State of the Planet, 4, pp.1-30. https://doi.org/10.5194/sp-4-osr8-1-2024

Wang, S., Foster, A., Lenz, E.A., Kessler, J.D., Stroeve, J.C., Anderson, L.O., Turetsky, M., Betts, R., Zou, S., Liu, W. and Boos, W.R. (2023). 'Mechanisms and impacts of Earth system tipping elements'. Reviews of Geophysics, 61(1), p.e2021RG000757. https://doi.org/10.1029/2021RG000757

Wilson, S.K., Graham, N.A., Pratchett, M.S., Jones, G.P. and Polunin, N.V. (2006). 'Multiple disturbances and the global degradation of coral reefs: are reef fishes at risk or resilient?' Global Change Biology, 12(11), pp.2220-2234. https://doi.org/10.1111/j.1365-2486.2006.01252.x

Witkowski, C.R., von der Heydt, A.S., Valdes, P.J., van der Meer, M.T., Schouten, S. and Sinninghe Damsté, J.S. (2024). 'Continuous sterane and phytane δ13C record reveals a substantial p CO2 decline since the mid-Miocene'. Nature Communications, 15(1), p.5192. https://doi.org/10.1038/s41467-024-47676-9

World Bank (2025). 'Rethinking Caribbean Tourism: Strategies for a More Sustainable Future'. World Bank, Washington. USA. https://hdl.handle.net/10986/43002

World Metereological Organization (2025) 'State of the Global Climate 2024'. WMO, Geneva. https://library.wmo.int/idurl/4/69455

Wunderling, N., Winkelmann, R., Rockström, J., Loriani, S., Armstrong McKay, D.I., Ritchie, P.D., Sakschewski, B. and Donges, J.F. (2023). 'Global warming overshoots increase risks of climate tipping cascades in a network model'. Nature Climate Change, 13(1), pp.75-82. https://doi.org/10.1038/s41558-022-01545-9

References 4.4

Åkesson, H., Nisancioglu, K. H., Giesen, R. H. and Morlighem, M (2017) 'Simulating the evolution of Hardangerjøkulen ice cap in southern Norway since the mid-Holocene and its sensitivity to climate change', The Cryosphere, 11(1), pp. 281–302. https://doi.org/10.5194/tc-11-281-2017.

Alaska Department of Fish and Game (2025) 'Alaska Sport Fishing Survey', Juneau sport fish harvest and effort estimates by fisheries and species, 2023. https://www.adfg.alaska.gov/sf/sportfishingsurvey/

Ambrosini, R., Azzoni, R. S., Pittino, F., Diolaiuti, G., Franzetti, A. and Parolini, M (2019) 'First evidence of microplastic contamination in the supraglacial debris of an alpine glacier', Environmental Pollution, 253, pp. 297–301. https://doi.org/10.1017/jog.2016.14.

Amundson, J. M (2016) 'A mass-flux perspective of the tidewater glacier cycle', Journal of Glaciology, 62(231), pp. 82–93. https://doi.org/10.1017/jog.2016.14.

Baccolo, G., Łokas, E., Gaca, P., Massabò, D., Ambrosini, R., Azzoni, R. S., Clason, C., Di Mauro, B., Franzetti, A., Nastasi, M., Prata, M., Prati, P., Previtali, E., Delmonte, B. and Maggi, V (2020) 'Cryoconite: An efficient accumulator of radioactive fallout in glacial environments', The Cryosphere, 14(2), pp. 657–672. https://doi.org/10.5194/tc-14-657-2020.

Beaudreau, A. H., Bergstrom, C. A., Whitney, E. J., Duncan, D. H. and Lundstrom, N. C (2022) 'Seasonal and interannual variation in high-latitude estuarine fish community structure along a glacial to non-glacial watershed gradient in Southeast Alaska', Environmental Biology of Fishes, 105, pp. 431–452. https://doi.org/10.1007/s10641-022-01238-2

Behnke, M. I., Fellman, J. B., Nagorski, S., Spencer, R. G. M. and Hood, E (2023) 'The role of glacier erosion in riverine particulate organic carbon export', Global Biogeochemical Cycles, 37(11), e2023GB007721. https://doi.org/10.1029/2023GB007721

Bellmore, J. R., J. B. Fellman, E. Hood, M. R. Dunkle and R. T. Edwards (2022) 'A melting cryosphere constrains fish growth by synchronizing the seasonal phenology of river food webs', Global Change Biology, 28(16), pp. 4807–4818. https://doi.org/10.1111/gcb.16273

Bidlack, A. L., Bisbing, S. M., Buma, B. J., Diefenderfer, H. L., Fellman, J. B., Floyd, W. C., Giesbrecht, I., Lally, A., Lertzman, K. P., Perakis, S. S., Butman, D. E., D'Amore, D. V., Fleming, S. W., Hood, E. W., Hunt, B. P. V., Kiffney, P. M., McNicol, G., Menounos, B. and Tank, S. E (2021) 'Climate-mediated changes to linked terrestrial and marine ecosystems across the Northeast Pacific coastal temperate rainforest margin', BioScience, 71(6), pp. 581–595. https://doi.org/10.1093/biosci/biaa171.

Bolibar, J., Rabatel, A., Gouttevin, I., Zekollari, H. and Galiez, C (2022) 'Nonlinear sensitivity of glacier mass balance to future climate change unveiled by deep learning', Nature Communications, 13, 409. https://doi:10.1038/s41467-022-28034-9.

Boyce, E. S., Motyka, R. J. and Truffer, M (2007) 'Flotation and retreat of a lake-calving terminus, Mendenhall Glacier, southeast Alaska, USA', Journal of Glaciology, 53(181), pp. 211–224. https://doi.org/10.3189/172756507782202928.

Brown, C.L., Bembenic, T., Brown, M., Cold, H., Coleman, J., Donaldson, E., Egelhoff, J., Jones, B., Keating, J.M., Sill, L.A., Urquia, M., Wilcox, C., Barnett, T (2023) 'Alaska Subsistence and Personal Use Salmon fisheries 2020 Annual Report, Technical Paper No'. 494. Alaska Department of Fish and Game Division of Subsistence. Available at https://www.adfg.alaska.gov/techpap/TP494.pdf (Accessed: 16. July 2025).

Bruns, C. J. and Andersen, I. V (2023) 'The worth of nature: Valuations of glaciers in Alaskan and Norwegian media discourse', Environmental Communication, 18(3), pp. 250–265. https://doi.org/10.1080/17524032.2023.2289031.

Bryant, M. D (2009) 'Global climate change and potential effects on Pacific salmonids in freshwater ecosystems of southeast Alaska', Climatic Change, 95(pp. 1–2), pp. 169–193. https://doi.org/10.1007/s10584-008-9530-x.

Carrlee, E (2006) 'Conservation and exhibit of an archaeological fish trap', Objects Specialty Group Postprints, 13, pp. 117–129.

Central Council of the Tlingit and Haida Indian Tribes of Alaska (2021) 'Climate Change Adaptation Plan: Socioeconomic Impacts of Climate Change in Southeast Alaska', Juneau, Alaska. Available at https://tlingitandhaida.gov/wp-content/uploads/ClimateChangeActionPlan-1.pdf (Accessed 12 July 2025)

Central Council of the Tlingit and Haida Indian Tribes of Alaska (2023) 'Q4 2023 Tribal News', Juneau, AK. Available at https://issuu.com/ccthita/docs/q42023tribalnews (Accessed 1 July 2025)'.

Central Council of the Tlingit and Haida Indian Tribes of Alaska (2025) 'Alaska Legislature Honors Tlingit and Haida for Exemplary Flood Response, Council of the Tlingit and Haida Indian Tribes of Alaska', Juneau, AK. Available at https://tlingitandhaida.gov/news/alaska-legislature-honors-tlingit-haida-for-exemplary-flood-response/ (Accessed 16 July 2025).

City and Borough of Juneau, (2024a). Local, tribal and federal partners join forces to find long-term solution for glacial lake outburst flooding, City and Borough of Juneau Newsroom, 13 December 2024, https://juneau.org/newsroom-item/local-tribal-and-federal-partners-join-forces-to-find-long-term-solution-for-glacial-lake-outburst-flooding (Accessed 14. July 2025).

City and Borough of Juneau, (2024b). HESCO Barrier Installation: Phase 1 – Alignment and Installation Considerations, statement released 19 Dec., Juneau, Alaska.

City and Borough of Juneau, (2025a) 'Alaska delegation delivers on end-of-year GLOF funding; funding to study a long-term solution to Mendenhall Glacial Lake Outburst Flooding (GLOF) included in the American Relief Act of 2025'. Available at https://juneau.org/newsroom-item/alaska-delegation-delivers-on-end-of-year-glof-funding-funding-to-study-a-long-term-solution-to-mendenhall-glacial-lake-outburst-flooding-glof-included-in-the-american-relief-act-of-2025 (Accessed 12 July 2025).

City and Borough of Juneau (2025b). Mendenhall Valley flood fighting maps published. Juneau, Alaska. Available at https://juneau.org/newsroom-item/mendenhall-valley-flood-fighting-maps-published (Accessed 12 July 2025).

Clague, J. J., Koch, J. and Geertsema, M (2010). 'Expansion of outlet glaciers of the Juneau Icefield in northwest British Columbia during the past two millennia', The Holocene, 20(3), 411–418. https://doi.org/10.1177/09596836093534.

Climate Adaptation Science Center (2021) 'Project Spotlight: Alaska CASC Helps Juneau Community Understand Mysterious Glacial Outburst Floods'. Available at https://www.usgs.gov/programs/climate-adaptation-science-centers/news/project-spotlight-alaska-casc-helps-juneau (Accessed: 7 July 2025).

Colgan, W., Pfeffer, W. T., Rajaram, H., Abdalati, W. and Balog, J (2012) 'Monte Carlo ice flow modeling projects a new stable configuration for Columbia Glacier, Alaska, c', 2020. The Cryosphere, 6(6), pp. 1395–1409. https://doi.org/10.5194/tc-6-1395-2012.

Cook, K. L., Andermann, C., Gimbert, F., Adhikari, B. R. and Hovius, N (2018) 'Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya', Science, 362(6410), pp. 53–57. https://doi.org/10.1126/science.aat4981.

Criscitiello, A. S., Kelly, M. A. and Tremblay, B (2010) 'The Response of Taku and Lemon Creek Glaciers to Climate', Arctic, Antarctic and Alpine Research, 42(1), pp. 34–44.

Crowell, Aron (2024) 'Laaxaayík, Near the Glacier: Indigenous History and Ecology at Yakutat Fiord, Alaska', Smithsonian Contributions to Anthropology, PP 68. http://dx.doi.org/10.5479/si.25420687.

Cruikshank, J (2001) 'Glaciers and climate change: Perspectives from oral tradition', Arctic, 54(4), pp. 377–393.

Cruikshank, J (2005) 'Do Glaciers Listen? Local Knowledge, Colonial Encounters and Social Imagination', 328 pp., University of British Columbia Press, Vancouver'.

Dame, J., Nüsser, M., Schmidt, S. and Zang, C (2023) 'Socio-hydrological dynamics and water conflicts in the upper Huasco valley, Chile', Frontiers in Water, 5. https://www.frontiersin.org/journals/water/articles/10.3389/frwa.2023.1100977.

Dauenhauer, N. M. and Dauenhauer, R (1987) ', Introduction', in N. M. Dauenhauer and R. Dauenhauer (Eds.), Haa Shuká, Our Ancestors in Tlingit Oral Narratives, pp. 514, University of Washington Press, Seattle and Sealaska Heritage Foundation, Juneau.

Davies, B., Bendle, J., Carrivick, J., McNabb, R., McNeil, C., Pelto, M., Campbell, S., Holt, T., Ely, J. and Markle, B (2022) 'Topographic controls on ice flow and recession for Juneau Icefield (Alaska/British Columbia)', Earth Surface Processes and Landforms, 47(9). https://doi.org/10.1002/esp.5383.

Davies, B., McNabb, R., Bendle, J., Carrivick, J., Ely, J., Holt, T., Markle, B., McNeil, C., Nicholson, L. and Pelto, M (2024) 'Accelerating glacier volume loss on Juneau Icefield driven by hypsometry and melt-accelerating feedbacks', Nature Communications, 15, 5099. https://doi.org/10.1038/s41467-024-49269-y.

Dennis, D (2024) 'Temperature controls on bedrock hillslope erosion in the high European Alps'. PhD Dissertation. Freie Universitaet Berlin. https://refubium.fu-berlin.de/handle/fub188/47749.

Draebing, D., Mayer, T., Jacobs, B. and McColl, S.T (2022) 'Alpine rockwall erosion patterns follow elevation-dependent climate trajectories', Communications Earth and Environment, 3(21). https://doi.org/10.1038/s43247-022-00348-2.

Dunkle, M. R., J. R. Bellmore, J. B. Fellman and C. C. Caudill (2024) 'Glaciers, snow and rain: Water source influences invertebrate community structure and secondary production across a hydrologically diverse subarctic landscape', Limnology and Oceanography, 69, pp. 232–245. https://doi:10.1002/lno.12451.

Dunning, S. A., Rosser, N. J., McColl, S. T. and Reznichenko, N. V (2015) 'Rapid sequestration of rock avalanche deposits within glaciers', Nature Communications, 6, 7964. https://doi:10.1038/ncomms8964.

Fellman, J. B., Nagorski, S., Pyare, S., Vermilyea, A. W., Scott, D. and Hood, E (2014) 'Stream temperature response to variable glacier coverage in coastal watersheds of Southeast Alaska', Hydrological Processes, 28(4), pp. 2062–2073. https://doi.org/10.1002/hyp.9742.

Garrett, J (2024) '"Building a weather-ready nation": What's new for Suicide Basin's outburst flooding, Juneau Empire, 4 June 2024. Available at https://www.juneauempire.com/news/building-a-weather-ready-nation-whats-new-for-suicide-basins-outburst-flooding/ (Accessed 13 July 2025).

Garrett, J (2025) 'UAS releases Juneau Glacial Flood Dashboard to help community plan for flooding', Juneau Empire. Available at https://www.juneauempire.com/news/uas-releases-juneau-glacial-flood-dashboard-to-help-community-plan-for-flooding/.

Gray, D (2022) 'LONGING FOR CEDAR: TRACING INDIGENOUS FAMILY IN THE PACIFIC NORTHWEST FROM LONGHOUSES TO URBAN SPRAWL AND BUREAUCRATIC COMMAND'. 2022 Fall Honors Capstone Projects, University of Texas-Arlington at Arlington. https://mavmatrix.uta.edu/honors_fall2022/3

Great Britain–United States Alaska Boundary Tribunal (1903) 'CONVENTION BETWEEN GREAT BRITAIN AND THE UNITED STATES OF AMERICA FOR THE ADJUSTMENT OF THE BOUNDARY BETWEEN THE DOMINION OF CANADA AND THE TERRITORY OF ALASKA, SIGNED AT WASHINGTON, JANUARY 24, 1903, in Reports of International Arbitral Awards, vol'. 15, pp. 481–540, United Nations, Geneva. Available at (Accessed: 8 July 2025). Available at https://legal.un.org/riaa/cases/vol_XV/481-540.pdf (Accessed 8 July 2025).

Hebda, R., Greer, S., Mackie, A (2017) 'Kwädąy Dän Ts'ìnchį: Teachings from Long Ago Person Found', The Royal British Columbia Museum, PP pp. 419–423.

Herbert, S (2025) 'UAF to get $7.5M for research into Alaska's critical mineral potential', Alaska Public Media. Available at https://alaskapublic.org/news/economy/2025-01-14/uaf-to-get-7-5m-for-research-into-alaskas-critical-mineral-potential (accessed 15 July 2025).

Hock, R., Bliss, A., Marzeion, B., Giesen, R. H., Hirabayashi, Y., Huss, M., Radić, V. and Slangen, A. B. A (2019) 'GlacierMIP – A model intercomparison of global-scale glacier mass-balance models and projections', Journal of Glaciology, 65(251), pp. 453–467. https://doi:10.1017/jog.2019.22.

Hood, E. and Scott, D (2008) 'Riverine organic matter and nutrients in southeast Alaska affected by glacial coverage', Nature Geoscience, 1, pp. 583–587. https://doi.org/10.1038/ngeo280.

Hood, E. and Berner, L (2009) 'Effects of changing glacial coverage on the physical and biogeochemical properties of coastal streams in southeastern Alaska', J. Geophys. Res. Biogeosci., 114(G3). https://doi.org/10.1029/2009JG000971.

Holt, A. D., Fellman, J., Hood, E., Kellerman, A. M., Raymond, P., Stubbins, A., Dittmar, T. and Spencer, R. G. M (2023) 'The evolution of stream dissolved organic matter composition following glacier retreat in coastal watersheds of southeast Alaska', Biogeochemistry, 164, pp. 99–116. https://doi.org/10.1007/s10533-021-00837-2.

House, L (2023) 'Healing the Land Together: salmon stream restoration with community forest partnerships', Sustainable Southeast Partnership, 17 Nov. Available at https://sustainablesoutheast.net/healing-the-land-together-salmon-stream-restoration-with-community-forest-partnerships/ (Accessed 11 Sep. 2025).

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

ICCI (2024) 'State of the Cryosphere 2024 – Lost Ice, Global Damage', International Cryosphere Climate Initiative (ICCI), Stockholm, Sweden. 72 pp.

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

Ing, R.N., Ely, J.C., Jones, J.M. and Davies, B.J (2025) 'Surface mass balance modelling of the Juneau Icefield highlights the potential for rapid ice loss by the mid-21st century', Journal of Glaciology, 71, pp. 11. https://doi.org/10.1017/jog.2024.82.

James, S (1987) ', Glacier Bay History, in N'. M. Dauenhauer and R. Dauenhauer (Eds.), Haa Shuká, Our Ancestors in Tlingit Oral Narratives, (pp. 245–260), University of Washington Press, Seattle and Sealaska Heritage Foundation, Juneau.

Jiskoot, H., Curran, C. J., Tessler, D. L. and Shenton, L. R (2009) 'Changes in Clemenceau Icefield and Chaba Group glaciers, Canada, related to hypsometry, tributary detachment, length–slope and area–aspect relations', Annals of Glaciology, 50(53), pp. 133–143. https://doi.org/10.3189/172756410790595796.

Jorgenson, T., Yoshikawa, K., Kanevskiy, M., Shur, Y., Romanovsky, V., Marchenko, S., Grosse, G., Brown, J. and Jones, B (2008) 'Permafrost characteristics of Alaska'. Institute of Northern Engineering, University of Alaska Fairbanks.

Kääb, A., Bazilova, V., Leclercq, P. W., Mannerfelt, E. S. and Strozzi, T (2023) 'Global clustering of recent glacier surges from radar backscatter data, 2017–2022', Journal of Glaciology, 69(277), pp. 1515–1523. https://doi.org/10.1017/jog.2023.98

Kienholz, C., Pierce, J., Hood, E., Amundson, J. M., Wolken, G. J., Jacobs, A., Hart, S., Wikstrom Jones, K., Abdel-Fattah, D., Johnson, C. and Conaway, J. S (2020) 'Deglacierization of a marginal basin and implications for outburst floods, Mendenhall Glacier, Alaska', Frontiers in Earth Science, 8, 137. https://doi.org/10.3389/feart.2020.00137.

Krumrey, Y. (2025). 'Juneau Assembly approves funding to boost staffing at Mendenhall Glacier this summer', KTOO, 20 May 2025. Available at https://www.ktoo.org/2025/05/20/juneau-assembly-approves-funding-to-boost-staffing-at-mendenhall-glacier-this-summer/ (accessed 13. July 2025).

KTOO News Department, (2024) 'Resources for Juneau residents affected by glacial flooding', KTOO. https://www.ktoo.org/2024/08/06/resources-for-juneau-residents-impacted-by-glacial-flooding/ (accessed 9 July 2025).

La Rose v. Her Majesty the Queen, T-1750-19 (Federal Court of Canada, 2020). Retrieved from https://climatecasechart.com/wp-content/uploads/non-us-case-documents/2019/20191025_T-1750-19_complaint.pdf.

Larsen, C. F., Motyka, R. J., Arendt, A. A., Echelmeyer, K. A. and Geissler, P. E (2007) 'Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise', Journal of Geophysical Research: Earth Surface, 112(F1). https://doi.org/10.1029/2006JF000586

Larson, C (2024) 'Alaska leaders work together following 'devastating' glacial flooding in Juneau', Alaska Public Media. https://alaskapublic.org/2024/08/08/alaska-leaders-work-together-following-devastating-glacial-flooding-in-juneau/ (accessed 9 July 2025)

Lindo J, Achilli A, Perego UA, Archer D, Valdiosera C, Petzelt B, Mitchell J, Worl R, Dixon EJ, Fifield TE, Rasmussen M, Willerslev E, Cybulski JS, Kemp BM, DeGiorgio M, Malhi RS (2017) 'Ancient individuals from the North American Northwest Coast reveal 10,000 years of regional genetic continuity', Proc Natl Acad Sci U.S.A., 114 (16) pp. 4093–4098. https://doi:10.1073/pnas.1620410114.

Łokas, E., Zaborska, A., Kolicka, M., Różycki, M. and Zawierucha, K (2016) 'Accumulation of atmospheric radionuclides and heavy metals in cryoconite holes on an Arctic glacier', Chemosphere, 160, pp. 162–172. https://doi.org/10.1016/j.chemosphere.2016.06.046.

Łokas, E., Wachniew, P., Baccolo, G., Gaca, P., Janko, K., Milton, A., Buda, J., Komędera, K. and Zawierucha, K (2022) 'Unveiling the extreme environmental radioactivity of cryoconite from a Norwegian glacier', Science of The Total Environment, 814, 152656. https://doi.org/10.1016/j.scitotenv.2021.152656.

Lundstrom, N. C., Beaudreau, A. H., Mueter, F. J. and Konar, B (2022) 'Environmental drivers of nearshore fish community composition and size structure in glacially influenced Gulf of Alaska estuaries', Estuaries and Coasts, 45, pp. 2151–2165. https://doi.org/10.1007/s12237-022-01052-3.

Makowska, N., Zawierucha, K., Nadobna, P., Piątek-Bajan, K., Krajewska, A., Szwedyk, J., Iwasieczko, P., Mokracka, J. and Koczura, R (2020) 'Occurrence of integrons and antibiotic resistance genes in cryoconite and ice of Svalbard, Greenland and the Caucasus glaciers', Science of The Total Environment, 716, 137022. https://doi.org/10.1016/j.scitotenv.2020.137022.

Marzeion, B., Kaser, G., Maussion, F. and Champollion, N (2018) 'Limited influence of climate change mitigation on short-term glacier mass loss', Nature Climate Change, 8(3), pp. 305–308. https://doi.org/10.1038/s41558-018-0093-1.

McDonald, M. E., Hershey, A. E. and Miller, M. C (1996) 'Global warming impacts on lake trout in Arctic lakes', Limnology and Oceanography, 41(5), pp. 1102–1108. https://doi.org/10.4319/lo.1996.41.5.1102.

McKinley Research Group (2023a). 'Economic Impact of Juneau's Cruise Industry – 2023', City and Borough of Juneau, Juneau, Alaska. Available at https://juneau.org/wp-content/uploads/2024/07/Juneau-Cruise-Impacts-Report-REV-7.26.24.pdf (accessed 19 June 2025).

McKinley Research Group (2023b), 'Juneau Tourism Survey', City and Borough of Juneau, Juneau, Alaska. Available at https://juneau.org/wp-content/uploads/2024/07/Juneau-Cruise-Impacts-Report-REV-7.26.24.pdf (accessed 19 June 2025).

McGrath, D., Sass, L., O'Neel, S., Arendt, A. and Kienholz, C (2017) 'Hypsometric control on glacier mass balance sensitivity in Alaska and northwest Canada', Earth's Future, 5(3), pp. 324–336. https://doi.org/10.1002/2016EF000479.

McNeil, C., O'Neel, S., Loso, M., Pelto, M., Sass, L., Baker, E. H. and Campbell, S (2020) 'Explaining mass balance and retreat dichotomies at Taku and Lemon Creek Glaciers, Alaska', Journal of Glaciology, 66(258), pp. 530–542. https://doi.org/10.1017/jog.2020.22.

Miller, M. M (1964) 'Inventory of terminal position changes in Alaskan coastal glaciers since the 1750s', Proceedings of the American Philosophical Society, 108(3), pp. 257–273. https://www.jstor.org/stable/985682.

Milner, A. M., Knudsen, E. E., Soiseth, C., Robertson, A. L., Schell, D., Phillips, I. T. and Magnusson, K (2000) 'Colonization and development of stream communities across a 200-year gradient in Glacier Bay National Park, Alaska, U.S.A', Can. J. Fish. Aquat. Sci., 57(11), pp. 2319–2335. https://doi.org/10.1139/f00-212.

Molnia, B. F (2007) 'Late nineteenth to early twenty-first century behavior of Alaskan glaciers as indicators of changing regional climate', Global and Planetary Change, 56(pp. 1–2), pp. 23–56. https://doi.org/10.1016/j.gloplacha.2006.07.011.

Motyka, R. J., O'Neel, S., Connor, C. L. and Echelmeyer, K. A (2002) 'Twentieth century thinning of Mendenhall Glacier, Alaska and its relationship to climate, lake calving and glacier run-off', Global and Planetary Change, 35(pp. 1–2), pp. 93–112. https://doi.org/10.1016/S0921-8181(02)00138-8.

Motyka, R. J (2003) 'Little Ice Age subsidence and post-Little Ice Age uplift at Juneau, Alaska, inferred from dendrochronology and geomorphology', Quaternary Research, 59(3), pp. 300–309. https://doi.org/10.1016/S0033-5894(03)00032-2.

Nagorski, S. A., Vermilyea, A. W. and Lamborg, C. H (2021) 'Mercury export from glacierized Alaskan watersheds as influenced by bedrock geology, watershed processes and atmospheric deposition', Geochimica et Cosmochimica Acta, 304, pp. 32–49. https://doi.org/10.1016/j.gca.2021.04.010.

Nash, D., Rutz, J.J. and Jacobs, A (2024) 'Atmospheric rivers in southeast Alaska: Meteorological conditions associated with extreme precipitation', Journal of Geophysical Research Atmospheres 129(4). https://doi.org/10.1029/2023JD039294.

Neal, E. G., M. T. Walter and C. Coffeen (2002) 'Linking the Pacific Decadal Oscillation to seasonal stream discharge patterns in Southeast Alaska', Journal of Hydrology, 263(pp. 1–4), pp. 188–197. https://doi:10.1016/S0022-1694(02)00058-6

Nyman, N and Leer, J (1993) ', Gagiwdul.at: Brought Forth to Reconfirm the Legacy of a Taku River Tlingit Clan, 294 pp., Alaska Native Language Center, Fairbanks, Alaska'.

O'Neel, S., Hood, E., Bidlack, A. L., Fleming, S. W., Arimitsu, M. L., Arendt, A., Burgess, E., Sergeant, C. J., Beaudreau, A. H., Timm, K., Hayward, G. D., Reynolds, J. H. and Pyare, S (2015) 'Icefield-to-ocean linkages across the northern Pacific coastal temperate rainforest ecosystem', BioScience, 65(5), pp. 499–512. https://doi.org/10.1093/biosci/biv027

Ord, A (2024) 'Decentering the ice: Place-based perspectives on the impacts of glacier retreat on downstream landscapes, ecosystems and communities in Lingít Aaní'. M.S. thesis, University of British Columbia. https://doi.org/10.14288/1.0444134.

Owens, P. N., Blake, W. H. and Millward, G. E (2019) 'Extreme levels of fallout radionuclides and other contaminants in glacial sediment (cryoconite) and implications for downstream aquatic ecosystems', Scientific Reports, 9, 12531. https://doi.org/10.1038/s41598-019-48969-3.

Petley, D (2025) 'The 28 April 2025 glacial outburst flood (GLOF) / landslide at Vallunaraju in Peru', Eos, 2, May 2025. Accessed July 27, 2025.

Pelto, M., Kavanaugh, J. and McNeil, C (2013) 'Juneau icefield mass

balance program 1946–2011', Earth System Science Data, 5(2), pp.pp. 319–330. https://doi.org/10.5194/essd-5-319-2013.

Pinto, A. A. S., L. F. S. Fernandes and R. J. F. O. Maia (2019) 'A method for selecting suitable technical solutions to support sustainable riverbank stabilisation', Area, 51(2), 285–298. https://doi.org/10.1111/area.12488.

Pitman, K. J., Moore, J. W., Sloat, M. R., Beaudreau, A. H., Bidlack, A. L., Brenner, R. E., Hood, E. W., Pess, G. R., Mantua, N. J., Milner, A. M., Radić, V., Reeves, G. H., Schindler, D. E. and Whited, D. C (2020) 'Glacier retreat and Pacific salmon', BioScience, 70(3), pp. 220–236. https://doi.org/10.1093/biosci/biaa015.

Powell, J., Tankersley, M., Ainsworth, T., Amundson, J., Armstrong, B., Botelho, B., Carstensen, R., D'Amore, D., Foy, R., Hood, E., Jacobs, A., Koester, K., Kruger, L., Maier, K., Mesdag, A., Mitchell, D., Nagorski, S., Paddock, R., Pearson, H., Romanoff, A., Snyder, D., Thoman, R., Thornton, T. F., Wilcox, P (2022) 'Juneau's Changing Climate and Community Response', Published by the Alaska Coastal Rainforest Center, July 2022. Available at https://acrc.alaska.edu/docs/juneau-climate-report (Accessed 16. July 2022).

Pritchard, H. D (2019) 'Asia's shrinking glaciers protect large populations from drought stress', Nature, 569(7758), pp. 649–654. https://doi.org/10.1038/s41586-019-1240-1.

Quilleré-Majzoub, F. and T. Majzoub (2010) 'À qui profitent les eaux des glaciers de montagne?' Les Cahiers de droit, 51(3–4), 659–677. https://doi.org/10.7202/045728ar.

Quinn, T. P (2005) 'The behavior and ecology of Pacific salmon and trout'. University of Washington Press, Seattle, WA, 378 pp.

Ravanel, L., Magnin, F. and Deline, P (2017) 'Impacts of the 2003 and 2015 summer heatwaves on permafrost-affected rock walls in the Mont Blanc massif', Science of the Total Environment, 609, pp. 132–143.

Ramage, J.M. and Isacks, B.L (2003) 'Interannual variations of snowmelt and refreeze timing on southeast-Alaskan icefields, USA', Journal of Glaciology, 49(164), pp. 102–116. https://doi.org/10.3189/172756503781830908.

Republic of Tajikistan (2024) 'Law No', 2026 "On Protection of Glaciers". Retrieved from https://faolex.fao.org/docs/pdf/taj224299.pdf

Riikilä, T. I., Tallinen, T., Åström, J. and Timonen, J (2015) 'A discrete-element model for viscoelastic deformation and fracture of glacial ice', Computer Physics Communications, 195, pp. 14–22. https://doi.org/10.1016/j.cpc.2015.04.025.

Roe, G. H. and O'Neal, M. A (2009) 'The response of glaciers to intrinsic climate variability: Observations and models of late-Holocene variations in the Pacific Northwest', Journal of Glaciology, 55(193), pp. 839–854. https://doi.org/10.3189/002214309790152438.

Rounce, D. R., Hock, R., Maussion, F., Hugonnet, R., Kochtitzky, W., Huss, M., Berthier, E., Brinkerhoff, D., Compagno, L. and McNabb, R. W (2023) 'Global glacier change in the 21st century: Every increase in temperature matters', Science, 379(6627), pp. 78–83. https://doi.org/10.1126/science.abo1324.

Sabbatini, M (2024) '30 Juneau households already OK'd for $605k in flood aid, FEMA official says as disaster center opens', Juneau Empire, 30 Oct. https://www.juneauempire.com/news/30-juneau-households-already-okd-for-605k-in-flood-aid-fema-official-says-as-disaster-center-opens/ (accessed 12. July 2025).

Salim, E., Ravanel, L., Deline, P. and Gauchon, C (2021) 'A review of melting ice adaptation strategies in the glacier tourism context', Scandinavian Journal of Hospitality and Tourism, 21, pp. 1–18. https://doi:10.1080/15022250.2021.1879670.

Schuster, L., Maussion, F., Rounce, D. R., Ultee, L., Schmitt, P., Lacroix, F., Frölicher, T. L. and Schleussner, C.-F (2025) 'Irreversible glacier change and trough water for centuries after overshooting 1.5 °C', Nature Climate Change, 15(6), pp. 634–641. https://doi.org/10.1038/s41558-025-02318-w.

Sergeant CJ, Sexton EK, Moore JW, Westwood AR, Nagorski SA, Ebersole JL, Chambers DM, O'Neal SL, Malison RL, Hauer FR, Whited DC, Weitz J, Caldwell J, Capito M, Connor M, Frissell CA, Knox G, Lowery ED, Macnair R, Marlatt V, McIntyre JK, McPhee MV, Skuce N (2022) 'Risks of mining to salmonid-bearing watersheds', Science Advances, 8(26). https://doi.org/10.1126/sciadv.abn0929.

Shanley, C. S. and Albert, D. M (2014) 'Climate Change Sensitivity Index for Pacific Salmon Habitat in Southeast Alaska', PLOS ONE, 9(11), e112926. https://doi.org/10.1371/journal.pone.0112926

Siegert, M., Sevestre, H., Bentley, M. J., Brigham-Grette, J., Burgess, H., Buzzard, S., Cavitte, M., Chown, S. L., Colleoni, F., DeConto, R. M., Fricker, H. A., Gasson, E., Grant, S. M., Gulisano, A. M., Hancock, S., Hendry, K. R., Henley, S. F., Hock, R., Hughes, K. A., Karentz, D., Kirkham, J. D., Kulessa, B., Larter, R. D., Mackintosh, A., Masson-Delmotte, V., McCormack, F. S., Millman, H., Mottram, R., Moon, T. A., Naish, T., Nath, C., Orlove, B., Pearson, P., Rogelj, J., Rumble, J., Seabrook, S., Silvano, A., Sommerkorn, M., Stearns, L. A., Stokes, C. R., Stroeve, J., and Truffer, M. (2025) 'Safeguarding the polar regions from dangerous geoengineering: a critical assessment of proposed concepts and future prospects'. Frontiers in Science, 3. https://doi.org/10.3389/fsci.2025.1527393.

Smith, W. D., Dunning, S. A., Ross, N., Telling, J., Jensen, E. K., Shugar, D. H., Coe, J. A. and Geertsema, M (2023) 'Revising supraglacial rock avalanche magnitudes and frequencies in Glacier Bay National Park, Alaska', Geomorphology, 425, 108591. https://doi:10.1016/j.geomorph.2022.108591

Southeast Conference (2024) 'Southeast Alaska By the Numbers 2024', Available at https://www.seconference.org/wp-content/uploads/2024/10/Meilani-Schijvens-SEAK-By-the-Numbers.pdf (Accessed 3. August 2025).

Soliman, A. (2025a). Some flood-zone residents worry Juneau's temporary levee won't hold next year. KTOO, 19 Aug. Available at https://www.ktoo.org/2025/08/19/some-flood-zone-residents-worry-juneaus-temporary-levee-wont-hold-next-year/ (Accessed 3. Sep. 2025).

Soliman, A. (2025b). "What else are we going to do?" View Drive residents weigh their options after repeated flooding. KTOO, 15 Aug. Available at https://www.ktoo.org/2025/08/15/what-else-are-we-going-to-do-view-drive-residents-weight-their-options-after-repeated-flooding/ (accessed 3. Sep. 2025).

Spencer, R. G. M., Vermilyea, A., Fellman, J., Raymond, P., Stubbins, A., Scott, D. and Hood, E (2014) 'Seasonal variability of organic matter composition in an Alaskan glacier outflow: insights into glacier carbon sources', Environmental Research Letters, 9(5), 055005. https://doi.org/10.1088/1748-9326/9/5/055005.

Sprenke, K. F., Miller, M. M., McGee, S. R., Adema, G. W. and Lang, M (1999) 'The high ice plateau of the Juneau Icefield, British Columbia: Form and dynamics', Canadian Geographies / Géographies canadiennes, 43(1), pp. 99–104. https://doi.org/10.1111/j.1541-0064.1999.tb01363.x.

State of Alaska, Department of Commerce, Community and Regional Affairs (2025) 'Community Development Block Grant – Disaster Recovery (CDBG-DR) – 2024 Juneau Flooding'. Juneau, Alaska. Available at (Accessed: 12 July 2025). https://www.commerce.alaska.gov/web/dcra/GrantsSection/CDBG-DR-Juneau (accessed 12 July 2025).

Stowell, H. H (2006) 'Geology of Southeast Alaska: Rock and Ice in Motion'. 152 pp., University of Alaska Press, Fairbanks, Alaska.

Stubbins, A., Hood, E., Raymond, P. A., Aiken, G. R., Sleighter, R. L., Hernes, P. J., Butman, D., Hatcher, P. G., Striegl, R. G., Schuster, P., Abdulla, H. A. N., Vermilyea, A. W., Scott, D. T. and Spencer, R. G. M (2012) 'Anthropogenic aerosols as a source of ancient dissolved organic matter in glaciers', Nature Geoscience, 5, pp. 198–201. https://doi.org/10.1038/ngeo1403.

TCW Economics (2010) 'Economic Contributions and Impacts of Salmonid Resources in Southeast Alaska'. TCW Economics, prepared for the Alaska Department of Fish and Game. Available at https://economic-impact-of-ag.com/AK/2010AK_Economic_Contributions_and_Impacts_of_Salmonid_Resources_in_Southeast_Alaska.pdf (accessed 16 July 2025).

Thiem, H (2024) '2024 Glacial outburst flood near Juneau sets record for second year in a row'. Climate.gov. Available at https://www.climate.gov/news-features/event-tracker/2024-glacial-outburst-flood-near-juneau-sets-record-second-year-row (accessed 15 July 2025).

Thornton, T. F (2008) 'Being and Place among the Tlingit', University of Washington Press, Seattle.

Tlingit and Haida. Co-Stewardship Áak'w T'áak Sít', Sít' Aant'aakú Mendenhall Glacier. Available at https://tlingitandhaida.gov/service/co-stewardship/.

U.S.F.S (2015) ', Tongass Salmon Factsheet', Published May 2015.

U.S. Department of Homeland Security (2023) 'Fiscal Years 2024–2027 Climate Adaptation Plan'. U.S. Department of Homeland Security, Washington, D.C. Available at https://www.sustainability.gov/pdfs/dhs-2024-cap.pdf (accessed 16. July 2025)

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J. F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J. and Rose, S. K (2011) 'The representative concentration pathways: An overview', Climatic Change, 109(pp. 1–2), pp. 5–31. https://doi.org/10.1007/s10584-011-0148-z.

Vermilyea, A. W., Nagorski, S. A., Lamborg, C. H., Hood, E. W., Scott, D. and Swarr, G. J (2017) 'Continuous proxy measurements reveal large mercury fluxes from glacial and forested watersheds in Alaska', Science of The Total Environment, pp. 599–600, pp. 145–155. https://doi:10.1016/j.scitotenv.2017.04.207.

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M. and Wada, Y (2020) 'Increasing dependence of lowland populations on mountain water resources', Nature Sustainability, 3, pp. 917–928. https://doi:10.1038/s41893-020-0530-9.

Wells, G. H., Sæmundsson, Þ., Pálsson, F., Aðalgeirsdóttir, G., Magnússon, E., Hermanns, R. L. and Guðmundsson, S (2025) 'Proglacial lake development and outburst flood hazard at Fjallsjökull glacier, southeast Iceland', Nat. Hazards Earth Syst. Sci., 25(6), pp. 1913–1936. https://doi.org/10.5194/nhess-25-1913-2025

Zekollari, H., Huybrechts, P., Noël, B., van de Berg, W. J. and van den Broeke, M. R (2017) 'Sensitivity, stability and future evolution of the world's northernmost ice cap, Hans Tausen Iskappe (Greenland)', The Cryosphere, 11(3), pp. 805–825. https://doi.org/10.5194/tc-11-805-2017.

Zekollari, H., Schuster, L., Maussion, F., Hock, R., Marzeion, B., Rounce, D.R., Compagno, L., Fujita, K., Huss, M., James, M. and Kraaijenbrink, P.D (2025) 'Glacier preservation doubled by limiting warming to 1.5° C versus 2.7° C', Science, 388(6750), pp.pp. 979–983. https://doi.org/10.1126/science.adu4675.

Zhang, Y., Gao, T., Kang, S., Allen, S., Luo, X. and Allen, D (2021) 'Microplastics in glaciers of the Tibetan Plateau: Evidence for the long-range transport of microplastics', Science of The Total Environment, 758, 143634. https://doi.org/10.1016/j.scitotenv.2020.143634.

Ziemen, F. A., Hock, R., Aschwanden, A., Khroulev, C., Kienholz, C., Melkonian, A. and Zhang, J (2016) 'Modeling the evolution of the Juneau Icefield between 1971 and 2100 using the Parallel Ice Sheet Model (PISM)', Journal of Glaciology, 62(231), pp. 199–214. https://doi.org/10.1017/jog.2016.13.